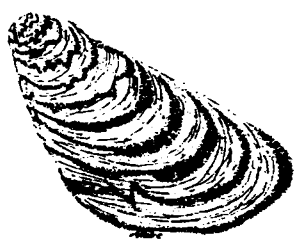
BAY TEAM

Invasion of an Exotic Species: Stop the Zebra Mussel!

Activities and Resources For Grades 8 - 12



Virginia Sea Grant
Marine Advisory Program

Forest Insect & Disease Leaflet 162

U.S. Department of Agriculture Forest Service

Gypsy Moth

M. McManus,[1] N. Schneeberger,[2] R. Reardon,[3] and G. Mason[4]

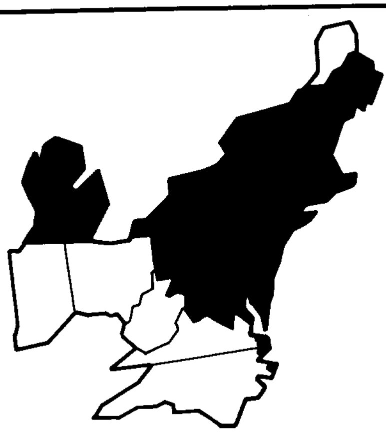


Figure 1—*Area of general infestation as of 1988.*

The gypsy moth, *Lymantria dispar* Linnaeus, is one of the most notorious pests of hardwood trees in the Eastern United States. Since 1980, the gypsy moth has defoliated close to a million or more forested acres each year. In 1981, a record 12.9 million acres were defoliated. This is an area larger than Rhode Island, Massachusetts, and Connecticut combined.

In wooded suburban areas, during periods of infestation when trees are visibly defoliated, gypsy moth larvae crawl up and down walls, across roads, over outdoor furniture, and even inside homes. During periods of feeding they leave behind a mixture of small pieces of leaves and frass, or excrement.

Gypsy moth infestations alternate between years when trees experience little visible defoliation (gypsy moth population numbers are sparse) followed by 2 to 4 years when trees are visibly defoliated (gypsy moth population numbers are dense).

The gypsy moth is not a native insect. It was introduced into the United States in 1869 by a French scientist living in Massachusetts. The first outbreak occurred in 1889. By 1987, the gypsy moth had established itself throughout the Northeast. The insect has spread south into Virginia and West Virginia, and west into Michigan (fig. 1). Infestations have also occurred in Utah, Oregon, Washington, California, and many other States outside the Northeast.

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Life Cycle

The gypsy moth passes through four stages: egg, larva, pupa, and adult (moth stage). Only the larvae damage trees and shrubs.

Gypsy moth egg masses are laid on branches and trunks of trees (fig. 2), but egg masses may be found in any sheltered location. Egg masses are buff colored when first laid but may bleach out over the winter months when exposed to direct sunlight and weathering.

The hatching of gypsy moth eggs coincides with budding of most hardwood trees. Larvae emerge from egg masses from early spring through mid-May (fig. 3).

Larvae are dispersed in two ways. Natural dispersal occurs when newly hatched larvae hanging from host trees on silken threads (fig. 4) are carried by the wind for a distance of about 1 mile. Larvae can be carried for longer distances. Artificial dispersal occurs when people transport gypsy moth eggs thousands of miles from infested areas on cars and recreational vehicles, firewood, household goods, and other personal possessions.

Figure 2—*Gypsy moth egg masses on the trunk and branch of a tree.*

Figure 3—*Gypsy moth larvae emerging from egg mass.*

Larvae develop into adults by going through a series of progressive molts through which they increase in size. Instars are the stages between each molt. Male larvae normally go through five instars (females, through six) before entering the pupal stage. Older larvae have five pairs of raised blue spots and six pairs of raised brick-red spots along their backs (fig. 5).

During the first three instars, larvae remain in the top branches or crowns of host trees. The first stage or instar chews small holes in the

Figure 4—*Gypsy moth larvae suspended on silken threads.*

leaves (fig. 6). The second and third instars feed from the outer edge of the leaf toward the center.

When population numbers are sparse, the movement of the larvae up and down the tree coincides with light intensity. Larvae in the fourth instar feed in the top branches or crown at night. When the sun comes up, larvae crawl down the trunk of the tree to rest during daylight hours. Larvae hide under flaps of bark, in crevices, or under branches—any place that provides protection. When larvae hide underneath leaf litter, mice, shrews, and *Calosoma* beetles can prey on them. At dusk, when the sun sets, larvae climb back up to the top branches of the host tree to feed.

When population numbers are dense, larvae feed continuously day and night until the foliage of the host tree is stripped (fig. 7). Then they crawl in search of new sources of food.

The larvae reach maturity between mid-June and early July. They enter the pupal stage (fig. 8). This is the stage during which larvae

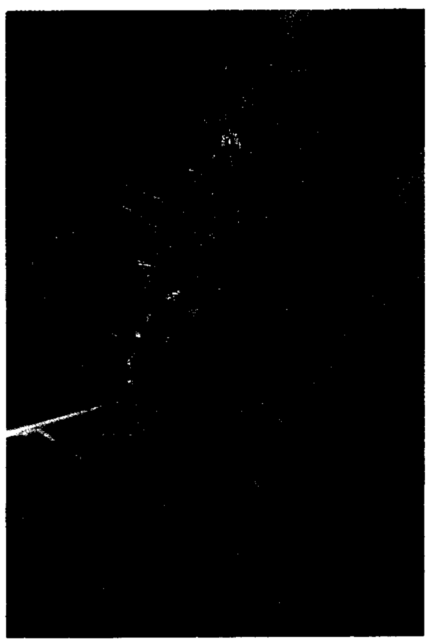


Figure 5—*Older gypsy moth larvae showing five pairs of raised blue spots and six pairs of raised brick-red spots.*

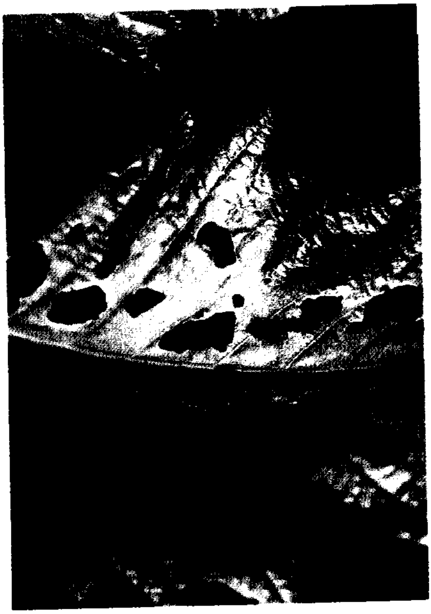


Figure 6—*First instar gypsy moth larvae chewing small holes in leaves.*

change into adults or moths. Pupation lasts from 7 to 14 days. When population numbers are sparse, pupation can take place under flaps of bark, in crevices, under branches, on the ground, and in other places where larvae rested. During periods when population numbers are dense, pupation is not restricted to locations where larvae rested. Pupation will take place in sheltered and nonsheltered locations, even exposed on the trunks of trees or on foliage of nonhost trees.

The male gypsy moth emerges first, flying in rapid zigzag patterns searching for females. When heavy, egg-laden females emerge, they emit a chemical substance called a pheromone that attracts the males (fig. 9). The female lays her eggs in July and August close to the spot where she pupated (fig. 10). Then, both adult gypsy moths die.

Four to six weeks later, embryos develop into larvae. The larvae remain in the eggs during the winter. The eggs hatch the following spring.

Figure 7—*A tree stripped by gypsy moth larvae.*

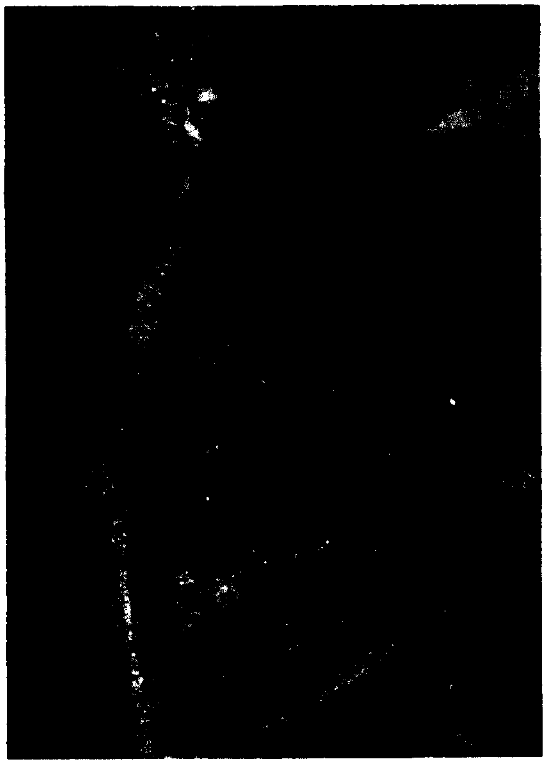


Figure 8—*Gypsy moth pupa.*

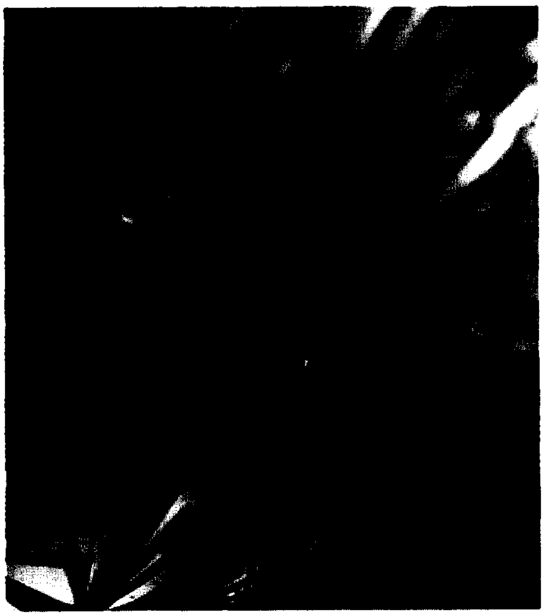


Figure 9—*Male gypsy moth.*

Hosts

Gypsy moth larvae prefer hardwoods, but may feed on several hundred different species of trees and shrubs. In the East the gypsy moth prefers oaks, apple, sweetgum, speckled alder, basswood, gray and white birch, poplar, willow, and hawthorn, although other species are also affected. The list of hosts will undoubtedly expand as the insect spreads south and west.

Older larvae feed on several species of hardwood that younger larvae avoid, including cottonwood, hemlock, southern white cedar, and the pines and spruces native to the East. During periods when gypsy moth populations are dense, larvae feed on almost all vegetation: To date, the gypsy moth has avoided ash, yellow-poplar, sycamore, butternut, black walnut, catalpa, flowering dogwood, balsam fir, red cedar, American holly, and shrubs such as mountain laurel, rhododendron, and arborvitae.

Effects of Defoliation on Trees

The effects of defoliation depend primarily on the amount of foliage that is removed, the condition of the tree at the time it is defoliated, the number of consecutive defoliations, available soil moisture, and the species of host.

If less than 50 percent of their crown is defoliated, most hardwoods will experience only a slight reduction (or loss) in radial growth.

If more than 50 percent of their crown is defoliated, most hardwoods will refoliate or produce a second flush of foliage by midsummer (figs. 11, 12). Healthy trees can usually withstand one or two consecutive defoliations of greater than 50 percent. Trees that have been weakened by previous defoliation or been subjected to other stresses such as drought are frequently killed after a single defoliation of more than 50 percent.

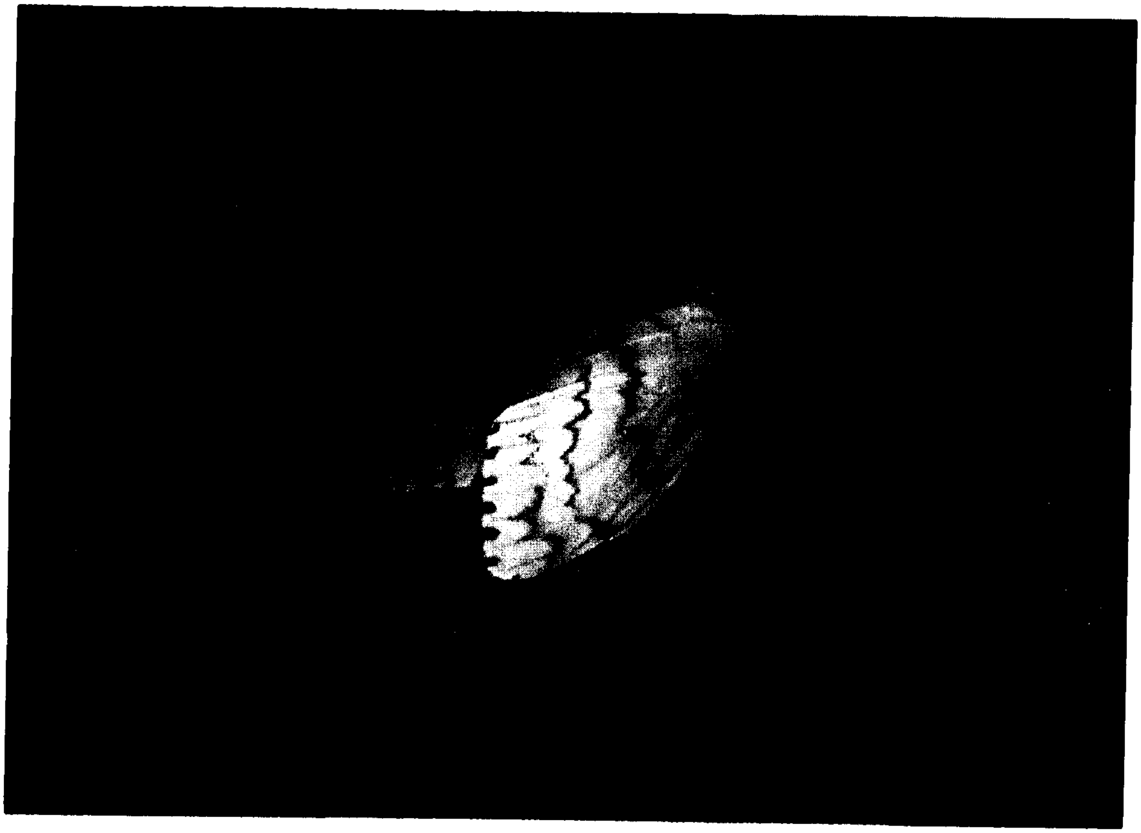


Figure 10—*Female gypsy moth laying eggs.*

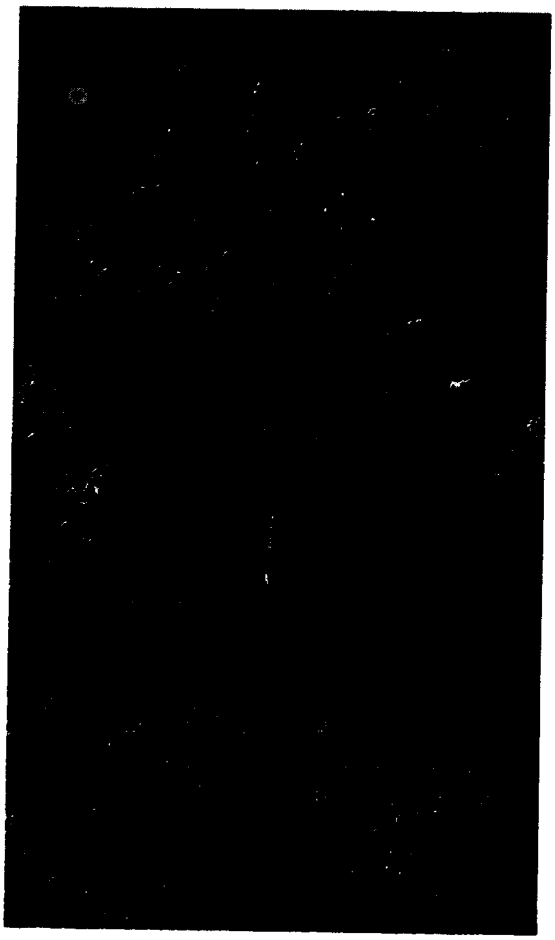


Figure 11—*Tree before defoliation.*

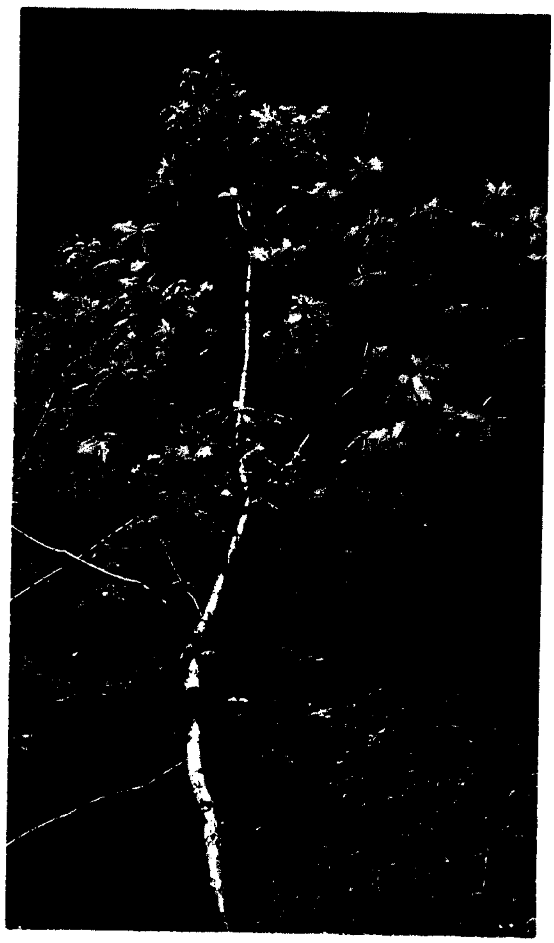


Figure 12—*Tree after refoliation.*

Trees use energy reserves during refoliation and are eventually weakened. Weakened trees exhibit symptoms such as dying back of twigs and branches in the upper crown and sprouting of old buds on the trunk and larger branches. Weakened trees experience radial growth reduction of approximately 30 to 50 percent.

Trees weakened by consecutive defoliations are also vulnerable to attack by disease organisms and other insects. For example, the *Armillaria* fungus attacks the roots, and the two-lined chestnut borer attacks the trunk and branches. Affected trees will eventually die 2 or 3 years after they are attacked.

Although not preferred by the larvae, pines and hemlocks are subject to heavy defoliation during gypsy moth outbreaks and are more likely to be killed than hardwoods. A single, complete defoliation can kill approximately 50 percent of the pines and 90 percent of the mature hemlocks.

Factors That Affect Gypsy Moth Populations

Natural enemies play an important role during periods when gypsy moth populations are sparse. Natural enemies include parasitic and predatory insects such as wasps, flies, ground beetles, and ants; many species of spider; several species of birds such as chickadees, bluejays, nuthatches, towhees, and robins; and approximately 15 species of common woodland mammals, such as the white-footed mouse, shrews, chipmunks, squirrels, and raccoons.

The *Calosoma* beetle, a ground beetle of European origin, cuckoos, and flocking birds, such as starling, grackles, and red-winged blackbirds, are attracted to infested areas in years when gypsy moth populations are dense.

Diseases caused by bacteria, fungi, or viruses contribute to the decline of gypsy moth populations, especially during periods when gypsy moth populations are dense and are stressed by lack of preferred foliage.

Wilt disease caused by the nucleopolyhedrosis virus (NPV) is specific to the gypsy moth and is the most devastating of the natural diseases. NPV causes a dramatic collapse of outbreak populations by killing both the larvae and pupae. Larvae infected with wilt disease are shiny and hang limply in an inverted "V" position (fig. 13).

Figure 13—*Larvae infected by the nucleo polyhedrosis virus (NPV) hanging in an inverted "V" position.*

Weather affects the survival and development of gypsy moth life stages regardless of population density. For example, temperatures of -20°F. (-29°C.) lasting from 48 to 72 hours can kill exposed eggs; alternate periods of freezing and thawing in late winter and early spring may prevent the overwintering eggs from hatching; and cold, rainy weather inhibits dispersal and feeding of the newly hatched larvae and slows their growth.

Managing the Gypsy Moth

A number of tactics have the potential to minimize damage from gypsy moth infestations and to contain or maintain gypsy moth populations at levels considered tolerable. These tactics include monitoring gypsy moth populations, maintaining the health and vigor of trees, discouraging gypsy moth survival, and treating with insecticides to kill larvae and protect tree foliage. The tactic or combination of tactics used will depend on the condition of the site and of the tree or stand and the level of the gypsy moth population. Tactics suggested for homeowners are probably too costly and too labor intensive for managers to use in forest stands.

Tactics Suggested for Homeowners

Homeowners might want to consider one or more of the following tactics when gypsy moth populations are sparse. These activities do not guarantee a reduction or elimination of gypsy moth populations, nor will the activities guarantee to reverse the trend of an infestation of the gypsy moth. These activities are more practical for homeowners to use on individual yard trees than for land managers to use in forest stands.

Tactics Directed Against the Gypsy Moth

- Remove objects around the outside of the home that provide shelter for gypsy moth larvae and pupae, such as flaps of bark, dead tree branches, dead trees, boxes, cans, or old tires.
- Diversify the composition of trees and plants on your property to include species not preferred by the gypsy moth, such as tulip or yellow poplar, honeylocust, ash, hickory, dogwood, mountain ash, and many conifers.
- Destroy egg masses found on outbuildings, on fencing, and in woodpiles. Simply scraping egg masses onto the ground will not destroy them. Burn them or soak them in kerosene or soapy water. Caution is urged because the hairs that coat the egg masses can cause allergic reactions. Egg masses can also be destroyed by painting them with commercially available products, such as liquid detergents.
- Place burlap on trees, especially oaks, to provide shade and shelter for older larvae when they seek out protected resting places during the day. The number of larvae and pupae that rest under the burlap provides valuable information about the severity of infestation on your property. When populations are sparse, larvae and pupae beneath burlap can be manually destroyed (fig. 14).

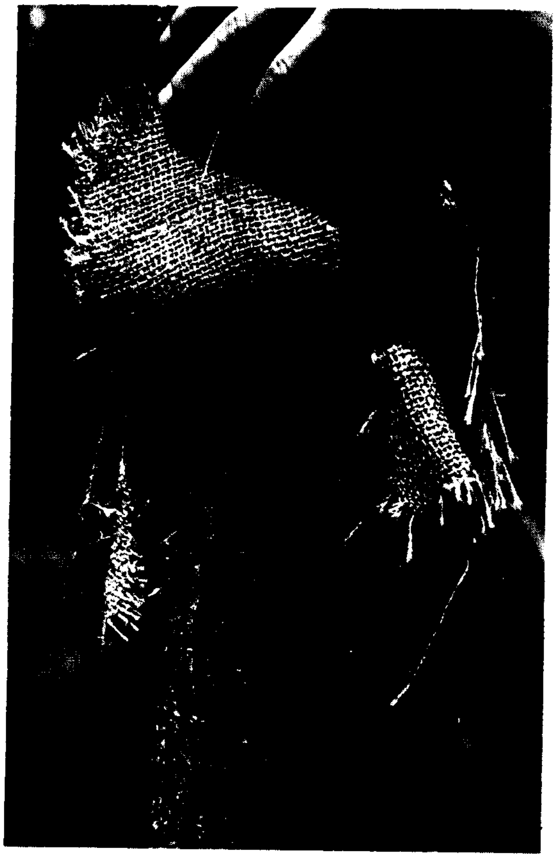


Figure 14—*Gypsy moth larvae and pupae under burlap.*

- Use barrier bands, consisting of commercially available double-sided sticky tapes, or sticky material such as Tanglefoot, petroleum jelly, or grease, to prevent larvae from crawling up the trunks of susceptible trees. These products should be applied to the surface of an impermeable material, such as duct tape or tar paper, and not applied directly to the bark. Petroleum-based products can cause injury (swelling and cankering) on thin-barked trees.

Maintaining and Enhancing the Health of Trees

- Enhance growth conditions for isolated trees by encircling them with mulch or ground cover plants that do not compete for moisture and nutrients the way dense grass layers do.
- Water shade and ornamental trees in periods of drought to maximize recovery during refoliation.
- Fertilize shade trees.
- Avoid stressing trees. For example, construction projects tend to compact soil and prevent moisture from penetrating to small feeder roots.
- Avoid applying lime or weed killers around trees. These chemicals can seriously damage shallow tree roots.
- Thin woodlot trees and groups of shade trees between outbreaks to reduce competition.

The Use of Pesticides Against the Gypsy Moth

The decision to use pesticides is influenced by a number of factors:

- The number of visible egg masses.
- The percentage of preferred hosts in a mixed stand of trees (50 percent or more of oak).
- Whether trees already have dead or dying branches, especially near the top branches or crown.
- Whether the property is located adjacent to wooded areas heavily infested with gypsy moths.

During periods when numbers of gypsy moth larvae are dense, pesticides may be the most effective method of reducing the number of larvae and protecting the foliage of host trees. Application of pesticides should be done by a certified applicator, because special equipment is required. Large acreages, such as wooded residential areas and forests, should be treated by aircraft.

Available pesticides fall into two broad groups: microbial or biological and chemical (table 1).

Microbial and biological pesticides contain living organisms that must be consumed by the pest. Microbials include bacteria, viruses, and other naturally occurring organisms; biologicals include manmade synthetics of naturally occurring organisms. These pesticides should be applied before the larvae reach the third stage or instar of development. As they mature, larvae become more resistant to microbial pesticides and are, therefore, more difficult to kill.

Nucleopolyhedrosis virus (NPV), a naturally occurring organism, has been developed as a microbial pesticide. It is presently registered under the name "Gypchek" and is available for use in USDA Forest Service–sponsored suppression programs. NPV and Gypcheck are specific to the gypsy moth.

Bacillus thuringiensis (Bt) is microbial and biological. It is the most commonly used pesticide. In addition to being used against the gypsy moth, *Bt* is used against a number of other pests, including the western spruce budworm, spruce budworm, and tent caterpillar. When *Bt* is taken internally, the insect becomes paralyzed, stops feeding, and dies of starvation or disease.

Chemical pesticides are contact poisons in addition to being stomach poisons. The timing of the chemical application is less critical to the successful population reduction of the pest than the timing of the application of the microbials and biologicals. Chemical pesticides can affect nontarget organisms and may be hazardous to human health.

Table 1—*Microbial and chemical pesticides commonly used for gypsy moth control*

Active ingredient	Representative trade names	Remarks
Bacillus thuringiensis	Dipel Thuricide	Registered for aerial and ground application. Available under a variety of trade names. Toxic to other moth and butterfly larvae. Can be used safely near water.
Acephate	Orthene	Registered for aerial and ground application. Available under a variety of trade names. Toxic to bees and some gypsy moth parasites. Commonly used from the ground to treat individual trees.
Carbaryl	Sevin	Registered for aerial and ground application. Available under a variety of trade names. Toxic to bees and gypsy moth parasites. At one time, the most widely used chemical in gypsy moth control programs.
Diflubenzuron	Dimilin	A restricted-use pesticide that can be applied only by certified applicators.

The most commonly used chemical pesticides currently registered by the U.S. Environmental Protection Agency (EPA) for use against the gypsy moth contain carbaryl, diflubenzuron, and acephate. Malathion, methoxychlor, phosmet, trichlorfon, and synthetic pyrethroids have also been registered by EPA for control of gypsy moth, but are used infrequently.

Diflubenzuron represents a new class of pesticides called insect growth regulators. It kills gypsy moth larvae by interfering with the normal molting process. Diflubenzuron has no effect on adult insects. Aquatic crustaceans and other immature insects that go through a series of molting stages are often sensitive to this pesticide.

Silvicultural Guidelines for Forest Stands and Woodlots

Several interrelated factors determine the vulnerability of forest stands and woodlots to gypsy moth defoliation. An awareness of these factors will enable land managers and woodlot owners to prescribe silvicultural actions that will minimize the impact caused by gypsy moth defoliation. Three of these factors include the abundance of favored food species (mainly oaks), site and stand factors, and tree conditions.

Stands of trees that are predominately oak and grow on poor, dry sites (such as sand flats or rock ridges) are frequently stressed and often incur repeated, severe defoliations. Trees growing under these conditions frequently possess an abundance of structural features such as holes, wounds, and deep bark fissures that provide shelter and habitats for gypsy moth larvae and aid their survival.

Stands of trees that are predominantly oak but grow on protected slopes or on sites with adequate moisture and organic matter are more resistant to defoliation by the gypsy moth.

Slow-growing trees on poor sites frequently survive a single, severe defoliation better than fast-growing trees typically found on well-stocked better sites.

More trees are killed in stands that contain mainly oak species than in oak–pine or mixed hardwood stands.

Subdominant trees are killed more rapidly and more often than dominant trees.

Silvicultural Treatment—What and When?

Appropriate silvicultural treatment will be determined by an anticipated occurrence of gypsy moth defoliation, by characteristics of the stand, and by the economic maturity of the stand. Foresters refer to treatments discussed here as "thinnings." Thinnings are cuttings made in forest stands to remove surplus trees (usually dominant and subdominant size classes) in order to stimulate the growth of trees that remain.

Predefoliation treatments: When gypsy moth defoliation is anticipated, but not within the next 5 years, **predefoliation thinning** to selectively remove preferred-host trees can reduce the severity of defoliation, increase the vigor of residual trees, and encourage seed production and stump sprouting. Thinnings should not be conducted in fully stocked stands that will reach maturity within the next 6 to 15 years. Thinning results in a short-term "shock effect" to residual trees. This shock effect, coupled with defoliation-caused stress, renders trees vulnerable to attack by disease organisms such as *Armillaria*.

In fully stocked stands that will reach maturity within the next 16 or more years, two kinds of thinning can be applied. The method of thinning should depend on the proportion of preferred host species present.

If more than 50 percent of the basal area in a stand is preferred host species (mainly oaks), **presalvage thinning** should be applied. Presalvage thinning is designed to remove the trees most likely to die (trees with poor crown condition) from stress caused by gypsy moth defoliation.

If less than 50 percent of the basal area in a stand is in preferred host species, **sanitation thinning** can be applied to reduce further the number of preferred host trees. This will result in fewer refuges for gypsy moth larvae and in improved habitats for the natural enemies of the gypsy moth.

Treatment during outbreaks: If defoliation is current or is expected within the next 5 years, thinnings should be delayed because of potential "shock effect." High-value stands can be protected by applying pesticides. In low-value stands or those that are at low risk (less than 50 percent basal area in preferred host species), protective treatments are optional.

Post-outbreak treatments: After a defoliation episode, the land manager or woodlot owner should pursue efficient salvage of dead trees, but should delay decisions about additional salvage, regeneration, or other treatments for up to 3 years. At the end of 3 years, most defoliation-caused mortality will be complete and the need for treatments can be assessed on the basis of damage level, current stocking conditions, and stand maturity.

Assistance

Homeowners can get advice about identifying and controlling the gypsy moth through the County Cooperative Extension Service, the State Entomologist or State Forester, or from specialists at the State University or Agricultural Experiment Station.

Some communities may qualify for State or Federal cooperative treatment programs. These programs are usually administered through local county or designated State agencies.

Information about regulations concerning the interstate movement of outdoor household articles from areas infested by gypsy moth can be obtained by contacting one of the following:

- The Plant Protection or Regulatory Division of the State Department of Agriculture.
- The Plant Protection and Quarantine Division of the Animal and Plant Health Inspection

Service, U.S. Department of Agriculture.
- The County Extension Agent listed in the local telephone directory.

References

Podgwaite, J.D. 1979. Diseases of the gypsy moth: How they help to regulate populations. Agric. Handb. 539. Washington, DC: U.S. Department of Agriculture. p. 2–15.

McManus, Michael L.; Houston, David R.; Wallner, William E. 1979. The homeowner and the gypsy moth: Guidelines for control. Home and Gard. Bull. 227. Washington, DC: U.S. Department of Agriculture. p. 4–33.

Gansner, D.A.; Herrick, O.W.; Mason, G.N.; Gottschalk, K.W. 1987. Coping with the gypsy moth on new frontiers of infestation. Southern Journal of Applied Forestry Research. 11: 201–209.

Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

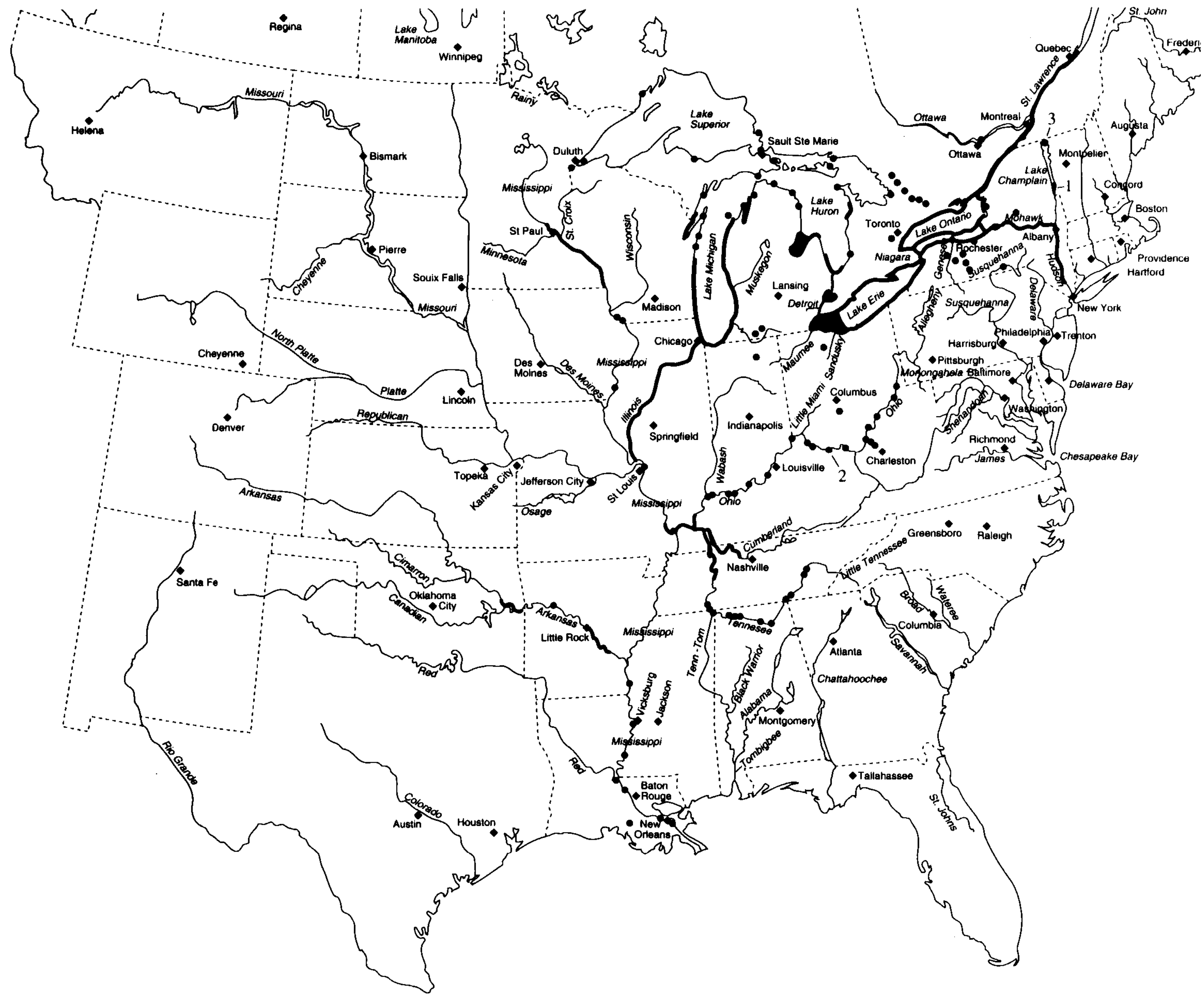
Revised October 1989

North American Range of the Zebra Mussel

as of 25 September 1993

Compiled by New York Sea Grant with information from: Empire State Electric Energy Research Corp., Fisheries and Oceans Canada, Great Lakes Sea Grant Network, Illinois Natural History Survey, Ontario Hydro, Ontario Ministry of Natural Resources, Tennessee Valley Authority, US Army Corps of Engineers, US Fish & Wildlife Service, and Utilities and others throughout North America.

1. Lake Champlain, East Shore, From Whitehall Locks (NY) To Chipman Point (Orwell, VT)
2. J. M. Stuart Station, Aberdeen, OH, Ohio River Mile 405
3. Lake Champlain, Windmill Point (Alburg, VT)



A Great Lakes Sea Grant resource list on zebra mussels and other nonindigenous species

This list includes material that is distributed by the six Sea Grant programs in the Great Lakes Sea Grant Network as of December 1993. Many of the other Sea Grant programs are producing material about the zebra mussel, too. For example, Rhode Island (401/792-6842), Virginia (804/924-5965) and North Carolina (919/515-2452) Sea Grant programs all currently have material available. Other U.S., state and Canadian agencies also have material available.

To order any item in this resource list, complete and mail the order form for the program distributing the material. Free items are for *single copies only* unless specified otherwise. For prices on bulk orders, contact the program that is distributing the material. Please prepay all orders.

Resources on zebra mussels

The first three publications provide information on how this species was introduced into the Great Lakes, areas colonized in the lakes, what methods of eradication exist, provides tips on what you can do to slow the mussel's spread, and the impact zebra mussels will have on industry, recreation and the Great Lakes ecosystems.

Zebra mussels in the Great Lakes: The invasion and its implications. December 1993. *Fred L. Snyder, David W. Garton*, and *Maran Brainard.* 4 pp. OHSU-FS-045. Free for any size order. **OH**

Zebra mussels: A 1992 Great Lakes overview. 1992. *Avery Klauber.* 8 pp. Free; multiple copies are $.10 each. **NY**

Zebra mussels in the Great Lakes. 1992. 2 pp. MICHU-SG-92-700. Free. **MI**

Mid-Atlantic zebra mussel fact sheet. Reprinted January 1994. *Barbara Doll.* 6 pp. Explores the possible routes of entry the zebra mussel might take and examines the environmental characteristics that would make this area a hospitable host, including the expansive estuaries and freshwater rivers and lakes. Free. To order, write N.C. Sea Grant, Box 8605, N.C. State University, Raleigh, NC 27695-8605.

Zebra mussel: An unwelcome visitor. 1993 *Karin A. Tammi.* 2 pp. Describes the biology, impact and history of zebra mussels in the United States along with identification information and help to Rhode Islanders to prevent their introduction into the state. $.50 To order, write R.I. Sea Grant Information Office, URI Bay Campus, Narragansett, RI 02882, 401/792-6842.

Zebra mussels in Virginia's future. March 1993. 2 pp. Includes the zebra mussel's physical requirements and a list of its potential range in Virginia's waters. Free. To order, write Virginia Institute Marine Science, Gloucester Point, VA 23062.

New concerns emerge as zebra mussel spreads. 1992. 2 pp. MICHU-SG-92-702. Free. **MI**

The zebra mussel (*Dreissena polymorpha*): An unwelcome North American invader. 1991. *Charles R. O'Neill, Jr. and David B. MacNeill.* 12 pp. NYSGI-G-91-013. $1.00 NY

Boaters—Slow the spread of zebra mussels and protect your boat, too. 1993. *David O. Kelch.* 2 pp. OHSU-FS-054. Free for any size order. **OH**

Identification of juvenile *Dreissena polymorpha* and *Mytilopsis leucophaeata*. 1992. *David B. MacNeill.* 3-fold brochure includes diagrams, glossary and references for the zebra mussel and dark false mussel. NYSGI-G-92-001. Free **NY**

Zebra mussel information needs survey for municipal and industrial water users—Summary report. 1992. *Robin Goettel and Gail Snowdon.* 8 pp. A survey of 29 southern Lake Michigan municipal and industrial water users provided findings on what types of zebra mussel information were most needed and in what form the information could best be delivered. Free. **IL-IN**

Control of zebra mussels in residential water systems. 1993. *Charles R. O'Neill, Jr.* 8 pp. $1.00 NY

Zebra mussels may clog irrigation systems. 1993. 2 pp. MICHU-SG-93-701. Free. **MI**

Engineering Notes. 1992. *Philip Keillor.* Free. **WI**

- #1: **Case studies of constructed filter bed intakes.** A description of 10 such systems in the western Great Lakes that range from one to 100 years old. Included is information on operational experience and whom to contact (plant operators and design engineers) for further information, plus commentary from marine contractors and design engineers. 16 pp.
- #2: **Infiltration intakes for very large water supplies: Feasible?** A review of four 20-year-old papers that considered design feasibility as a means of protecting larval organisms from entrainment in power plant and water diversion project intakes. 11 pp.
- #3: **Zebra mussel (*Dreissena polymorpha*) distribution: Reported size, depth and temperature variables.** A summary of relevant data about zebra mussels intended for project design engineers. 7 pp.
- #4: **Using filtration and induced infiltration intakes to exclude organisms from water supply systems.** A literature review plus an overview of slow sand filtration and infiltration systems. 13 pp.

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Sand filter intakes could safeguard vital water-supply systems from zebra mussels. 1991. *Philip Keillor*. 4 pp. WIS-SG-91-428-13. Free. **WI**

Don't let these invaders hijack your boat! is a 17"x22" humorous cartoon poster telling boaters what to do to slow the spread of zebra mussels. Perfect for fishing/bait shops. Pub X6. Free. **MN**

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Zebra mussel watch identification card. *Christine Kohler and Stephen Wittman*. Wallet-sized cards have a color picture of the zebra mussel with text describing their appearance and what to do if you find a mussel. Free; 20 cards for $1.00. Available from each program. Order customized cards from Wisconsin. **WI**

Zebra mussel distribution map from the latest issue of *Dreissena polymorpha information review*. Free. **NY**

Zebra mussel distribution in Michigan. Free. **MI**

Zebra mussels: From spawning to settlement. January 1994. 20-minute video shot through a microscope shows mussels spawning naturally and induced. Voice-over provides details. $15.00. **OH**

Zebra mussels. 1993. Produced by New York Sea Grant and PBS-affiliate WLIW, Long Island as 30-minute show. $12.00. **NY**

Protecting your boat from zebra mussels. Revised 1993. This 15 minute video gives pointers on how to prevent damage to your recreational boat and tips on preventing the spread of the mussel to inland waters. $10.00. **NY**

Too much mussel. January 1991. This 5.5 minute video (VHS format) provides an overview of the impact of zebra mussels to Lake Erie. $15.00. **OH**

Zebra mussel features. Collection of 90 second feature stories produced by Outreach Communications TV at Michigan State University. Contact Carol Swinehart at MSU 517/353-9723. $10.00.

Nonindigenous Species Graphics Library contains slides, photographs and illustrations of zebra mussels and other aquatic nuisance species. Also includes a videotape resource list. Contact Michigan Sea Grant at 313/764-1138 for more information.

Resources on other species

A field guide to aquatic exotic plants and animals. 1992. Developed by MN Sea Grant, MN DNR and Bell Museum of Natural History. 10-page, four-fold, color brochure describes eleven common exotics in the Great Lakes region. Pub X9. Free. **MN**

Biology and potential impacts of the rudd in the Great Lakes. October 1993. *David MacNeill*. 4 pp. Free. **NY**

The Ruffe invasion, *Gymnocephalus cernuus*. 1993. *Mike McLean*. Describes the aggressive, perch-like fish found in Lake Superior. This invader was first identified in the St. Louis River in 1987. It is now the most numerous forage fish in the estuary and its range is expanding. PUB X7. Free. **MN**

Effects of spiny tailed *Bythotrephes* on Great Lakes fish. 1993. *D. Rae Barnhisel*. Explains affect of *Bythotrephes* on fish predation. 2 pp. MICHU-SG-93-704. Free. **MI**

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The spiny water flea, *Bythotrephes*: A newcomer to the Great Lakes. 1991. *David J. Berg*. 2 pp. OHSU-FS-049. Free. **OH**

Spiny tailed *Bythotrephes*: Its life history and effects on the Great Lakes. 1990. *Carla E. Caceres and John T. Lehman*. Explains the anatomy, reproductive cycle and behavior of *Bythotrephes* and how this exotic may affect the Great Lakes ecosystems. 7 pp. MICHU-SG-90-700. Free. **MI**

Pacific Salmon in the Great Lakes: The history and future. 1986. *Warren Downs*. 5 pp. WIS-SG-86-149. Free. **WI**

Sea Lamprey: Invader of the Great Lakes. 1982. *Warren Downs*. 8 pp. WIS-SG-82-138. $.50. **WI**

Is it a white bass or a white perch? Reprinted 1991. *Fred L. Snyder*. 1 p. OHSU-FS-005. Free. **OH**

Getting to know your catch: Lake Erie Salmonid identification. Reprinted 1991. *David O. Kelch*. 2 pp. OHSU-FS-031. Free. **OH**

Scientific publications on zebra mussels

"Biology of recent invertebrate invading species in the Great Lakes: The spiny water flea, *Bythotrephes cederstroemi* and the zebra mussel, *Dreissena polymorpha*" by *David W. Garton, David J. Berg, Ann M. Stoeckmann and Wendell R. Haag* reprinted from *Biological Pollution: The Control and Impact of Invasive Exotic Species, Bill McKnight* (ed.), pp. 63-84, 1993. OHSU-RS-165. Free. **OH**

"Reduced survival and fitness in native bivalves in response to fouling by the introduced zebra mussel (*Dreissena polymorpha*) in western Lake Erie" by *Wendell R. Haag, David J. Berg, David W. Garton and J.L. Farris* reprinted from *Can J Fish and Aquat Sci* 50(1):13-19, 1993. OHSU-RS-157. Free. **OH**

"Changes in planktonic diatoms and water transparency in Hatchery Bay, Bass Island Area, Western Lake Erie since the Establishment of the zebra mussel" by *Ruth E. Holland* reprinted from *J Great Lakes Res* 19(3):617-624, 1993. MICHU-SG-93-306. Free. **MI**

"Effects of deionized water on viability of the zebra mussel, *Dreissena polymorpha*" by *J.L. Ram and J.U. Walker* reprinted from *Comp Biochem Physiol* 105C(3):409-414, 1993. MICHU-SG-93-304. Free. **MI**

"The zebra mussel (*Dreissena polymorpha*), a new pest in North America: Reproductive mechanisms as possible targets of control strategies" by *J.L. Ram, P. Fong, R.P. Croll, S.J. Nichols and D. Wall* reprinted from *Invertebrate Reproduction and Development* 22:1-3 (1992) 77-86. MICHU-SG-93-303. Free. **MI**

"Spawning in the zebra mussel (*Dreissena polymorpha*): Activation by internal or external application of serotonin" by *J.L. Ram, G.W. Crawford, J.U. Walker, J.J. Mojares, N. Patel, P. Fong and K. Kyozuka* reprinted from *J Experimental Zoology* 265:587-598, 1993. MICHU-SG-93-300. Free. **MI**

"Attitudes of 1990, 1991, and 1992 Mid-America Boat Show and 1991 Fairport Symposium patrons concerning the zebra mussel (*Dreissena polymorpha*), Lake Erie, and Great Lakes pollution" by *Frank R. Lichtkoppler, David O. Kelch and M. Annie Berry* reprinted from *J Great Lakes Res* 19(1):129-135, 1993. OHSU-RS-158. Free. **OH**

"Seasonal reproductive cycle and settlement patterns of *Dreissena polymorpha* in western Lake Erie" by *David W. Garton and Wendell R. Haag* reprinted from *Zebra Mussels: Biology, Impacts and Control*, Thomas F. Nalepa and Donald W. Schloesser (eds.), pp. 111-128, 1992. OHSU-RS-159. Free. **OH**

"Investigations of the toxicokinetics of hydrophobic contaminants in the zebra mussel" by *Susan W. Fisher, Duane C. Gossiaux, Kathleen A. Bruner and Peter F. Landrum* reprinted from *Zebra Mussels: Biology, Impacts and Control*, Thomas F. Nalepa and Donald W. Schloesser (eds.), pp. 465-490, 1992. OHSU-RS-160. Free. **OH**

"The use of endod to control the zebra mussel" by *Harold H. Lee, Akilulu Lemma and Harriett J. Bennett* reprinted from *Zebra Mussels: Biology, Impacts and Control*, Thomas F. Nalepa and Donald W. Schloesser (eds.), pp. 643-656, 1992. OHSU-RS-161. Free. **OH**

"Early detection of the zebra mussel (*Dreissena polymorpha*)" by *Clifford Kraft* reprinted from *Zebra Mussels: Biology, Impacts and Control*, Thomas F. Nalepa and Donald W. Schloesser (eds.), pp. 705-714, 1993. WISCU-R-93-001. Free. **WI**

"Multivariate model for predicting population fluctuations of *Dreissena polymorpha* in North American Lakes" by *Charles W. Ramcharan, Dianna K. Padilla and Stanley I. Dodson* reprinted from *Can J Fish Aquat Sci* 49(1):150-158, 1992. WIS-SG-92-944. Free. **WI**

"Models to predict potential occurrence and density of the zebra mussel (*Dreissena polymorpha*)" by *Charles W. Ramcharan, Dianna K. Padilla and Stanley I. Dodson* reprinted from *Can J Fish Aquat Sci* 49(12):2611-2620, 1992. WISCU-R-92-032. Free. **WI**

"Bioenergetics model of zebra mussel, *Dreissena polymorpha*, growth in the Great Lakes" by *Daniel W. Schneider* reprinted from *Can J Fish Aquat Sci* 49(7):1406-1416, 1992. WISCU-R-92-017. Free. **WI**

"Synchronous spawning in a recently established population of the zebra mussel, *Dreissena polymorpha*, in western Lake Erie, USA" by *Wendell R. Haag and David W. Garton* reprinted from *Hydrobiologica* 234:103-119, 1992. OHSU-RS-151. Free. **OH**

International zebra mussel research conference (1991) proceedings sponsored by the Great Lakes Sea Grant Network and hosted by New York Sea Grant. 52 pp. $8.00. **NY**

"Heterozygosity, shell length and metabolism in the European mussel, *Dreissena polymorpha*, from a recently established population in Lake Erie" by *David W. Garton and Wendall R. Haag* reprinted from *Comp Biochem Physiol* 99A(1/2):45-48, 1991. OHSU-RS-140. Free. **OH**

"Molluscicidal activity of potassium to the zebra mussel, *Dreissena polymorpha*: Toxicity and mode of action" by *Susan Warwick Fisher, Paul Stromberg, Kathleen A. Bruner and J. Denise Boulet* reprinted from *Aquatic Toxicology* 20:219-234, 1991. OHSU-RS-146. Free. **OH**

"Zooplankton grazing and phytoplankton abundance: An assessment before and after invasion of *Dreissena polymorpha*" by *Lin Wu and David A. Culver* reprinted from *J Great Lakes Res* 17(4):425-436, 1991. OHSU-RS-149. Free. **OH**

"Methods for evaluating zebra mussel control products in laboratory and field studies" by **Susan Warwick Fisher and Dennis Bernard** reprinted from *J Shellfish Res* 10(2):367-371, 1991. OHSU-RS-150. Free. **OH**

International zebra mussel research conference (1990) proceedings sponsored by the Great Lakes Sea Grant Network and hosted by Ohio Sea Grant. 32 pp. OHSU-TS-019 also available as **"Abstracts of technical papers presented at the International Zebra Mussel Research Conference Columbus, Ohio 1990"** reprinted from *J Shellfish Res* 10(1):243-260, 1991. OHSU-RS-144. Both are free. **OH**

Scientific publications on other species

"Embryonic and postembryonic development in *Bythotrephes cederstroemi*" by *P.M. Yurista* reprinted from *Can J Fish Aquat Sci* 49(6):1118-1125, 1992. MICHU-SG-92-307. Free. **MI**

"Zooplankton *Bythotrephes cederstroemi*) spine induces aversion in small fish predators" by *D. Rae Barnhisel* reprinted from *Oecologia* 88:444-450, 1991. MICHU-SG-92-303. Free. **MI**

"Causes and consequences of cladoceran dynamics in Lake Michigan: Implications of species invasion by *Bythotrephes*" by *John T. Lehman* reprinted from *J Great Lakes Res* 17(4):437-445, 1991. MICHU-SG-92-302. Free. **MI**

***Genetics and ecology of an invading species:* Bythotrephes cederstroemi *in western Lake Erie*.** 1991. *David J. Berg*. 164 pp. TD-030. On loan from the Sea Grant Depository, Pell Library Building/Bay Campus, University of Rhode Island, Narragansett, Rhode Island 02882. (All items listed in this publication can be borrowed from the Depository.)

"Occurrence of *Bythotrephes cederstroemi* (Schoedler 1877) in Lake Superior, with evidence of demographic variation within the Great Lakes" by *David W. Garton and David J. Berg* reprinted from *J Great Lakes Res* 16(1):148-152, 1990. OHSU-RS-138. Free. **OH**

"Thermal tolerances of the predatory cladocerans *Bythotrephes cederstroemi* and *Leptodora kindti*: Relationship to seasonal abundance in western Lake Erie" by *David W. Garton, David J. Berg and Robert J. Fletcher* reprinted from *Can J Fish Aquat Sci* 47(4):731-738, 1990. OHSU-RS-125. Free. **OH**

The white perch and its interaction with yellow perch in Lake Erie. 1989. *Donna L. Parrish*. 137 pp. TD-021. $15.50. **OH**

Newsletters

***Dreissena polymorpha* information review.** Summaries of research, meetings, legislation and sitings of the zebra mussel for the interested professional. Bimonthly. $60.00 annual subscription rate includes other benefits. Contact Zebra Mussel Clearinghouse at 800/285-2285.

Zebra mussel update reports on the status of the zebra mussel invasion in the region, zebra mussel-related research, upcoming conferences, new publication, etc. Written by *Clifford Kraft*. Published irregularly; Free. **WI**

The following Sea Grant program newsletters cover Great Lakes issues, education, environment, economic development, fisheries and aquaculture activities in each state. Conferences, publications and journal articles may also be listed. Contact your closest Sea Grant program for a subscription. Some programs also produce additional topic-specific newsletters.

- ***The HELM***, issued quarterly by Illinois-Indiana. Free.
- ***Upwellings***, issued quarterly by Michigan. Free.
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- ***Coastlines***, issued quarterly by New York. Free.
- ***Twine Line***, issued bimonthly by Ohio. $4.50 a year. Each issue includes a zebra mussel update.
- *Littoral Drift*, issued monthly by Wisconsin. Free.

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ZEBRA MUSSEL

INTRODUCTION

Zebra mussels (*Dreissena polymorpha*) are exotic, freshwater bivalves that were inadvertently delivered to U.S. waters around 1986 through the discharge of European shipping ballast water. For two years, they reproduced and colonized the Great Lakes without detection. Then, in July 1988, they were sighted in Lake St. Clair near Detroit, Mich. The 1- to 2-inch-long striped mollusks originated in the drainages of the Black, Caspian and Aral seas. Since their arrival, zebra mussels have spread rapidly throughout the Great Lakes and into several major river systems of the eastern United States, including the Ohio, Illinois, Mississippi, Mohawk, Hudson, Susquehanna, Tennessee and Arkansas rivers.

Zebra mussel colonization of water-intake pipes, boats, docks, piers and other structures in the Great Lakes region has already cost millions of dollars. Some speculate that it's only a matter of time until they spread throughout most of the United States. If they colonize the Mid-Atlantic, they could interfere with municipal and industrial water-users, sport and recreational fisheries, food webs, navigation, recreational boating and beach use.

THE MID-ATLANTIC REGION

The Mid-Atlantic Sea Grant region consists of New Jersey, Delaware, Maryland, Virginia and North Carolina. To date, zebra mussels have not foraged into any of these five states. In the future, however, this region will likely present the mussel with a different and more variable environment than the Great Lakes.

The eastern portion of the region is comprised of expansive estuaries. The Chesapeake Bay, Delaware Bay and Albemarle/Pamlico estuarine system represent more than half of the East Coast estuarine waters. This large system is very dynamic, often experiencing rapid fluctuations in temperature and salinity.

Freshwater resources are also plentiful in the Mid-Atlantic. The region is composed mostly of Atlantic-bound drainages and a few watersheds in the western portions of Maryland, Virginia and North Carolina that feed the Mississippi River network. There are very few natural lakes within the region, but thousands of man-made impoundments lie within these drainages, including farm ponds, aquaculture facilities, drinking water supplies, detention facilities for water quality or flood control, and recreational or multipurpose lakes.

CONCERNS

Zebra mussels can securely attach to nearly any surface by secreting durable elastic strands called byssal fibers. They colonize to form barnacle-like encrustations. And because of their affinity for water currents, zebra mussels can extensively colonize water pipelines and canals, often severely reducing the water flow and, upon death, imparting a foul taste to drinking water. The intake pipes at drinking water, power generation and industrial facilities serve as excellent habitat and commonly fall prey to zebra mussel infestations. The water flow provides a continuous source of food and oxygen and carries away wastes, while the structures themselves protect the mussels from predation.

Once in a drinking water treatment facility, zebra mussels can colonize any surface within the distribution system up to the first oxidation or filtration stage, including intake mains, raw wells, screen

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house walls, traveling or stationary screens, strainers and settling tanks. Impacts associated with colonization are: loss of intake head, obstruction of valves, putrescence from the decay of protein-rich mussels, obnoxious methane gas production and increased corrosion of steel and cast iron pipe.

A similar fouling problem can occur in power plants and industrial water systems. Condenser and heat exchanger tubing can become clogged, leading to loss of heat exchange capacity and overheating. The mollusks can also block service water lines for fire protection or lubrication and/or cooling of bearings and transformers, potentially damaging vital plant components or creating safety hazards if sprinkler systems fail.

Zebra mussels also impact recreational boating. Attached to boat hulls, they increase the amount of drag, reduce a boat's speed and increase fuel consumption. Larval mussels drawn into a boat's engine-cooling water intake may grow and obstruct the system, leading to overheating and possible engine damage. Mussel shells drawn into the engine could abrade cooling system parts, especially impellers.

The zebra mussels can also attach to docks, piers, marker buoys, ladders, pilings and ropes. Their waste excretions speed the corrosion of these structures, and dense colonies of the mollusks can even sink buoys and floating docks. Colonization of lock systems may negatively impact navigation canals.

Recreational beaches in infested areas may be littered by shells washed up by storm waves. Some Great Lakes beachgoers use footgear to prevent cuts from zebra mussel shells. Mussel decomposition produces odors that also detract from the enjoyment of shoreline recreation.

Further, zebra mussels can biologically impact the environment. An adult zebra mussel filters on average 1 liter of water per day using siphons and a ciliated gill system, but rates of up to 2 liters per day have been observed. They feed on small phytoplankton and zooplankton in lakes and detritus in rivers. They can also filter and consume their own larval stage known as veligers. Particles of an unsuitable size or chemical composition that are not ingested are consolidated into a mucus bolus (pseudofeces) and discharged. European studies indicate that zebra mussel filtration can dramatically increase lake water clarity. Since zebra mussels were introduced into the western and central basin of Lake Erie, water clarity has increased dramatically and the chlorophyll a content has decreased. But the extent to which changes in the lake's clarity and productivity can be attributed to zebra mussel activity is still unknown.

Although zebra mussel filtration may improve water clarity, the phytoplankton and detritus they remove are important links in lake and riverine food webs. Therefore, filtration could negatively impact fisheries. In lakes, excessive removal of phytoplankton from the water column could cause a decline in zooplankton species that eat phytoplankton. Also, zebra mussels eat small zooplankton. So reductions in small zooplankton could reduce survival of larger zooplankton and larval fish, which could in turn affect higher trophic species within the food chain. Similar to lakes, excessive removal of detritus from rivers may cause a decline in aquatic insects and other detrital consumers, which are an important food source for many fish. Growing mussel populations could alter vital links in the food web. In addition, improved water clarity may make zooplankton more visible to fish predators and reduce the ability of larval fish to avoid predation.

Native mussel populations may be endangered by the sheer numbers of zebra mussel colonies competing for food and space. In Lake St. Clair, zebra mussel colonization has coincided with the rapid disappearance of the native unionid clam population. Numerous live and dead unionids have been observed covered with mussel growths. Many unionids appear to die as zebra mussel colonies interfere with host shell movements or cause damage to the shell edges.

REPRODUCTION

The zebra mussel has a reproductive strategy unique to freshwater mussels, which is responsible for its rapid expansion in Europe and the Great Lakes. Sexual maturity is typically reached at age 2 but may occur in the first year at a size of 3 to 5 millimeters (mm). Zebra mussels are separately sexed, but some hermaphroditism has been reported. Mature female mussels can produce 30,000 to 40,000 eggs per year, although some produce up to 1 million annually. Based on these observations, zebra mussels may have the highest fecundity among freshwater mollusks. Young, first-year mussels as small as 3 mm may produce as many as 6,000 eggs per year. Individuals are able to spawn several times a season, and spawning activity may occur year-round in warm, productive waters.

Although poorly understood, the reproductive cycle is apparently influenced by environmental cues such as water temperature, mussel population density, phytoplankton abundance and species composition. Evidence from Lake Erie suggests that reproductive activity may be cued by such seasonal phytoplankton dynamics as blooms and algal species succession. Spawning patterns can show considerable year-to-year variations. Studies from Lake Erie suggest that cool water temperatures, storms, elevated turbidity and increased population densities can delay spawning, resulting in possible synchronous spawning activity. It may also be induced by the presence of mussel gametes (sex products) in the water.

BIOLOGY

Once water temperatures reach 14-16 C, a fertilized zebra mussel egg becomes a planktonic larvae known as a veliger within two to three days. Swimming veligers search for food for two to three weeks, often traveling considerable distances. Within three weeks of hatching, they reach their "settling stage" and attach to bottom debris or other solid surfaces in the water. But mortalities of settling larvae can be very high due to hypoxia, temperature shock or failure to locate a suitable attachment substrate.

During their first year of life, zebra mussels are able to crawl along a substrate at speeds of 3.8 cm per hour in search of a more suitable location to attach. Juveniles can attach by secreting a few temporary byssal threads, which can be detached later to move elsewhere. Sessile mussels develop byssal fibers and remain stationary in most cases. However, larger mussels may be able to detach as well. During winter, the young mussels migrate to deeper, warmer waters to escape cold surface temperatures. Their life spans are highly variable, depending on several environmental conditions, but they can live up to five years.

PREDATION

Predation of zebra mussels by other animals has not been significant in relation to the size of their colonies. In the Great Lakes, the freshwater drum and a few other types of fish, crayfish and some species of diving ducks have been unable to significantly reduce their populations. In some European lakes, crayfish predation of the mollusks has been substantial. However, zebra mussels attach to any firm surfaces in water, including crayfish, and they can severely limit the mobility of their host.

Typically, when *Dreissena* is introduced to a suitable area outside of its native range, a population will establish and rapidly increase in number, often by a factor of two or three. This population explosion usually lasts for several years, followed by a marked reduction in size and subsequent oscillations. In western and central Lake Erie, zebra mussel populations appear to have peaked and are starting to decrease as a result of crowding for food and space. As their population thins out, predation will likely have a greater impact on their numbers.

ENVIRONMENTAL REQUIREMENTS

Zebra mussels are capable of withstanding a wide range of environmental parameters. Even though they are a freshwater mollusk, they have demonstrated their ability to acclimate to salinities of 10-12 parts per thousand (ppt) for very short periods. Temperature has a bearing on this ability. If zebra mussels are removed from fresh water and gradually exposed to fairly low salinities of 2-3 ppt, their mortality will significantly increase if water temperatures rise above 10 C. Rapid temperature fluctuations, characteristic of estuarine environments, also inhibit their salinity tolerance. Physiological differences among zebra mussels may further affect their ability to tolerate salinity.

Zebra mussels begin to grow at temperatures between 6 and 12 C and continue growing up to 33 C. The maximum temperature of extended exposure for zebra mussels is unknown, but it likely exceeds 30 C. Zebra mussel spawning temperatures range from 12-23 C, but laboratory tests have concluded that the optimal temperature for nurturing larvae is 17-18 C.

Zebra mussels are intolerant to prolonged exposure to acidic waters. They prefer basic waters with a pH in the range of 8-10, and in general do not persist in waters with a mean pH below 7.9. All freshwater mussels need calcium to grow and build shells, however, zebra mussels tend to require higher calcium concentrations than other bivalve mussel species that live in the same areas. Research has shown that zebra mussels are unable to maintain a balance between uptake from the water and metabolic loss of calcium if concentrations drop much below 12-14 milligrams per liter (mg/l).

The optimal range of dissolved oxygen concentrations for zebra mussels is 8-10 mg/l. As dissolved oxygen concentrations begin to drop, they consume less oxygen. However, they typically do not colonize waters with continual concentrations of 4 mg/l and less, due to respiration difficulty.

Zebra mussels are most often found within 2 to 7 meters of the water surface. However, they are able to colonize at depths of up to 50 meters. Since flowing waters provide a continuous source of food and oxygen and carry away their waste, velocities of 0.5-0.7 meters per second (m/s) are optimal for colonization. Velocities in excess of 2 m/s inhibit their feeding and growth, and they are also fairly intolerant of rapid fluctuations in water levels. They generally withstand desiccation for only a few days, depending on atmospheric humidity. Zebra mussels prefer very firm substrates such as rock, wood, gravel, shells, concrete, metal or plastic for attachment. But they can attach to most any surface, including sand, rope or even aquatic weeds and grasses.

DISPERSAL

Three natural and 20 human-related dispersal mechanisms have been identified for zebra mussels. Natural mechanisms include currents, birds and other animals such as beaver, muskrats, turtles, fish, crayfish and others. Of all animal mechanisms, birds are believed to be the most significant. They can move zebra mussel adults, larvae or eggs that are attached to their plumage, legs or feet; carry them internally following consumption and subsequent defecation or regurgitation; and directly transport them in their beaks.

But many human activities can disperse the mollusks more rapidly than natural mechanisms. And in some cases, humans have built canals and waterways that aided natural dispersal. Construction of shipping canals helped zebra mussels migrate from their place of origin in western Russia into European fresh waters in the late 1700s. The transport and discharge of ballast water is another dispersal method that was believed to be responsible for introducing zebra mussels and other non-native species into the Great Lakes from Europe.

Mussels can also be transported by attaching to boat trailers, vessel hulls, hull openings or to recreational boat and motor components such as outdrive units, trim plates, transducers, prop guards, propellers, shafts and anchors. Fisheries-related dispersal includes movement of fish cages, fish stocking water, fish bait, bait-bucket water and fishing gear such as tackle, nets or traps. Other dispersal mechanisms are discharge or release of water from aquariums, fire trucks, research projects and amphibious plane pontoons.

CONTROL MEASURES

Numerous methods for controlling the infestation of water-intake systems have been developed in Europe, Russia and the Great Lakes. For instance, filter systems or high water velocities (above 2-2.5 m/s) can deter the mussels from entering and attaching to water intakes; scraping can remove mussels already attached; organometallic anti-biofouling coatings and electrical currents can discourage them from attaching to pipes; and adult and larval mussels can be killed by depriving them of oxygen, flushing water systems with hot water or treating intake water with copper sulfate, chlorine, ozone or other chemicals. Scientists continue to develop new control methods.

The choice of a control method depends on many site-specific variables, including the type of water-intake facility, use of the intake water, intake pipe size, length and accessibility, federal and state environmental regulations and zebra mussel population densities.

WHAT'S DIFFERENT ABOUT THE MID-ATLANTIC?

COLONIZATION RISK

Assessing the risk of colonization appears to be site-specific. Two major factors should be considered: mechanisms by which zebra mussels can be introduced to an area and the mollusks' ability to survive the environmental conditions of that area. Determining their ability to survive requires a close examination of several environmental parameters. A number of Mid-Atlantic environments are at risk of colonization, and each should be individually examined to determine its risk. A few areas within the region have distinct environmental characteristics that qualify them as suitable or unsuitable for zebra mussel colonization. However, it is difficult to make basic generalizations about the risks involved for the entire region.

Similar to other systems, the estuaries of the Mid-Atlantic typically undergo fairly rapid temperature and salinity fluctuations, especially following rainfall. Zebra mussels can tolerate significant salinity concentrations for short periods of time. However, they are unable to colonize, reproduce and proliferate in highly saline waters, especially estuarine environments. Therefore, it is unlikely that dense, inhibitory colonies of zebra mussels will establish in the Mid-Atlantic estuaries. But the zebra mussel is constantly evolving through the process of natural selection. It may develop a greater tolerance for higher salinities. European and Russian studies indicate that other species of *Dreissena* have greater salinity tolerances.

Summertime surface-water temperatures usually exceed the preferred range for zebra mussels in the southern reaches of the Mid-Atlantic, especially in the shallower, low-salinity fringes of the estuaries and lakes. And in many of these areas, the deeper, cooler waters that the mollusks are more likely to colonize often have dissolved oxygen concentrations below desired levels. Another important characteristic is the drastic reduction in suitable attachment substrates for zebra mussels as the Atlantic-bound rivers of the Mid-Atlantic approach the estuaries. The region is well-known for the blue crab populations in its estuaries, and the male crabs that frequent the low-salinity waters will likely enjoy feasting on zebra mussels.

The acidity of Mid-Atlantic inland waters depends on the acidity of rainfall and bedrock composition, whereas the acidity or pH of estuarine waters is more dependent on the presence of salts, which act as buffers. Acidic waters such as the Pine Barrens of southern New Jersey would not serve as suitable Mid-Atlantic environments for zebra mussels.

A large number of lakes are classified as eutrophic within the region, with the highest concentration occurring in the warmer southern portion. These algae-rich bodies of water would provide plenty of food for zebra mussels. However, many lakes within the southern region have calcium concentrations too low to

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support healthy populations. On the other hand, isolated limestone deposits are scattered throughout the entire Mid-Atlantic. The presence of limestone (calcium carbonate) results in much higher calcium concentrations that are suitable for zebra mussels.

ROUTES OF ENTRY

Zebra mussels have several potential routes to access the region's waters. They are rapidly encroaching on the Mid-Atlantic estuaries from the Susquehanna, a tributary of the Chesapeake Bay. And even though zebra mussels are not likely to establish in these estuaries, they can survive salinities of up to 12 ppt for several days, enabling them to attach to barges or other slow-moving vessels and travel through the estuarine fringes into the mouths of uninfested freshwater rivers. Once there, barge and boat traffic will provide the mussels with an easy means of dispersing to other tributaries within the associated watersheds.

The Susquehanna is not the only source of zebra mussel entry into the Chesapeake Bay. They could also be introduced by the discharge of infested shipping ballast water. The Chesapeake Bay is linked to the Delaware Bay by the Chesapeake and Delaware (C&D) Canal; it's also linked to North Carolina's Albemarle/Pamlico estuarine system by the man-made canals of the Intracoastal Waterway. These connections make all drainages feeding the Mid-Atlantic estuaries vulnerable to the migration of zebra mussels through the Chesapeake Bay.

The Delaware River, which lies just west of the already infested Hudson River, will provide easy Delaware Bay if it becomes colonized. The Potomac River drainage lies just southwest of the Susquehanna drainage and extends into the southern portion of Pennsylvania. If zebra mussels are transported into the Potomac River system, they will move easily into northwestern Maryland, south into northern Virginia and on to the Chesapeake Bay. Zebra mussels are also in the Ohio River system. The New River forms in northwestern North Carolina, travels through western Virginia and finally drains into the Ohio River at the border between West Virginia and Ohio. Deep Creek Lake at the far western tip of Maryland feeds the Youghiogheny River, which is also a tributary of the Ohio River. Therefore, movement of zebra mussels upstream through the Ohio River network exposes western Virginia as well as small portions of North Carolina and Maryland. Currently in the Tennessee River, upstream movement of zebra mussels threatens the far-western drainages of North Carolina.

KEY DISPERSAL MECHANISMS

Many of the Mid-Atlantic region's larger lakes serve recreational uses for residents and visitors from other parts of the country. Of most concern are those who bring their boats from states where zebra mussel invasion has already occurred, such as Michigan, Illinois, Ohio, Pennsylvania, Tennessee and others.

Water is regularly transported to Mid-Atlantic drainages from the Mississippi, the Tennessee and other river networks through the sale of fish for bait and for stocking aquaculture operations. Preliminary investigation has shown that fish producers generally use well water to fill their live-haul trucks for transport, and many fish ponds are filled with well water or are located in very small upstream tributaries that are fed by watershed water. However, this is not true in all cases, and the potential for zebra mussel adults, larvae or eggs attaching to the fish must also be considered.

POTENTIAL IMPACTS

Numerous drinking water plants, industries, pulp and paper mills, power generation facilities, processing plants, golf courses and agricultural operations draw water from rivers, streams and reservoirs in the Mid-Atlantic region. Many of these users have already incurred zebra mussel expenditures by monitoring for their arrival and developing plans of action for a potential colonization. The potential economic impacts of an actual invasion to these water users is even more significant.

Shoreline property owners within the Mid-Atlantic would likely be impacted by zebra mussels that colonize docks, piers, pilings and other shoreline structures. Boat owners would be burdened by preventing and repairing damage to motor intake lines that are clogged and hulls and other exposed surfaces that are fouled. The Intracoastal Waterway provides a vital commerce link for the East Coast. Barge traffic transports seafood, gravel, fertilizers, fuel and other products through numerous ports along the waterway and connecting river systems. There are also many recreational uses of the waterway, such as pleasure boating, sailing and yachting. Navigation through the Mid-Atlantic region could be inhibited by zebra mussels colonizing locks and other structures.

The region supports several important commercial and recreational fisheries. Each year, recreational anglers spend millions of dollars on fishing licenses, bait, could suffer economically if a zebra

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mussel infestation caused severe reductions in fisheries. Even though zebra mussels have not yet reached the Mid-Atlantic, some local economies have already suffered where lakes were temporarily closed to boaters for fear of an invasion.

Close to 300 species and subspecies of freshwater mussels are found in the United States, but the Southeast has the greatest diversity. Human activities have already placed considerable stress on these mussels. A few species are considered extinct and many others are listed as endangered or threatened. According to the U.S. Fish and Wildlife Service, if the zebra mussel establishes itself in reservoirs and larger rivers throughout the eastern United States, at least 20 additional freshwater species could become extinct. Their extinction would probably be a direct result of competition with the zebra mussel for food and space, coupled with existing stresses. If mid-sized and smaller rivers are also colonized, the death toll is expected to rise even higher.

MONITORING

Unlike the Great Lakes region, the Mid-Atlantic has the opportunity to prepare for zebra mussels. A good plan of preparedness requires keeping abreast of the zebra mussel migration, establishing a plan of action to minimize their economic and environmental impacts upon arrival and continuous monitoring to alert their presence. Once the mussels arrive, continuous monitoring data can provide important information about the development and expansion of the population.

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References

Alderman, John. 1993. Freshwater Mussels in *Swift Creek Subbasin Biological Inventory*. Funded by the N.C. Recreation and Natural Heritage Trust Fund.

Baker, Patrick K. A graduate student at the School of Marine Science, Virginia Institute of Marine Science, Baker researched and provided much of the information on environmental parameters.

Carlton, James T. 1991. *Dispersal Mechanisms of the Zebra Mussel* Dreissena. Maritime Studies Program, Williams College — Mystic Seaport, Mystic, Conn.

O'Neill, Charles R. Jr. and MacNeill, David B. 1989. Dreissena Polymorpha*: An Unwelcome New Great Lakes Invader*. New York Sea Grant Extension Program, Brockport, N.Y.

Rice, James A. Personal correspondence on Nov. 20, 1992. Zoology Department, N.C. State University, Raleigh, N.C.

Zebra Mussels: Biology, Impacts and Control. 1992. Lewis Publishers, Boca Raton, Fla.

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FS-058 | Zebra mussel migration to inland lakes and reservoirs: A guide for lake managers

Ohio Sea Grant College Program

OHSU-FS-058
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Heath is funded by Ohio Sea Grant College Program as a researcher and is a member of the program's Executive Committee.

The Great Lakes Sea Grant Network is a cooperative program of the Illinois-Indiana, Michigan, Minnesota, New York, Ohio, and Wisconsin Sea Grant programs. Sea Grant is a university-based program designed to support greater knowledge and wise use of the Great Lakes and ocean resources.

Through its network of advisory agents, researchers, educators and communicators, the Great Lakes Sea Grant Network supplies the region with usable solutions to pressing problems and provides basic information needed to better manage the Great Lakes for both present and future generations.

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Since the introduction of zebra mussels (*Dreissena polymorpha*) from Europe into Lake St. Clair in 1986, they have spread to all the other Great Lakes and the inland navigation system of major rivers, notably the Cumberland, Mississippi, Ohio, Susquehanna, Hudson and Tennessee rivers. They have recently been sighted in some small inland lakes and reservoirs, and it is generally believed that they will soon spread to many others. Which environmental factors are most important in determining whether a lake can support large populations of zebra mussels? What will be the ecological and economic impacts of zebra mussels in inland lakes and reservoirs? What can be done to prevent and mitigate the spread of zebra mussels? The purpose of this publication is to summarize current views on these topics to aid resource managers in planning.

Lake conditions most likely to support zebra mussels

Moderately hard-water lakes with calcium (Ca^{2+}) concentrations above 12 mg/L, alkalinity above 50 mg $CaCO_3$/L and pH above 7.2 provide the necessary chemical environment for adult zebra mussels. Zebra mussels will tolerate oxygen concentrations as low as 25 percent saturation (about 2 mg/L at 25°C), but they die in anoxic water. Lakes with prolonged periods above 54° F (12°C) and with maximum temperatures of 64-74°F (18-23°C) provide optimum conditions for growth and reproduction. Development of large populations of zebra mussels also depends on sufficient hard substrate onto which the adults can attach, as well as an abundant edible phytoplankton community. For example, the western basin of Lake Erie, with Ca^{2+} concentrations above 30 mg/L, alkalinity of 86 mg $CaCO_3$/L, pH of 8.4, mean temperatures around 68°F and a rocky bottom, is able to support massive populations of zebra mussels; more than 100,000 adults/m^2 have been reported in some places.

Although these are the optimum conditions for production of large populations, managers need to recognize that zebra mussels readily adapt to a wide range of conditions. In Europe, their range extends from the southern parts of Sweden to the Mediterranean shores. Recent physiological studies indicate that zebra mussels are more tolerant of mild salinity and wide swings of temperature than many indigenous bivalve mollusks, indicating that they may successfully invade some regions that offer only marginal environments to other mollusks. Zebra mussels are genetically diverse and readily produce genetic variants, a characteristic that permits them to invade a wide variety of habitats and that may permit them to expand their limits of tolerance.

Recent field and laboratory studies report that calcium and alkalinity are the major factors that determine growth and reproductive success of zebra mussels. Zebra mussels require Ca^{2+} concentrations greater than 12 mg/L to establish significant populations, which is considerably higher than required by other bivalve mollusks (typically 3-4 mg/L). Adult mussels are unable to survive in aquaria below 3.6 mg Ca^{2+}/L and an alkalinity of 4.7 mg $CaCO_3$L. Larval veligers are more sensitive to low calcium and alkalinity than adults.

Mussels are sensitive to acidic waters, too. Below pH 6.8, adult zebra mussels have a net loss of calcium, sodium and potassium to the surrounding water; however, they are able to adapt to mildly acidic conditions. After several days at pH 5.5-6.0, adults adapt to these conditions and their net rate of ion loss decreases. Zebra mussels are unable to withstand prolonged periods below pH 5.2 and eventually die because of ionic imbalance. Veligers are more sensitive to low pH than adults.

Temperature is another factor that can limit the extent of zebra mussel colonization. Each mature female produces several hundred thousand eggs during the breeding season, which occurs when the water temperature is above 54°F (12°C). The longer this period the more successful colonization is likely to be. Adults are unable to survive prolonged exposure to temperatures above 90°F (32°C). They can tolerate temperatures as low as 32°(0°C), provided they do not freeze.

✓ Ecological effects of zebra mussels in inland lakes

Zebra mussels graze on several species of algae at different rates and can remove large portions of the phytoplankton community from the water column, greatly increasing water clarity. Zebra mussels graze on particles greater than 0.00004 in. (1μm) in size. Free-living bacteria are smaller than this and apparently are not grazed by zebra mussels. These mussels graze on algae, protozoans and rotifers, but not indiscriminately. Recent investigations in Saginaw Bay indicate that zebra mussels establish abundant populations most readily in regions with large populations of diatoms and small edible green algae. Zebra mussels appear to graze on large filamentous blue-green algae and colonial algal forms less readily, and they greatly decrease their filtering rate in the presence of toxins released from certain blue-green algae (even if those algae aren't present).

The particles zebra mussels filter and eat are digested and released through the exhalant siphon as fecal material, which rapidly decomposes. The particles zebra mussels filter and reject are coated with mucous and expelled through the inhalant siphon as pseudofeces, which sink and decompose slowly at the sediment surface. The net effect of zebra mussels on the benthic (bottom-dwelling) community is unclear; some organisms benefit from their presence, others are harmed. Gammarid amphipods feed on feces and pseudofeces and seem to benefit from the increased food supply on the bottom of the lake. On the other hand, zebra mussels compete with other organisms (e.g. mysid decapods) for the same plankton resources. Populations of burrowing unionid clams have been nearly eliminated from Lake St. Clair because of zebra mussels that attach to the exposed portion of their shells.

Recent studies indicate that zebra mussels may mobilize toxic materials from the sediments into the food chain in two ways. When zebra mussels filter algae to which toxic materials are sorbed, they either ingest these toxic algae or release them in pseudofeces. Zebra mussels are capable of accumulating toxic compounds (PAHs and PCBs) in their fatty tissues, reaching concentrations 50,000 times greater in concentration than the surrounding water and about 10 times greater than other invertebrates. If edible fish begin to eat zebra mussels in large quantities, biomagnification of these accumulated toxic organic materials could increase the toxic load to humans. Also, zebra mussels provide a new mechanism of introducing toxins to the food chain, as amphipods that graze on pseudofeces containing toxin-sorbed algae are then eaten by fish.

Removal of significant proportions of plankton at the base of the food chain will diminish the energy available for fish production. Inland lakes that support large populations of zebra mussels may experience a diminished fish yield, especially of fish feeding in the open water. On the other hand, stimulation of the benthic community may increase the productivity of bottom-dwelling fish. Open-water piscivorous fish may change their feeding habits to prey more on benthivorous fish or may decrease in production. As water clarity increases, changes in fish populations may occur as conditions become more favorable for "clear-water" fish (e.g. pike) and less favorable for "turbid-water" fish (e.g. walleye). Increased water clarity will increase the light penetration into the water, increasing growth of aquatic weeds, providing increased habitat for fish that prefer to spawn and hide in weed beds (e.g. sunfish).

Increased water clarity can also cause community and ecosystem changes. Abundant growth of these aquatic weeds will oxygenate the bottom waters, further supporting benthic community life. Recent studies indicate that zebra mussels increase the remineralization and recycling rate of nitrogen and phosphorus, providing an increased availability of nutrients such as nitrate and phosphate, essential for growth of benthic organisms.

Economic impact of zebra mussels on inland lakes

Hydroelectric power plants, municipal drinking water facilities and other water-using industries are likely to be most heavily impacted by zebra mussel populations. Mussels colonize the surfaces of pipes, diminishing the flow rate through water intake pipes. Unless preventive measures are taken, larval zebra mussels colonize the interior parts of turbines and other equipment, leading to costly repairs. Preventive measures such as retrofitting backwash filters or pre-chlorination devices for water intake pipes are also costly. Great Lakes industries have spent millions of dollars combating and preventing zebra mussel damage.

Zebra mussels can also attach to water intake pipes of boats, preventing sufficient flow of coolant water, leading to engine failure. Mussel attachment to boat hulls increases drag and decreases fuel efficiency. Removal of mussels from boat hulls can be time-consuming and costly. Anti-fouling paints are expensive; some are highly toxic, heavily regulated and need to be applied by a licensed specialist.

The full economic impact of zebra mussels is still under investigation. Recent studies report that zebra mussels hasten the corrosion rate of iron and steel structures at the point of attachment. Enhanced growth of aquatic weeds resulting from increased water clarity has led to taste and odor problems in drinking water supplies, necessitating more expensive and aggressive water treatment procedures.

Prevention and remediation of the zebra mussel invasion

Boat and barge traffic is the major vector spreading zebra mussels inland from the Great Lakes through the inland waterways. From these inland waterways, it is expected that zebra mussels will be carried unwittingly to inland lakes and reservoirs on the hulls of boats. They also may be carried in live wells and bait buckets, on fish nets and possibly by waterfowl and other wildlife moving from infested waters.

Controlling the movement of contaminated boats appears to be the only significant means of preventing, or at least slowing, the spread of zebra mussels from infested waters. The most effective and least environmentally damaging method of control is to drain the boat thoroughly and let it dry for several days before transferring it to other waters. Although the veligers are sensitive to drying, individual adult mussels are very hardy and can survive at least several days out of water, especially in moist environments. Washing the boat with hot water (at least 110°F; 42°C) using a high pressure hose is also effective in removing zebra mussels attached to boat surfaces. Inspection of boat hulls and scrubbing have a limited effectiveness because very young mussels are difficult to detect, often being smaller and more transparent than a sesame seed.

Zebra mussels are sensitive to potassium and to modest amounts of chlorine bleach (one part bleach to ten parts water). Chlorine bleach is useful for disinfection of live wells and bilges. Although dipping boats into holding ponds of potassium chloride or chlorine bleach for several hours has been contemplated as a means of decontaminating boat hulls, this is generally not considered feasible because both the economic and environmental costs may outweigh the benefits. Chemical treatments are expensive in the large quantities required and can damage some boat equipment. Disposal of large quantities of chemicals is problematic because of toxicity to aquatic life. For more information, boaters should request the publication *Slow the Spread of Zebra Mussels, and Protect Your Boat, Too*, FS-054, from Ohio Sea Grant.

What can be done to remove zebra mussels once they have become established in a lake? Much current research is directed at identifying procedures of reducing or removing zebra mussel populations from lakes. Adult zebra mussels are resistant to toxins generally used to remove mollusks. Molluscicide concentrations sufficient to kill zebra mussels do considerable damage to other forms of aquatic life and are considered an inappropriate means of control. Biological control seems also to be inadequate. Diving ducks are natural predators of these mussels, but their numbers are insufficient to control massive populations. Some fish (e.g. yellow perch) are learning to eat zebra mussels, but so far fish do not consume them to the extent sufficient to control large populations.

Whole-lake control may be possible for impoundments that can be drawn down over winter. Although a draw-down cannot be done on all inland lakes and reservoirs, it is a procedure that needs to be explored as a possible means of control in those lakes that can be drawn down.

NOTE TO READERS

Because research is on-going and zebra mussels readily adapt to a wide range of conditions, this publication will be updated to incorporate new information as appropriate.

Aquatic nuisance species and Sea Grant

Kelly Kershner, Ohio Sea Grant Communications

In 1869, it was purple loosestrife. In 1873, alewife and chinook salmon. In 1879, common carp.

Exotics are nothing new in the Great Lakes. Scientists believe the sea lamprey led the way back in the 1830s. Today, scientists estimate that 136 foreign plants, fish and mollusks make the Great Lakes home.

Perhaps the most definitive zebra mussel characteristic is a seeming urge to roam. They're native to the Ponto-Caspian region of western Russia. But with the construction of canals across Europe in the 1700s and 1800s, they rapidly expanded their range. By the 1830s, zebra mussels covered much of the continent and had invaded Great Britain.

Today, zebra mussels have made their mark on the Great Lakes. Since their discovery in Lake St. Clair in 1988, the tiny striped mollusks have spread rapidly to all of the Great Lakes and inland waters in 18 states and two provinces. No matter where it colonizes, Lake Erie—with its shallow, warm, nutrient-enriched environment—is expected to always be the most significantly affected of the Great Lakes.

Zebra mussels have also affected the environment in significant ways. So far, scientists have learned that zebra mussels are prodigious filter feeders—they remove tiny organisms from the water column at the rate of about a liter per day. Since the invasion, water clarity in Lake Erie has increased almost six-fold, allowing rooted aquatic plants to flourish and even clog harbors. Diatoms and rotifers -microscopic plants and animals at the base of the aquatic food chain—have been reduced by as much as 80 percent in some areas.

Also, scientists have learned that the zebra mussel, though small, is dangerous. In parts of Lake Erie and Lake St. Clair where zebra mussels and native clams are both present, the native clams are now almost gone.

Further, data suggest that zebra mussels' fatty tissues allow them to accumulate toxic chemicals at levels 10 times higher than native mussels. When eaten, zebra mussels pass this contaminant burden on to fish and on to small, shrimp-like organisms called gammarids, which eat both zebra mussel waste products and dead mussel tissue.

Still unclear in all of this are the implications—for fisheries, biodiversity and pollution. Do zebra mussels hurt the walleye fishery by stealing food from the smaller fishes that walleye feed on? Will zebra mussels cut a simplifying swath through the complex ecosystem, doing to lakes what purple loosestrife has done to marshes? Will zebra mussels pass super-concentrated pellets of pollutants back up the food chain? Scientists seek answers to these and other questions.

Zebra mussels pose a complex set of challenges, both now and for the future. The spread is continuing and mussel densities at Lake Erie water intakes are approaching 1 million per square meter. To meet those challenges, research must continue. Control methods must be developed, tested and made affordable. Industries, marinas—all those directly affected by zebra mussels—must have a direct line to the latest information. The general public must get involved — even simple precautions will help slow the spread.

That's where Sea Grant comes in.

Sea Grant is a bridge between government and academia, scientist and private citizen. Sea Grant is a commitment to solve coastal problems and develop marine resources. It's a bond uniting 29 state programs, 300 colleges and universities and millions of people. It's a partnership with a purpose—to help Americans understand and more wisely use our precious Great Lakes and ocean waters.

Sea Grant scientists make progress on the important marine issues of our time. Extension agents quickly take this information out of the laboratory and into the field, working to help save a coastal business, a fishery, sometimes even a life. A dedicated corps of writers and communications specialists spreads the word to the public. And Sea Grant educators bring the discoveries into the nation's schools, using them to pioneer new and better ways of teaching, helping to create a new generation of scientifically literate Americans.

Together, separate elements create a cohesive whole, ensuring that Sea Grant meets the challenges of its mandate.

Sea Grant's strength is its ability to meet problems head-on and efficiently solve them.

Today, one of those challenges is zebra mussels. Sea Grant is meeting this challenge. Proceeding as it always has, Sea Grant is drawing on a wealth of scientific expertise to develop feasible solutions. But it's also keeping the public informed in all the effective and innovative ways the collective creativity within Sea Grant can generate.

For more information about Sea Grant's work on zebra mussels, contact the program nearest you. For a list of resources available from the six Sea Grant programs in the Great Lakes Sea Grant Network, request a copy of *A Great Lakes Sea Grant resource list on zebra mussels and other nonindigenous species.*

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Wisconsin Sea Grant Institute
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Other U.S., state and Canadian agencies are also working on this issue. Some of the agencies working as a Great Lakes panel on nonindigenous species include:

- U.S. Fish & Wildlife—monitor and research
- Coast Guard—regulatory activities
- Great Lakes Environmental Research Lab, NOAA—research
- Great Lakes Fishery Commission—research
- Great Lakes Commission—policy development and coordination
- Sea Grant—university-based research, education and technology transfer

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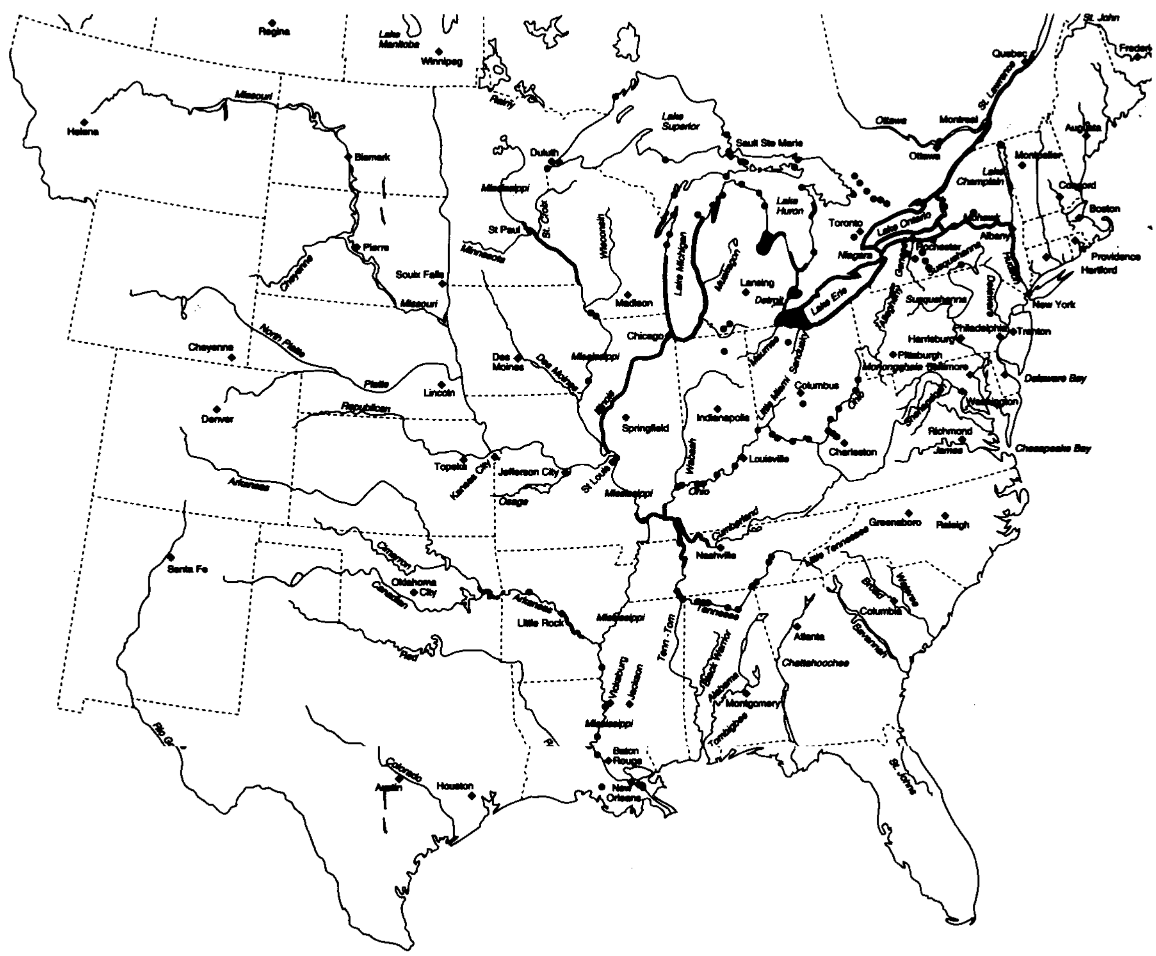
Range of the zebra mussel in North America

as of August/September 1993

Compiled by New York Sea Grant with information from: Empire State Electric Energy Research Corp., Fisheries and Oceans Canada, Great Lakes Sea Grant Network, Illinois Natural History Survey, Ontario Hydro, Ontario Ministry of Natural Resources, Tennessee Valley Authority, US Army Corps of Engineers, US Fish & Wildlife Service, and utilities and others throughout North America.



CRITERIA FOR PREDICTING ZEBRA MUSSEL INVASIONS IN THE MID-ATLANTIC REGION

BY

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INTRODUCTION

The following document is from the proceedings of a 1993 zebra mussel workshop, conducted in Baltimore, Maryland. At the workshop forecasts were presented concerning the future of zebra mussels, Dreissena polymorpha, *in the mid-Atlantic states.*

What is the probability that zebra mussels will invade specific bodies of water within a given state? If they do invade, will they become economic and ecological pests as they have in portions of the Great Lakes? These and similar questions are addressed, with the expectation that management strategies can be developed to delay, mitigate, or possibly even prevent zebra mussel invasions, in some areas.

The probability of invasion is related to the frequency with which a specific body of water is inoculated with zebra mussels and their ability to survive in that body of water. The variety of dispersal mechanisms, and the frequency and relative importance of each potential inoculation affect the overall chance that a reproducing population of zebra mussels will become established in a lake or estuary.

Prior experience with zebra mussel invasions in Europe and other parts of North America indicates that, at least initially, population growth is not limited by predators, parasites, or other biological factors. Certain abiotic parameters, however, seem to limit zebra mussel populations in Europe. For these reasons, the criteria for predicting zebra mussel invasion success in the mid-Atlantic region are primarily physical environmental parameters, and especially aspects of water chemistry. The degree to which a particular body of water conforms to the known optimum physiological requirements for zebra mussels is here termed its *susceptibility*. The second part of this document is a review of the physiological requirements used to predict susceptibility. For an example of similar predictions for other regions, see Neary and Leach (1992).

A second species of *Dreissena*, with at present only the common designation "quagga mussel" (its taxonomic identity is uncertain), has been found in parts of the Great Lakes and New York inland waters (May and Marsden, 1992). At present, nothing is known about the dispersal or physiological requirements of the quagga mussel, other than that it lives with *Dreissena polymorpha*, and dominates some deep-water populations (Marsden, 1993). Throughout this chapter, *Dreissena* is used to indicate both the zebra mussel and the quagga mussel.

A zebra mussel is a small, striped mollusk capable of raising havoc. (Although the mollusk can grow up to two inches, it is usually much smaller —fingernail size.) Zebra mussels have cost millions of dollars in the Great Lakes region where they rapidly colonized water-intake pipes, boats, docks, piers, and other structures. *Dreissena polymorpha* was inadvertenly delivered to U.S. waters around 1986 through the discharge of European shipping ballast water. —ed.

I. INVASION RISK

DISPERSAL MECHANISMS OF ZEBRA MUSSELS

Invasion *risk* is here defined as the probability, relative to other bodies of water, that zebra mussels will be inoculated to a specific body of water in sufficient numbers to establish a viable population. As will be explained, risk is related to the numbers of zebra mussels inoculated, and the conditions of inoculation, which are in turn related to the mechanisms of inoculation.

Terminology for biological invasions merits a brief discussion. An *invasion* is the successful (reproducing) establishment of a species in an area in which it had historically been absent. The vector for invasion can be either human-mediated or natural. When an invasion is known to be human-mediated, it can be termed an *introduction*. Thus, *Dreissena* was *introduced* to Lake St. Clair, in Michigan, and from there they *invaded* (by natural *dispersal*) Lake Erie and Lake Ontario. The actual event that leads to an introduction, such as the release of ballast water containing larvae, is termed *inoculation*, and the process by which the new species becomes a self-maintaining population is termed *establishment*. Thus, *inoculation* and *establishment* are events within an *introduction*, which is itself a specific form of *invasion*. These usages come from no single source, and alternate terms are used elsewhere, but the above are generally consistent with modern literature on aquatic biological invasions.

Population Establishment

One of the most difficult aspects of predicting biological invasions is forecasting when (how soon) an invasion will occur. *Dreissena* invaded the Great Lakes some time shortly prior to 1988 (Hebert *et al.*, 1989), but the mechanism responsible for invasion, ballast water (Carlton, 1993), has existed for decades before *Dreissena* became established. Similarly, the rate and direction of dispersal by both natural and human-mediated means from the Great Lakes has often defied prediction. For example, *Dreissena* has been present in an upper portion of the Susquehanna River, in New York, since at least 1991 (Lange and Cap, 1992), but to date has not appeared in downstream portions. This absence does not mean that zebra mussels will not invade downstream, only that we cannot predict closely when they will.

We do have limited understanding of how some inoculations may be favored over others. *Dreissena* reproduces sexually, releasing male and female gametes into the water. Prior research on other aquatic organisms (Pennington, 1985; Lasker and Stewart, 1992) show that gamete viability decreases dramatically with dilution, so that low-density populations of benthic invertebrates have much lower reproductive success than high-density populations. Not only does this mean that the initial inoculation of *Dreissena* must result in animals in sufficient proximity to spawn successfully, but also that there must be enough offspring produced so that they, too, can reproduce successfully. Larvae disperse in the plankton and face high mortality; those that survive to settlement are widely scattered, and only those that settle near others can reproduce. Thus, the greater the founding population, the greater the chance of subsequent establishment, and the more quickly the population will attain high levels. Dispersal mechanisms which deliver many individuals to the same location are the most likely to spread invasions (Johnson and Carlton, 1993).

There are two practical aspects to the above observation, and its corollary, that not every inoculation will result in invasion. First, it is cost-effective for management agencies to concentrate first on major invasion vectors, rather than trying to prevent every possible mechanism for invasion. Second, when obtaining public cooperation in limiting *Dreissena* invasion, it is important to make individuals believe that their own reasonable efforts can make a difference in *Dreissena* invasion. This latter aspect has been discussed by Johnson and Carlton (1993).

Natural Dispersal

Larval Dispersal

Dreissena is unusual among freshwater bivalves in that it has planktonic larvae and postlarvae (Griffiths *et al.*, 1991; McMahon, 1991). Postlarvae drift passively with currents by means of long byssal threads (Martel, 1992). Larvae swim by means of the velum, a ciliated organ, but most bivalve larvae have swimming rates of less than 1 mm·s^{-1} (Mann and Wolf, 1983; Jonsson *et al.*, 1991; Mann *et al.*, 1991), and therefore cannot swim against most currents. Juveniles and adults can crawl actively but not rapidly, and it is extremely improbable that a juvenile or adult could crawl upstream against a current as far in its lifetime as it would be carried downstream as a larva (planktonic period of about 12 days: Neumann *et al.*, 1993) or postlarva. *Dreissena*, therefore, is ecologically adapted more for lakes (no net currents) or estuaries (bidirectional currents), than for rivers (unidirectional current) (Neumann *et al.*, 1993). Rivers which have attached oxbow lakes, navigational locks, or other calm backwaters, could probably support significant populations of *Dreissena* (e.g. Biryukov *et al.*, 1968). The native range of *Dreissena* is estuaries in southern Russia, Ukraine, and Kazakhstan, and the largest populations outside of the native range, in Europe and North America, have been in lakes, estuaries, and other calm waters (Shtegman, 1968; Wolff, 1969; Sta czykowska, 1977; Griffiths *et al.*, 1991). High densities of *Dreissena* in non-estuarine rivers can be maintained only by a continual input of individuals from upstream lakes or backwaters. Thus, streams without such areas cannot be successfully invaded by *Dreissena*. Unfortunately, most major North American rivers, including those along the eastern coastline of the U.S., have upstream reservoirs that could support *Dreissena* populations, given the correct water quality parameters. High densities of *Dreissena* can be attained in rivers downstream of lakes (e.g. Piesik, 1983; Neumann *et al.*, 1993). There is no data on the effect of reservoir size or flushing rates on downstream *Dreissena* population densities, so for now, all freshwater downstream of a lake capable of supporting *Dreissena* populations must be considered at risk from invasion.

Dreissena are limited in their ability to tolerate salt water, but most major eastern estuaries in North America have large freshwater tidal portions. Even in years of low freshwater input, significant portions of most estuaries remain fresh. *Dreissena* larvae and postlarvae could be retained within the estuary by the same mechanisms used by oyster larvae (Seliger *et al.*, 1982; Mann, 1988). A native species closely related to *Dreissena*, the false mussel *Mytilopsis leucophaeata*, is already present in oligohaline and freshwater portions of estuaries from New York to Texas (Abbott, 1974). Water chemistry of these estuaries, in terms of pH and calcium, is often nearly ideal for *Dreissena*, and many must be considered at risk from *Dreissena* invasion. Furthermore, any freshwater portions of an estuary will eventually be invaded if there are *Dreissena* populations established in upstream lakes or reservoirs. The St. Lawrence River in Quebec and the Hudson River in New York are two North American examples of invaded freshwater estuaries (New York Sea Grant, 1992).

Adult and Juvenile Dispersal

Adults and juveniles of *Dreissena* can crawl by alternately attaching and releasing byssal threads. Based on crawling rates of juvenile marine mussels, *Mytilus* spp. (these authors, unpubl. data), *Dreissena* individuals can probably move several meters per day. A very short stream between a *Dreissena*-infested reservoir and an upstream, non-infested reservoir, would probably not be a barrier against invasion by crawling individuals. Two examples of this situation include a series of ponds in a typical golf course, and the network of ponds, canals, and ditches in many coastal cities in the mid-Atlantic region. *Dreissena* individuals probably cannot circumnavigate a waterfall or spillway, however, nor crawl up a rapidly flowing stream more than several hundred meters in sufficient numbers to establish a new population in an upstream reservoir.

Adult and juvenile *Dreissena* attach to a variety of substrates with sturdy byssal threads. A number of natural mechanisms (amphibious animals) have been proposed that could transfer byssally-attached adults or juveniles between very close but separate bodies of water. These mechanisms have been reviewed by Carlton (1993), and an example includes aggregations attached to the carapaces of turtles, which often migrate between nearby bodies of water. Certain species of turtle may become important in dispersing *Dreissena* within regions with many small lakes, or in coastal regions with many small estuaries isolated from each other by high-salinity barriers, but only low, narrow terrestrial barriers. This last condition is typical of the coastal plain from New Jersey to Texas. In the mid-Atlantic region, the eastern musk turtle (*Stenotherus odoratus*), a common species living in a variety of bodies of water, is noted for having heavy algal fouling (McCauley, 1945; Martoff *et al.*, 1980), and the much larger snapping turtle (*Chelydra serpentina*) can also be heavily fouled (J. Brown, Virginia Inst. Marine Science, pers. comm.).

Waterfowl have been suggested by a variety of authors as potential vectors of transport, and Carlton (1993) reviews evidence both for and against this as a mechanism of invasion. Birds could transport *Dreissena* many kilometers by a variety of means, although the actual numbers transported by any one bird would be small relative to the numbers that could be transported by almost any human-mediated process. The role of large flocks of migratory birds in dispersing *Dreissena* is worth investigating, however.

It should be noted that so far the spread of *Dreissena* in North American across natural barriers can be attributed to human actions alone. Thus while amphibious animals may be mechanisms of invasion, most emphasis should be placed on controlling human-mediated dispersal mechanisms.

Human-Mediated Dispersal Mechanisms

Overland Transport

Overland transport of *Dreissena* associated with recreational vessels, or the trailers that transport them, has received much attention, and is thought to be the primary mechanism whereby inland lakes separated from other navigable waters will be invaded. Baltimore County, Maryland, has restricted the use of recreational vessels in several municipal reservoirs in response to this threat. McMahon and Payne (1992) have shown that *Dreissena* can survive several days out of water even at high temperatures, and dispersal by overland transport is known to have occurred (Carlton, 1993). Public education has focused on the potential for *Dreissena* attached to vessel hulls to be moved between lakes, but it has recently been noted that under certain circumstances more *Dreissena* will probably be transported on strands of aquatic macrophytes that become entangled in boat trailers (Carlton, unpubl. data).

Known or suspected invasions that have occurred as a result of overland transport have been fewer, so far, than have been expected. The reason may be that, normally, few individuals are introduced by a single inoculation. Several overland invasions *have* occurred, however, including the invasion of the upper Susquehanna drainage in New York state (Lange and Cap, 1992), and either vessel hulls or their trailers are the most probable vector.

Juveniles or adults, not larvae, will be transported overland by the above mechanisms. To be introduced to the new location, the *Dreissena* must detach from the vessel or trailer. Juveniles are more likely to move than adults (Eckroat *et al.*, 1993). If the *Dreissena* are attached to macrophytes associated with the boat trailer, it is simply necessary for the plant to detach in the new body of water. Furthermore, a piece of drifting plant with attached *Dreissena* could drift rapidly down a river until it reached a lake, where a population could be established, whereas adult *Dreissena* sinking individually into a river would be less likely to reach a downstream lake or successfully establish a population.

Ballast Water, Bilges, Bait Wells

It is believed that the introduction of *Dreissena* into the North American Great Lakes was accomplished by the release of ballast water, containing larvae or postlarvae, from the holds of ore carriers from Europe. Evidence for this route has been well documented (see Carlton, 1993, for review). Guidelines to prevent further introductions or exotic species by ballast water into the Great Lakes have been set up, but compliance is not thought to be 100% (J. Carlton, pers. comm.), and probably a single inoculation under optimal conditions is sufficient to permit invasion. Furthermore, ballast into other North American freshwater ports remains undocumented. For example, Richmond, Virginia, a freshwater estuarine port, is regularly visited by container ships from Antwerp, Belgium, and other European ports (Meehan Overseas Terminal, Inc., 1991). Alexandria, Virginia, another freshwater port, is visited six to seven times annually by ships from Quebec City, Quebec, in the St. Lawrence River, where *Dreissena* is established (Robinson Terminal Warehouse Corp., Alexandria, VA, pers. comm.). The amount of ballast water exchanged, and the nature of the exchange, is undocumented and unregulated, but represents a potential vector for the introduction of *Dreissena* into Virginia. Port logs, sometimes available upon request, will no doubt reveal many further points of potential introduction, and it may be chance that the Great Lakes were invaded by *Dreissena* before another North American body of water.

Bait wells, bilge water, shipments of live fish or bait, and many other means of transporting water between bodies of water may harbor larvae or postlarvae for several days, although to date no specific examples of this occurring in North America are known. This means of transport is reviewed at length by Carlton (1993).

VESSEL TRANSPORT BETWEEN ESTUARIES

Once established in Lake St. Clair and Lake Erie in 1989, *Dreissena* was subsequently identified at many isolated points elsewhere in the Great Lakes and in the Erie Canal, New York. The vector of dispersal in these cases was thought to be vessel hulls with byssally-attached adults or juveniles (Griffiths *et al.*, 1991). Since vessels can move upstream or across salinity barriers relatively rapidly, they are a major mechanism for expanding the range of *Dreissena.* Postlarvae and juveniles attached to the hull of a recently moved vessel can detach at a new moorage, and accumulate on nearby stationary substrate. Alternately, adults attached to the hull can spawn at a new location. The relative importance of these two phenomena depends on the number of postlarvae or juveniles transferred in the first case, or the number of adults and the amount of time spent at the new moorage in the second case. The resettlement of postlarvae and juveniles from vessel hulls as a means of dispersal is likely to be favored during the reproductive season, by vessels with relatively clean hulls that do not spend extended periods at any particular mooring. Even a high density of microscopic *Dreissena* postlarva and juveniles would be unnoticed by persons visually inspecting vessel hulls in an attempt to prevent the spread of *Dreissena.* On the other hand, some vessels, especially barges, spend weeks or months at any particular moorage, giving fouling organisms attached to their hulls multiple opportunities to spawn. In such cases, vessels with large fouling populations of adult *Dreissena* would be favored as a method for introducing this species.

Barges in particular represent a major vector for *Dreissena* dispersal. They have large hull areas for colonization from the source population, they are infrequently cleaned, and they often have long residence periods at any particular moorage. Once moved, barges may be moored for months or even years, giving any fouling organisms many opportunities to reproduce. In addition, freshwater regions are attractive to many vessel owners for long-term moorage, because of the relative lack (prior to *Dreissena*) of fouling organisms. The hulls of other vessels that travel between estuaries are generally smaller and cleaner than barge hulls, but the possibility of introduction via these cannot be ruled out. Even a small, possibly unnoticed portion of a hull could harbor tens of thousands of adult, juvenile, and postlarval *Dreissena.*

Given the ability of *Dreissena* to tolerate moderately saline waters for at least a short period, vessel traffic represents a major intracoastal vector for the spread of *Dreissena* between estuaries. *Dreissena* is present in both the Hudson and Susquehanna Rivers (New York Sea Grant, 1992), and could potentially spread from those sites to most other estuaries with barge traffic between New York and Florida. At present no records on commercial or recreational traffic between freshwater estuarine ports in North America have been compiled. The length of time that *Dreissena* can tolerate full seawater, perhaps by completely closing their valves, is unknown, but they have been shown to be able to survive several days out of water, attached to pleasure craft hulls, under certain circumstances (McMahon and Payne, 1992), and can survive several days without oxygen (Mikheev, 1968).

Introduction of *Dreissena* to a body of water via the hull of a vessel does not automatically ensure establishment. Establishment is favored by high survival of *Dreissena* during the passage overland or through high salinity, by large numbers (e.g. millions) of individuals, by favorable water conditions for growth and reproduction in the host estuary, and by long moorage of the fouled vessel.

INTENTIONAL INTRODUCTION

The possibility of deliberate, misguided introductions of *Dreissena* must be seriously considered. *Dreissena* populations are believed to be responsible for a dramatic increase in water clarity in Lake Erie (Wright and Mackie, 1990; Greenberg *et al.*, 1992; MacIsaac and Sprules, 1992; Leach, 1993), and would probably do the same for any small lake to which they were successfully introduced. Water clarity, while of uncertain ecological advantage, is enormously attractive aesthetically, and the impact of *Dreissena* on water clarity in Lake Erie has been well-publicized (e.g. Di Vincenzio, Newport News *Daily Press,* Dec. 5, 1991; Walker, 1991; Cohen, 1992; Sisson, 1993). Other reasons to intentionally introduce *Dreissena* could be a desire to increase biodiversity, provide food for other organisms, or to provide a new bait source. If *Dreissena* are used as bait, there is also a risk of recreational fishermen dumping left-over bait into a pond or lake. Many previous introductions of freshwater mollusks are believed to have been carried out by private landowners, intentionally or through carelessness (Carlton, 1993), and *Dreissena* are exceptionally easy to collect and transport. Because *Dreissena* larvae disperse, a small lake that retains and concentrates successive generations may be as much at risk from a single introduction as a large lake.

II. Susceptibility To Invasion

Physiological Requirements of Zebra Mussels

This section reviews published data on the physiological requirements of *Dreissena* with respect to water quality and chemistry. Four common aspects appear critical to the persistence and reproduction of *Dreissena* populations; temperature, salinity, alkalinity (pH), and calcium content. Table I summarizes this information for adults and larvae.

Temperature

Stanczykowska (1977) stated that adult *Dreissena* began growth at 11-12° C in European lakes, similar to a value of 10-12° C reported by Mackie (1991) for *Dreissena* in the Great Lakes. Bij de Vaate (1989), however, reported that growth of *Dreissena* in the Netherlands occurred at temperatures as low as 6° C, and in a review of European lakes with *Dreissena*, Strayer (1991) reported that the largest populations were in lakes with a mean annual temperature of only 6-9° C, inferring that temperatures exceeded 6-9° C only half of the year. Borcherding (1991), who reported gametic growth at temperatures as low as 2-4° C, suggested that reported differences could be due in part to food quality and quantity for different populations. Differences may also reflect methods of measuring or defining growth. Schneider (1992) predicted that growth rate is strongly affected by temperature, with slower growth rates at low temperatures. The minimum temperature tolerance for survival appears to be just above freezing (Strayer, 1991). Nowhere in the mid-Atlantic region are there temperature regimes cold enough to limit *Dreissena* populations. The maximum temperature that permits growth by adult *Dreissena* has been reported variously as 26-33°C (Stanczykowska, 1977).

Table 1. Physiological Requirements of Zebra Mussels: Summary

Values experssed as ranges; optimums are enclosed in parentheses. References are given in text of Section II.

Adult Survival	0.33°C	0-12ppt	7.0-?	unknown
Adult Growth	6-3°C	0.6ppt (0-0.6ppt)	7.5-?	(34.5-76)
Larval Growth	12-24°C (17-18°C)	Oppt-?	7.4-9.4 (8.4-8.5)	12-106+ (40-?)

Gametogenesis in *Dreissena* has been reported at temperatures as low as 2-4° C in the presence of good food quality (Borcherding, 1991), and spawning is known to occur at 12° C (Sprung, 1987; Bij de Vaate, 1989; Borcherding, 1991) and at 22-23° C (Haag and Garton, 1992). Sprung (1987) reported a loss of sperm motility in *Dreissena* at 26° C, and zygote failure above 24° C. This last evidence indirectly supports predictions by Strayer (1991) that populations of *Dreissena* will be heat-limited in the southernmost regions of North America. Haag and Garton (1992), however, reported that *Dreissena* in Lake Erie spawned during a period of water temperatures above 26°C; the maximum temperature at this time was 30°C. Temperatures as high as 30°C, therefore, may not inhibit reproduction. Strayer (1991), in a review of climatological conditions in Europe, reported that the highest mean monthly temperature tolerated by *Dreissena* was 26.4°C. Optimum larval rearing temperatures in the laboratory were reported to be about 17-18° C by Sprung (1987).

In temperate regions, with seasonal temperature fluctuations, the maximum temperature that permits *Dreissena* reproduction is less important than the temperature tolerance of adults, since there will always be optimal temperature windows at some point of the year for spawning. *Dreissena* tolerates extended periods of temperatures in excess of 25° C, so the majority of the United States and southern Canada are within the temperature tolerance of this species.

Salinity

Mackie and Kilgour (1992) reported an LC_{50} of 7.6 salinity at 96 hours for unacclimated adult *Dreissena*, at 19° C. Over a period of 42 days, *Dreissena* which had been slowly acclimated had only 15% mortality at 8.0 salinity at 4° or 10° C. Barber (1992), however, reported 100% mortality within 52 days of adult *Dreissena* in water slowly raised from 0 to 2.7, at 15° C. Wolff (1969) cites an unpublished source stating that *Dreissena* could survive salinities as high as 12.2, although the circumstances of exposure were not given. In the Delta region of the Netherlands, adult *Dreissena* tolerate continual salinity of 4 in ponds, but were not found in estuaries with mean salinities above 0.6, in which salinity fluctuated with tides (Wolff, 1969). Wolff (1969) concluded that the higher mean salinities could be tolerated only if there were not tidally-driven fluctuations.

The apparent difference in reported salinity tolerance in *Dreissena*, between Mackie and Kilgour (1992) and Barber (1992) (above), may reflect a strong interaction of salinity and temperature (with higher tolerance at lower temperatures), or it may reflect physiological differences in the experimental animals. Hebert *et al.* (1989), and Garton and Haag (1991), reported high genetic variability, for an introduced species, among *Dreissena* in the Great Lakes and this may be reflected in variation in physiological tolerances.

When plotting potential spread of *Dreissena* in North America, it is safest to assume that they can tolerate salinities of at least 12.2 for a few days. This would be significant for *Dreissena* fouling slow-moving vessels, such as barges, that are periodically moved between freshwater portions of estuaries. For example, a barge fouled by *Dreissena* in the Susquehanna River, in Pennsylvania or Maryland, could probably be towed to a new anchorage (and a new watershed) in Philadelphia, Pennsylvania, or Alexandria, Virginia, without submitting the *Dreissena* to lethal osmotic stress. On the other hand, only areas with salinity below 1 are likely to maintain high *Dreissena* densities. Walton (1993) found *Dreissena* in salinities as high as 6 in the Hudson river, but high densities (>1000 m^{-2}) were maintained only at a site that never exceeded 3 salinity, and was often fresh.

The salinity tolerances of *Dreissena* spawning adults, eggs, veliger larvae, or planktonic postlarvae, have not been reported. Mann *et al.* (1991), however, in a review of physiological tolerances of oysters of the genus *Crassostrea*, reported that the ranges of salinity tolerances for spawning adults or for larvae were equal to or less than those for adult survival.

pH, Calcium, Other Ions

pH in North American fresh waters varies depending on rainfall acidity and bedrock composition. Adult *Dreissena* have a heavy periostracum covering all but the oldest, thickest portion of the shell (pers. obs.). The periostracum in freshwater mollusks is thought to aid in prevention of shell dissolution (McMahon, 1991), and *Dreissena* may thus be able to survive periods of relative acidity. The minimum pH tolerance of adult *Dreissena* appears to be 7.0, the point at which shell dissolution exceeds calcium uptake (Vinogradov *et al., 1993),* but Ramcharan *et al.* (1992), in a literature survey of European lakes, reported that significant populations of *Dreissena* persisted only above a mean pH of 7.5.

Larval development in *Dreissena* appears to be tightly regulated by pH. Sprung (1987) reported *Dreissena* egg survival between only pH 7.4 and 9.4, and optimal survival between pH 8.4 to 8.5, at temperatures of 18-20° C. Even if these values vary among *Dreissena* populations, or with rearing conditions, it appears that at least during the reproductive season, *Dreissena* requires slightly alkaline water.

Calcium, a major component of mollusk shells, appears to be limiting in some cases. Ca^{2+} (from $CaCO_3$) is expressed either as "hardness" (milliequivalents, or meq), or as mg per liter. European lakes with large populations of *Dreissena* have hardness levels of about 1.73 to 3.16 meq (Strayer, 1991), or a minimum of about 34.5 mg Ca^{2+} l^{-1}, a mean of about 45-52 mg Ca^{2+} l^{-1}, and a maximum of 76 mg Ca^{2+} l^{-1} (Ramcharan *et al.*, 1992). These values should not be considered limits, but only the range for which large populations of *Dreissena* have been recorded in Europe. Actual requirements for adult *Dreissena* have not been determined in the laboratory. Sprung (1987) reported minimum embryo survival at 12 mg Ca^{2+} l^{-1}, and optimum survival at levels of 40 mg Ca^{2+} l^{-1} (2.0 meq) and above. Larvae grew relatively well at calcium levels of 106 mg l^{-1}, the maximum level tested.

Other salts, including $MgSO_4$, NaCl, $KHCO_3$, $NaHCO_3$, and $MgCl_2$, do not appear limiting to *Dreissena* embryos (Sprung, 1987). Potassium (KCl) is lethal at levels of about 100 ppm (LC50 for 24 hours) (Fisher and Stromberg, 1992), but concentrations rarely approach this level in natural waters. Ramcharan *et al.* (1992), in a review of European lakes, reported that the mean phosphate (PO_4) level of lakes with stable populations of *Dreissena* is about 0.12 mg l^{-1}, with a maximum level of 0.18 mg l^{-1} and a minimum of 0.05 mg l^{-1}, although *Dreissena* have been reported in lakes with no measurable free phosphate. Phosphorus and nitrogen may have indirect roles on *Dreissena* population growth rates, since they are critical nutrients for freshwater phytoplankton, and thus affect abundance of phytoplankton, the primary food source for *Dreissena*. Ammonia (NH_3) is lethal at a level of about 2 mg l^{-1} (Nichols, 1993), but this level is lethal to many other aquatic organisms as well.

Oxygen

Sprung (1987), with limited data, concluded that *Dreissena* larvae survived for short periods at oxygen levels as low as 20% of saturation, at 18°C. This oxygen level in natural systems is considered to be a hypoxic condition, and aquatic systems with oxygen levels of 20% for significant periods have problems far worse than zebra mussel infestations. During periods of highest pollution in the 1970s, hypoxia eradicated *Dreissena* from much of the Rhine River in Germany (Neumann *et al.*, 1993). Survival of adults in hypoxia is unknown, but juvenile oysters have been shown to be significantly more tolerant of hypoxia than larvae (Widdows *et al.*, 1989), so adult and juvenile *Dreissena* are probably more tolerant of hypoxia than are larvae. Under anoxic conditions, 100% mortality of *Dreissena* occurs in about 6 days at 17-18°C, and 3 days at 23-24°C (Mikheev, 1968). McMahon and Alexander (1991) concluded that *Dreissena* are poorly adapted for survival at low oxygen levels in warm water (25°C), which indirectly supports Strayer's (1991) predictions of a warm-water limitation to *Dreissena* invasion. In general, however, only severely stressed aquatic systems would have oxygen levels low enough to inhibit *Dreissena* invasions.

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REFERENCES

Abbott, R.T. 1974. *American Seashells.* 2nd Ed. Van Nostrand Reinhold Co., New York, NY. 663 pp.

Barber, B.J. 1992. Preliminary investigation of the salinity tolerance of zebra mussels, *Dreissena polymorpha*: implications for Chesapeake Bay. (Abstract). *J. Shellfish Res.* 11:218.

Bij de Vaate, A. 1989. Occurrence and population dynamics of the zebra mussel, *Dreissena polymorpha* (Pallas, 1771), in the Lake Ijsselmeer area (the Netherlands). (Abstract). *Proceedings of the New York Sea Grant Conference on Zebra Mussels in the Great Lakes.*

Biryukov, I.N., M.Ya. Kirpichenko, S.M. Lyakhov, and G.I. Segeeva. 1968. Living conditions of the mollusk *Dreissena polymorpha* Pallas in the Babinski backwater of the Oka River. 32-38. **In** Shtegman, B.K. (ed.). *Biology and Control of Dreissena. Israel Program for Scientific Translations, Ltd., Jerusalem, Israel, and U.S. Dept. Commerce, National Technical Information Service, Springfield, VA.*

Borcherding, J. 1991. The annual reproductive cycle of the freshwater mussel *Dreissena polymorpha* Pallas in lakes. *Oecologia* 87:208-218.

Carlton, J.T. 1993. Dispersal mechanisms of the zebra mussel (*Dreissena polymorpha*). 677-697. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

Cohen, T. 1992. Pests with redeeming value. *Technology Review* 95(5):15-16. (July, 1992).

Eckroat, L.E., E.C. Masteller, J.C. Shaffer, and L.M. Steele. 1993. The byssus of the zebra mussel (*Dreissena polymorpha*): Morphology, byssal thread formation, and detachment. 239-263. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

Fisher, S.W. and P.C. Stromberg. 1992. The status of potassium for use in zebra mussel control. Report to Ohio Sea Grant for project R/ZM-11, grant NA90AAD-SG496. 1 p.

Garton, D.W. and W.R. Haag. 1991. Heterozygosity, shell length and metabolism in the European mussel, *Dreissena polymorpha*, from a recently established population in Lake Erie. *Comp. Biochem. Physiol.* 99A:45-48.

Greenberg, A., G. Matisoff, G. Gubanich, and J. Ciaccia. 1992. Zebra mussel densities and water quality parameters in Lake Erie at the Cleveland water intakes. (Abstract) *J. Shellfish Res.* 11:227.

Griffiths, R.W., D.W. Schloesser, J.H. Leach, and W.P. Kovolak. 1991. Distribution and dispersal of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes region. *Can. J. Fish. Aquat. Sci.* 48:1381-1388.

Haag, W.R. and D.W. Garton. 1992. Synchronous spawning in a recently established population of the zebra mussel, *Dreissena polymorpha*, in western Lake Eries, USA. *Hydrobiologia* 234:103-110.

Hebert, P.N.D., B.W. Muncaster, and G.L. Mackie. 1989. Ecological and genetic studies on *Dreissena polymorpha* (Pallas): a new mollusc in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 46:1587-1591.

Johnson, L.E., and J.T. Carlton. 1993. Counter-productive public information: the "Noah Fallacy" and mussel myths. *Dreissena polymorpha Information Review* 3(3):2-4.

Jonsson, P.R., C. André, and M. Lindegarth. 1991. Swimming behavior of marine bivalve larvae in a flume boundary-layer flow: evidence for near-bottom confinement. *Mar. Ecol. Prog. Ser.* 79:67-76.

Lange, C.L. and R.K. Cap. 1992. The range extension of the zebra mussel (*Dreissena polymorpha*) in the inland waters of New York State. *J. Shellfish Res.* 11:228-229.

Lasker, H.R., and K.M. Stewart. 1992. Gamete dilution and fertilization success among broadcast spawning octocorals. Abstracts of the 20th Ann. Marine Benthic Ecology Meeting, Newport, RI.

Leach, J.H. 1993. Impacts of the zebra mussel (*Dreissena polymorpha*) on water quality and fish spawning reefs in western Lake Erie. 381-397. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

McCauley, R.H., Jr. 1945. *The Reptiles of Maryland and the District of Columbia.* Publ. by the author. 227 pp. Available Virginia Institute of Marine Science library.

MacIsaac, H.J. and W.G. Sprules. 1992. Filtering impacts of larval and adult zebra mussels in western Lake Erie. (Abstract) *J. Shellfish Res.* 11:230.

Mackie, G.L. and B.W. Kilgour. 1992. Effects of salinity on growth and survival of zebra mussels (*Dreissena polymorpha*). (Abstract). *J. Shellfish Res.* 11:230.

McMahon, R.F. 1991. Mollusca: Bivalvia. 315-399. **In** Thorp, J.H. and A.P. Covich. (Eds.). *Ecology and Classification of North American Freshwater Invertebrates.* Academic Press, New York, NY.

McMahon, R.F. and J.E. Alexander, Jr. 1991. Respiratory responses to temperature, hypoxia and temperature acclimation of the zebra mussel, *Dreissena polymorpha* (Pall.). (Abstract). *Amer. Zool.* 31(5):74A.

McMahon, R.F. and B.S. Payne. 1992. Effects of temperature and relative humidity on desiccation resistance in zebra mussels (*Dreissena polymorpha*): Is aerial exposure a viable control option. *J. Shellfish Res.* 11:233.

Mann, R. 1988. Distribution of bivalve larvae at a frontal system in the James River, Virginia. *Marine Ecology Progress Series* 50:29-44.

Mann, R. and C.C. Wolf. 1983. Swimming behavior of larvae of the ocean quahog *Arctica islandica* in response to pressure and temperature. *Mar. Ecol. Prog. Ser.* 13:211-218.

Mann, R., B.M. Campos, and M.W. Luckenbach. 1991. Swimming rate and responses of larvae of three mactrid bivalves to salinity discontinuities. *Mar. Ecol. Prog. Ser.* 68:257-269.

Marsden, J.E. 1993. "Quagga mussel" update. *Dreissena polymorpha Information Review* 3(3):1.

Martel, A. 1992. Occurrence of post-metamorphic drifting in zebra mussels: Implications on dispersal and recruitment. *J. Shellfish Res.* 231-232.

Martoff, B.S., W.M. Palmer, J.R. Bailey, and J.R. Harriman, III. 1980. *Amphibians and Reptiles of the Carolinasa and Virginia.* University of North Carolina Press, Chapel Hill, NC. 264 pp.

May, B. and J.E. Marsden. 1992. Genetic identification and implications of another invasive species of dreissenid mussel in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 49:1501-1506.

Meehan Overseas Terminals, Inc. 1991. Port of Richmond Harbor Master Monthly Waterborne Tonnage Reports, January-December, 1991. Meehan Overseas Terminals, Inc., Richmond, VA.

Mikheev, V.P. 1968. Mortality rate of Dreissena in anaerobic conditions. 65-68. In Shtegman, B.K. (ed.). Biology and Control of Dreissena. Israel Program for Scientific Translations, Ltd., Jerusalem, Israel, and U.S. Dept. Commerce, National Technical Information Service, Springfield, VA.

Neary, B.P. and J.H. Leach. 1992. Mapping the potential spread of the zebra mussel (*Dreissena polymorpha*) in Ontario. *Can. J. Fish. Aquat. Sci.* 49:406-415.

Neumann, D., J. Borcherding, and B. Jantz. 1993. Growth and seasonal production of *Dreissena polymorpha* in the Rhine River and adjacent waters. 95-109. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

New York Sea Grant. 1992. North American Range of the Zebra Mussel as of 15 October, 1992. New York Sea Grant, Ithaca, NY. 1 page map.

Nichols, S.J. 1993. Maintenance of the zebra mussel (*Dreissena polymorpha*) under laboratory conditions. 733-747. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

Pennington, J.T. 1985. The ecology of fertilization of echinoid eggs: the consequences of sperm dilution, adult aggregations, and synchronous spawning. *Biological Bull.* 169:417-430.

Piesik, Z. 1983. Biology of *Dreissena polymorpha* (Pall.) settling on stylon nets and the role of this mollusc in eliminating the seston and the nutrients from the water-course. *Pol. Arch. Hydrobiol.* 30:353-361.

Ramcharan, C.W., D.K. Padilla, and S.I. Dodson. 1992. A multivariate model for predicting population fluctuations of *Dreissena polymorpha* in North American lakes. *Can. J. Fish. Aquat. Sci.* 49:158-158.

Schneider, D.W. 1992. A bioenergetics model of zebra mussel, *Dreissena polymorpha*, growth in the Great Lakes. *Can. J. Fish. Aquat. Sci.* 49:1406-1416.

Seliger, H.H., J.A. Boggs, R.B. Rivkin, W.H. Biggley, and K.R.H. Aspden. 1982. The transport of oyster larvae in an estuary. *Marine Biology* 71:57-72.

Shtegman, B.K. (ed.). 1968. Biology and Control of *Dreissena*. Israel Program for Scientific Translations, Ltd., Jerusalem, Israel, and U.S. Dept. Commerce, National Technical Information Service, Springfield, VA. 145 pp.

Sisson, P.K. 1993. Despite zebra mussels, Erie walleye hatches up. *Soundings: Trade Only* January 1993: p 44.

Sprung, M. 1987. Ecological requirements of developing *Dreissena polymorpha* eggs. *Arch. Hydrobiol./Suppl.* 79:69-86.

Stanczykowska, A. 1977. Ecology of *Dreissena polymorpha* (Pall.) (Bivalvia) in lakes. *Pol. Arch. Hydrobiol.* 24:461-530.

Strayer, D.L. 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha* in North America. *Can. J. Fish. Aquat. Sci.* 48:1389-1395.

Vinogradov, G.A., N.F. Smirnova, V.A. Sokolov, and A.A. Bruznitsky. 1993. Influence of chemical composition of the water on the mollusk *Dreissena polymorpha*. 283-293. **In** Nalepa, T.F. and D.W. Schloesser (eds.). *Zebra Mussels: Biology, Impact, and Control.* Lewis Publishers, Ann Arbor, MI.

Walker, T. 1991. *Dreissena* disaster. *Science News* 139:282-284.

Walton, W.C. 1993. The invasion of the Hudson River estuary by the zebra mussel *Dreissena polymorpha*, and its subsequent range overlap with the dark false mussel, *Mytilopsis leucophaeata*. Final Report to Polgar Fellowship Program. 31 pp. (Available from W. Walton, Inst. Marine & Coastal Sciences, Rutgers Univ., New Brunswick, NJ.)

Widdows, J., R.I.E. Newell, and R. Mann. 1989. Effects of hypoxia and anoxia on survival of oyster larvae (*Crassostrea virginica*, Gmelin). *Biol. Bull.* 177:154-166.

Wolff, W.J. 1969. The Mollusca of the estuarine region of the rivers Rhine, Meuse and Scheldt in relation to the hydrography of the area. II. The Dreissenidae. *Basteria* 33:93-103.

Wright, C. and G.L. Mackie. 1990. Removal of seston, nutrients and B.O.D. from activated sewage sludge and its biodeposition by the zebra mussel, *Dreissena polymorpha* (Bivalvia, Dreissenidae). (Abstract). Proc. Ann. Meeting Am. Soc. Limnol. Oceanogr., Williamsburg, VA, p. 92.

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Zebra Mussels in Virginia's Future

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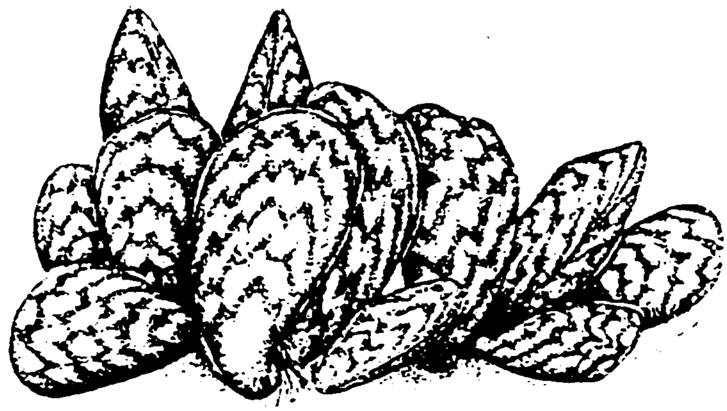
INTRODUCTION



Zebra Mussels, *Dreissena polymorpha*

The zebra mussel, *Dreissena polymorpha*, is an alien species introduced to the Great Lakes in the 1980s, via ballast water from Europe. It has since invaded all of the Great Lakes, and the Hudson, Ohio, and Mississippi Rivers. The zebra mussel is also in the upper Susquehanna River, and is expected to appear in other mid-Atlantic drainages. As a consequence of their ability to heavily foul submerged surfaces, zebra mussel populations have had severe ecological and economic impacts in areas in which they have become established.

This report summarizes the physiological requirements, dispersal mechanisms, and potential range in Virginia, of zebra mussels. Critical physiological parameters are temperature, salinity, pH, and calcium. Dispersal mechanisms discussed include both natural and human-mediated vectors. Water quality and vectors of introduction are used to predict whether zebra mussels are likely to become established in specific bodies of water in and near Virginia.

REQUIREMENTS

Optimum temperatures for growth and reproduction of zebra mussels are between 12 and 26°C, so temperatures in the mid-Atlantic region are unlikely to be limiting. While zebra mussels are found primarily in freshwater, they can persist in slightly brackish water (0.5 ‰), and tolerate salinities of up to 12 ‰ for a few days. Zebra mussels can survive short periods of acidity, but require relatively alkaline water (above pH 7.5) to reproduce. Calcium, required for shell growth, may be limiting in some bodies of water.

DISPERSAL

Zebra mussel adults and juveniles can crawl short distances, but the primary means of natural dispersal is by planktonic larvae and postlarvae. Zebra mussels are more likely to become initially established in lakes or estuaries, than in rivers where the dispersing forms would be swept away. Zebra mussels may reach high densities in rivers, however, if there are lakes or reservoirs upstream which have reproducing populations. Once zebra mussels are established in a lake, all lakes and estuaries downstream are subject to invasion by drifting larvae. Most mid-Atlantic estuaries have large freshwater portions, many with nearly ideal water chemistry, in which zebra mussels can become established.

Zebra mussels can be introduced to bodies of water by several human-mediated means. Larvae and postlarvae may be transported long distances in the ballast water of commercial ships, and it was by this means that they were introduced to the Great Lakes. The hulls of commercial vessels also represent a means of transport. Adults and juveniles attach to the hulls of vessels which may subsequently move upstream or across salinity barriers. At the new location, the zebra mussels can detach and reattach to a nearby substrate, or adults may reproduce and release larvae at the new location. Barges are an important example of this, because they remain in one place for long periods of time and are infrequently cleaned of fouling organisms, but any vessel could serve as a vector. Zebra mussels can survive several days out of water and can be introduced via the hulls of recreational craft trailered between watersheds. Alternately, larvae or postlarvae could inadvertently be transported in the bilge or bait wells of recreational vessels. The possibility also exists that zebra mussels may be deliberately introduced by landowners to increase water clarity of ponds or lakes.

POTENTIAL RANGE: ESTUARIES

Potomac River

The freshwater portion of the Potomac estuary stretches from Washington, to near Quantico, Virginia. Zebra mussels are most likely to be introduced to the Potomac River by vessels traveling from nearby estuaries or the Great Lakes, either attached to hulls or in ballast water. Water quality in the Potomac is suitable for zebra mussel reproduction. The risk of invasion is high and, once established, zebra mussels would rapidly attain pest proportions.

Rappahannock River

The tidal freshwater portion of the Rappahannock estuary extends from Fredricksburg to near Tappahannock. Invasion of the Rappahannock could occur from upstream reservoirs, or vessels from other estuaries could bring in zebra mussels attached to their hulls. Water quality is not conducive to reproductive success of zebra mussels. Invasion risk and establishment potential are moderate for the Rappahannock.

Piankatank River

The Piankatank and the adjoining freshwater tidal portion, Dragon Swamp, have no major upstream reservoirs, and limited vessel traffic. The water has low pH and calcium, and is unlikely to support zebra mussels. Risk of invasion and establishment is low compared to other estuaries.

Mattaponi and Pamunkey Rivers

The Mattaponi and Pamunkey Rivers unite at West Point to form the York River estuary; however, the freshwater portions remain separate. The Mattaponi River has several upstream reservoirs which are at risk of introduction via recreational vessels. Traffic from other estuaries is moderate. Water chemistry is unlikely to support large populations of zebra mussels. Risk of introduction is moderate but reproductive success would be low.

James River

The freshwater tidal portion of the James River extends from Richmond to Jamestown, Virginia, and includes portions of the Chickahominy and Appomattox Rivers. The James River drainage has many large reservoirs with heavy recreational use. Zebra mussels may be introduced to these lakes via trailered pleasure craft. The James River is industrialized and traffic from other estuaries is heavy. Large vessels carrying ballast water visit the Port of Richmond from freshwater European ports. Conditions favorable for zebra mussel reproduction are found throughout the estuary, and zebra mussels will attain pest populations if introduced. Risk of invasion and establishment are high for the James River.

Elizabeth River/Albemarle Sound

The South Branch Elizabeth River in Chesapeake, Virginia, is Albemarle Sound in North Carolina via the Chesapeake and Albemarle Canal and the Dismal Swamp Canal. Back Bay, in Virginia, is the northernmost portion of Albemarle Sound, and is usually fresh. These bodies of water are interconnected by an intricate network of canals and ditches. If zebra mussels become established in any part of the system they will spread to all other portions that have adequate water chemistry. They are most likely to be introduced to the system by the heavy vessel traffic from other estuaries. Water chemistry is sufficient for zebra mussels throughout much of the system although populations in Back Bay would be limited in some years by salinity, and the Dismal Swamp Canal is too acidic for zebra mussel survival. In general, however, invasion risk and establishment potential are high for these bodies of water.

POTENTIAL RANGE: LAKES

Claytor Lake

Claytor Lake is a multi-purpose reservoir on the New River (Kanawha River), a tributary of the Ohio. Recreational use is heavy and zebra mussels are likely to be introduced via recreational vessels. Risk of invasion is high but water chemistry varies, making establishment potential moderate.

Flannagan Reservoir

John W. Flannagan Reservoir is on the Pound River, a tributary of the Ohio via the Big Sandy River. Opportunities for introduction by the hulls of small recreational vessels are high. The water is alkaline but calcium varies; zebra mussels will survive but reproduction may be calcium-limited in some years.

Kerr Reservoir and Lake Gaston

John H. Kerr Reservoir and Lake Gaston, just downstream, are large multi-use impoundments on the Roanoke River, which ends in the Albemarle Sound. The lakes are heavily used by recreational boaters and fishermen and are downstream of a variety of public-access reservoirs. Kerr Reservoir and Lake Gaston are, therefore, at higher risk of invasion by zebra mussels via recreational vessels than any other lakes in Virginia. Water chemistry is optimal for reproduction in portions of both lakes and, once introduced, zebra mussels will rapidly become established.

Lake Anna

Lake Anna, on the North Anna River, is the largest reservoir in the Pamunkey River drainage. Recreational boaters use Lake Anna as well as two other lakes upstream, thus, opportunities for introduction are high. Water chemistry is not favorable for zebra mussels, however; the chance that they will become established is low.

Lake Chesdin

Lake Chesdin, on the Appomattox River, receives heavy recreational use but water chemistry is unsuited for zebra mussels. Therefore, risk of invasion is high but establishment potential is low.

Philpott Reservoir

Philpott Reservoir is on the Smith River, a tributary of the Roanoke River via Dan River. Opportunities for introduction via recreational vessels is high. The water is generally alkaline but calcium levels are low making zebra mussel reproduction unlikely and establishment success low. If zebra mussels did become established in Philpott Reservoir, they would spread downstream to Kerr Reservoir and Lake Gaston.

Smith Mtn. Lake and Leesville Lake

Smith Mountain Lake is a large reservoir on the headwaters of the Roanoke River, and Leesville Lake is directly below it. Smith Mountain Lake is heavily used by boaters and fishermen and opportunities for introduction are numerous. Water chemistry conditions will support zebra mussels but in some years population levels may be limited by calcium.

Western Branch Reservoir

Western Branch Reservoir is one of many similar lakes in the Nansemond River drainage. Recreational use, and therefore risk of introduction, is moderate. Water chemistry is favorable for zebra mussels so once introduced, they would reach high population levels.

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Potential Range of the Zebra Mussel, *Dreissena polymorpha*, In and Near Virginia

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INTRODUCTION

The following document is from the proceedings of a 1993 zebra mussel workshop, conducted in Baltimore, Maryland. At the workshop, forecasts were presented concerning the future of zebra mussels, Dreissena polymorpha, *in the mid-Atlantic states.*

This publication is devoted to predictions of the probability of invasion by the zebra mussel, *Dreissena polymorpha* (and the quagga mussel, *Dreissena* sp.) to specific bodies of water in Virginia. Probability of invasion is divided into *risk* and *susceptibility*. *Risk* refers to the chance, relative to other sites, that a body of water will be inoculated with *Dreissena*, in sufficient number to establish a population. Inoculation can occur by natural dispersal, but in the mid-Atlantic region is most likely to occur through accidental introduction by humans, especially via boat traffic. *Susceptibility* of a body of water refers to the probability, based on known physiological requirements, that *Dreissena* could survive and reproduce. In this publication predictions are made, concerning both risk and suceptibility, for several bodies of water in Virginia.

Original *Dreissena* populations are native to freshwater or brackish portions of estuaries, with bidirectional water flow, in eastern Europe and central Asia (Staczykowska, 1977), and most subsequent invasions have occurred in lakes and freshwater portions of estuaries (Shtegman, 1968; Wolff, 1969; Staczykowska, 1977; Griffiths *et al.*, 1991). Freshwater portions of estuaries, and natural and artificial reservoirs in the mid-Atlantic region of the United States (here defined as drainages east of the Appalachian Mountains between New York and South Carolina) are therefore at risk from invasion by *Dreissena*, given correct water quality parameters. *Dreissena* populations cannot be maintained at high levels in freshwater rivers without an upstream reservoir or lake, because it has planktonic larvae and postlarvae stages. This topic is discussed at greater length in *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region,* a Virginia Sea Grant Publication, which can be obtained from the Virginia Institute of Marine Science.

A zebra mussel is a small, striped mollusk capable of raising havoc. (Although the mollusk can grow up to two inches, it is usually much smaller — fingernail size.) Zebra mussels have cost millions of dollars in the Great Lakes region where they rapidly colonized water-intake pipes, boats, docks, piers, and other structures. *Dreissena polymorpha* was inadvertently delivered to U.S. waters around 1986 through the discharge of European shipping ballast water. —ed.

TEMPERATURE-LIMITED SYSTEMS

None of the systems in the mid-Atlantic region fall below the minimum temperature requirements for *Dreissena* reproduction (refer to *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region*), but most estuaries and lowland reservoirs in South Carolina and Georgia have summer temperatures that may exceed *Dreissena* tolerances, based on reported European limits (Strayer, 1991), and reported physiological limits of zygotes and adults (Sprung, 1987; McMahon and Alexander, 1991). Reported European temperature limits for *Dreissena* may be based on geography as much as temperature, however, since the Mediterranean Sea acts as a southern barrier. The movement of *Dreissena* down the Mississippi River, tracked recently as far as Vicksberg, Mississippi (New York Sea Grant, 1993), should be closely monitored as a natural test of temperature tolerance of this species in North America.

ESTUARIES

Virtually all estuaries with permanent freshwater inputs in the mid-Atlantic region have tidal freshwater portions, and are potentially suceptible to invasion by *Dreissena*. Examples of major estuaries (more than 1000 ha. of open, permanently fresh water) between New York and North Carolina include the Hudson River; the Delaware River; the Susquehanna, Potomac, Rappahannock, Mattaponi, Pamunkey, and James Rivers in the Chesapeake Bay; Currituck and Albemarle Sounds, and Pamlico, Pungo and Neuse Rivers in North Carolina (Coupe and Webb, 1984; U.S. Army Corps of Engineers, 1984; NOAA, 1985).

Estuaries can be invaded by *Dreissena* in several ways, all discussed at length in *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region.* Briefly, they can be invaded overland, usually with recreational vessels, either directly to the freshwater estuarine portion, or to a lake, from where, if they become established, they will subsequently invade all downstream waters. Alternately, estuaries can be invaded from the seaward direction, with vessels traveling from other estuaries. Ballast water containing *Dreissena* larvae is a well-known vector, but under some circumstances, *Dreissena* may also be introduced as adults on the hulls of vessels, if the time spent in high-salinity water is not long. This is often possible, as discussed below.

Natural terrestrial and high-salinity barriers between major estuaries and smaller estuaries have been partially eliminated by canals of the Intracoastal Waterway, and may facilitate *Dreissena* transfer between basins. For example, the Chesapeake-Delaware canal, between oligohaline portions of those respective estuaries, is at times of high freshwater runoff, fresh or nearly fresh at both ends (U.S. Army Corps of Engineers, 1985; NOAA, 1985; Mellor, 1986), and thus represents a route for natural invasion by *Dreissena* of the Delaware estuary from the Susquehanna drainage, where it is found at present (Lange and Cap, 1992; New York Sea Grant, 1993). Two canals, the Dismal Swamp Canal and the Chesapeake and Albemarle Canal, connect the Elizabeth River estuary in southern Chesapeake Bay, Virginia, to freshwater portions of the Albemarle and Currituck Sounds in North Carolina so that freshwater portions of the two formerly separate estuaries are now a single body of water. The Alligator River and Pungo River Canal connect tidal fresh waters of Albemarle and Pamlico Sounds, respectively, in North Carolina. Similar examples can be found elsewhere along the Intracoastal Waterway. Even if there are high salinity regions that act as barriers to natural range expansion by *Dreissena*, barge and other boat traffic carrying *Dreissena* along these canals could pass relatively quickly through high salinity areas and *Dreissena* can tolerate at least several days of relatively high salinity.

Dreissena has already invaded the Hudson River estuary (Walton, 1993), and appears poised to invade the Susquehanna River estuary (Lange and Cap, 1992; New York Sea Grant, 1993). These estuaries will serve as models of the sorts of biological and economic impacts to expect in other mid-Atlantic estuaries. In addition, they will serve as reservoirs of *Dreissena* to invade adjacent estuaries, particularly on the hulls of vessels travelling between estuaries, as discussed in *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region.*

Some, but not all, of Virginia's freshwater estuarine regions are at risk of, or susceptible to, invasion and establishment by *Dreissena*. The risk of inoculation varies between estuaries, according to the level of boat traffic and other human factors. Susceptibility of establishment, on the other hand, varies according to water chemistry, independently of human use. In the following discussion for each estuary, values for pH and calcium are the maximum reported monthly averages for summer (May to September), based on existing water chemistry data.

Pocomoke River

The Pocomoke River is at low risk of inoculation, and is not susceptible to establishment of *Dreissena*. Like other estuaries on the Delmarva Peninsula, it has relatively low freshwater inflow, and no major upstream reservoirs for *Dreissena* to invade. There is little commercial vessel traffic into the estuary, although the channel is maintained to Snow Hill, Maryland, and there is a marina near Snow Hill. Opportunities for inoculation, therefore, are relatively limited, relative to other Chesapeake Bay estuaries.

Water chemistry data for February 1991 near the upstream tidal limit at Snow Hill showed low pH (6.1) and calcium content (4.3 ppm) (James *et al.*, 1991). If *Dreissena* were to invade this estuary, they probably would not attain high population levels.

Potomac River

The Potomac River is at high risk of inoculation, and highly susceptible to establishment of *Dreissena*. The tidal freshwater portion of the Potomac estuary stretches from Washington, D.C., to Quantico, Virginia in most years. There are few lakes adjoining the Potomac River estuary; therefore, the invasion of the Potomac River drainage by *Dreissena* carried by recreational vessels transported from an adjoining drainage is less likely to occur than in some other systems. The Virginia portion of the Potomac/Shenandoah drainage, for example, has only about 40 public boat ramps (most of which are on rivers) compared to more than twice that number for some other Virginia drainages of similar size (DeLorme Mapping Co., 1989). Resource managers have fewer major lakes to monitor in a program to prevent the introduction of *Dreissena*. Invasion could occur via intentional, misguided introduction to a farm pond or other small impoundment, however. This possibility can be prevented only through education of landowners and users.

Inoculation of the Potomac by *Dreissena* could also occur from the seaward direction, via ballast water of the hulls of incoming vessels. Ballast water containing *Dreissena* larvae or postlarvae is a distinct risk to the Potomac estuary. Bulk cargo ships from Quebec City, Quebec, arrive in Alexandria, Virginia, 6-7 times annually (Robinson Terminal Warehouse Corp, Alexandria, VA, pers. comm.). Alexandria is the largest port in the freshwater portion of the Potomac; Quebec City is on a portion of the St. Lawrence River that has established populations of *Dreissena* (New York Sea Grant, 1993). The amount of ballast water exchanged, and the nature of the exchange, are unknown. Commercial and recreational traffic into the Potomac estuary from adjoining estuaries is very high, and the Potomac is the closest Virginia estuary to the Susquehanna River, where *Dreissena* is already present.

Water chemistry data indicate that both pH (8.1-8.4, May to September at Washington, D.C.) and calcium content (32-40 ppm) (Prugh *et al.*, 1992) are suitable for *Dreissena* reproduction. If *Dreissena* becomes established in the Potomac estuary, all indications are that it would rapidly attain pest proportions. This region has already experienced invasion by the asiatic clam, *Corbicula fluminea*, which has attained high abundance (Phelps, 1991).

Rappahannock River

Risk of innoculation to, and susceptibility of, the Rappahannock River to *Dreissena* invasion, are moderate. The tidal freshwater portion of the Rappahannock estuary extends upstream from Fredricksburg, Virginia, to somewhere between Port Royal and Tappahannock, depending on freshwater inflow levels. Invasion of the Rappahannock could occur from upstream, where there are several reservoirs of moderate size, if they were invaded. There are 11 public boat ramps in the freshwater portion of the Rappahannock drainage (DeLorme Mapping Co., 1989), and there are also several large, privately maintained reservoirs, such as Lake of the Woods, which is surrounded by a housing development. Inoculation could also occur from the seaward direction, via fouling on the hulls of vessels moved from nearby estuaries already invaded by *Dreissena*, but both commercial and recreational movement from other estuaries to the Rappahannock is low to moderate.

The lower Rappahannock River has relatively low pH (7.8 in August, at Fredricksburg) and very low calcium (5.2 ppm) (Prugh *et al.*, 1992). Based on these data, even if *Dreissena* becomes established here, it is not predicted to have high reproductive success most years, and is unlikely to maintain pest proportions.

Piankatank River

The tidal freshwater portion of the Piankatank River is at relatively low risk of inocculation, and is not suceptible to establishment of *Dreissena*. The Piankatank, and its adjoining freshwater tidal portion, Dragon Swamp, is the largest of a number of small estuaries on the west side of Chesapeake Bay for which the drainage basins arise entirely within the coastal plain region. There are no large upstream reservoirs, and no commercial traffic into freshwater tidal portions, so the only likely mechanisms of *Driessena* inoculation would be via private introductions to upstream farm ponds, or via the hulls of small pleasure vessels from other estuaries. The Piankatank has low pH (6.5 in July at Mascot) and low calcium (13 ppm) (Prugh *et al.*, 1992), so *Dreissena* would be unlikely to survive or reproduce.

Data for other small Virginia estuaries are limited, and while some (e.g. the Pocomoke, discussed above) are known to be acidic, pH and calcium of small- to medium-sized impoundments upstream on these varies dramatically within the same drainage (Virginia Department of Game and Inland Fisheries, unpubl. data). No small estuary, therefore, should be considered safe from *Dreissena* invasion until water quality has been measured and determined to be unsuitable for *Dreissena* growth and reproduction.

Mattaponi and Pamunkey Rivers

The Mattaponi and Pamunkey Rivers, which unite at West Point, Virginia, to form the York River estuary, are both at moderate risk of inoculation by *Dreissena*, and are moderately susceptible to establishment of this species. The York River is rarely fresh or oligohaline, even at West Point (NOAA, 1985), so freshwater portions of the Mattaponi and Pamunkey are normally distinct from each other. Small tributaries of the two subestuaries are very close to each other, though, and could be host to brief overland transmigration by animals such as turtles (see *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region*).

Inoculation of either estuary by *Dreissena* could occur from upstream reservoirs which had been previously invaded overland. The Mattaponi River has several upstream reservoirs of moderate size and recreational use, such as Ni River Reservoir, and Caroline Reservoir, and in the Pamunkey drainage there is the relatively large Lake Anna (discussed separately in this chapter in the section on lakes). There are about 12 and 15 public boat ramps in the Mattaponi and Pamunkey drainages, respectively (DeLorme Mapping Co., 1989). Inoculation of the estuaries could also occur via *Dreissena* attached to hulls of vessels incoming from other, already invaded estuaries, but probability of invasion by this method is low, due to the relatively limited traffic, compared to other major estuaries. Barges with wood chips travel between the upper York River and other estuaries, but the major moorage site, in the lower Pamunkey, is rarely fresh, and the salinity regime probably is suboptimal for reproduction of *Dreissena*.

Both rivers are slightly acidic and have low calcium, and are thus only marginal for *Dreissena* growth and reproduction. Near Beulahville, pH of the Mattaponi in July is about 6.9, while calcium content is only about 3.7 ppm. Near Hanover, pH of the Pamunkey in June is about 6.9, with a calcium content of about 9 ppm (Prugh *et al.*, 1992). Even if *Dreissena* becomes established, it is unlikely that they would attain pest proportions in either estuary.

James River

The James River is at high risk of inoculation by *Dreissena*, and is highly susceptible to subsequent establishment of large populations. The freshwater tidal portion of the James River extends downstream from Richmond to Jamestown, and includes large portions of the Chickahominy and Appomattox Rivers, with over 8000 ha of open freshwater. The James River drainage has many large reservoirs with heavy recreational use (high risk of inoculation), and some of these reservoirs could support *Dreissena* populations. Examples include Briery Creek Reservoir, Lake Chesdin, Swift Creek Reservoir, Lake Moomaw, and Little Creek Reservoir. (Lake Chesdin, the largest of these, is discussed separately under the section on lakes.) The danger of introduction via vessel hulls or trailers increases with the amount of recreational use, and the James River drainage has over 90 public boat ramps, mostly on lakes (DeLorme Mapping Co., 1989). In addition, there are annual professional bass fishing tournaments on the tidal freshwater portions of the James and Chickahominy Rivers, with many vessels trailered in from other states, where they may have been in *Dreissena*-infested waters only a day or two previously.

The risk of inoculation from the seaward direction is also high, via both ballast water and the hulls of incoming vessels. Large vessels containing varying amounts of ballast water regularly visit the Port of Richmond from freshwater European ports (Meehan Overseas Terminal, Inc., 1991), some of which have large *Dreissena* populations. Whether freshwater ballast containing *Dreissena* larvae is acquired in Europe and released, undiluted by seawater, in Richmond, is unknown, but it appears probable. Barge and other vessel traffic between industrialized areas of the James River and other estuaries in Chesapeake Bay is heavy. There is also heavy recreational traffic from other estuaries.

Conditions for *Dreissena* reproduction are favorable throughout much of the estuary, and two other non-native bivalves, *Corbicula fluminea* and *Rangia cuneata*, have already successfully invaded freshwater and oligohaline portions of this estuary (Diaz, 1977, 1989). The native bivalves *Mytilopsis leucophaeata* (a close relative to *Dreissena*), *Sphaerium transversum*, and *Pisidium casertanum* are also common in oligohaline and freshwater portions of the James River (Diaz, 1977). Near Cartersville, pH in August is 8.1, and calcium content is about 22 ppm (Prugh *et al.*, 1992), both within the minimum requirements for *Dreissena* reproduction.

Elizabeth River and Albemarle Sound

Tidal freshwaters of southeast Virginia, including the Elizabeth River and parts of the Albemarle Sound system, are at risk of inoculation by *Dreissena*, and some regions within this area are susceptible to establishment of the species. The Elizabeth, Nansemond, and Lynnhaven Rivers in southeast Virginia, Currituck Sound and the Pasquotank River in North Carolina (Albemarle Sound), and many lesser bodies of water, form an extremely complex estuarine and freshwater system, because of the Intracoastal Waterway and many lesser canals. The northernmost portion of Currituck Sound is Back Bay, in Virginia; other connected bodies of water include Lake Drummond (Dismal Swamp), Lafayette River (Norfolk), Rudee Inlet (Virginia Beach), and various small lakes in the cities of Virginia Beach, Chesapeake, Norfolk, and Suffolk. The freshwater portions of the Elizabeth, Nansemond, and Lynnhaven Rivers are relatively small, but the Chesapeake and Albemarle Canal, the Dismal Swamp Canal, and lesser waterways are usually fresh, and all of Currituck Sound and most of Albemarle Sound are oligohaline or fresh water, depending on freshwater inflow (NOAA, 1985). All of these bodies of water are intimately connected by a network of canals or ditches (refer to United States Geological Survey topographical maps), so if *Dreissena* becomes established in any part of this system it could eventually spread to all others.

Inoculation of the above region by *Dreissena* is most likely to occur via the heavy recreational and commercial traffic incoming from other estuaries. There are few freshwater lakes in Virginia Beach with boat ramps, so the risk of inoculation by *Dreissena* on the hulls of recreational vessels trailered from other systems is low. Conversely, there are thousands of small recreational vessels which use creeks, canals, and oligohaline portions of the many small subestuaries in this area, and there is heavy barge traffic along the Chesapeake and Albemarle Canal, part of the Intracoastal Waterway. *Dreissena* need become established only in one of the other Chesapeake estuaries and, sooner or later it will appear in Virginia Beach or the City of Chesapeake waterways, as fouling organisms on small vessel hulls.

The Chesapeake and Albemarle Canal is potentially important in aiding dispersal of *Dreissena*. Even if the canal does not serve as a reservoir for *Dreissena* recruits, it will serve as a temporary relief of osmotic stress to *Dreissena* that are fouling vessels traveling along the Intracoastal Waterway. This could prolong the survival of *Dreissena* on vessels otherwise traveling in relatively high-salinity areas.

Some regions within southeast Virginia are susceptible to establishment of *Dreissena*; others are not. Back Bay, the northernmost extension of Currituck Sound, is normally fresh, but in some years, salinity can increase to as high as 10 for extended periods, although small tributary estuaries remain fresh (Norman and Southwick, 1991). The only bivalve which presently persists in Back Bay is the non-native oligohaline clam, *Rangia cuneata* (Lane and Dauer, 1991). Alkalinity and calcium levels for Back Bay are marginal for *Dreissena* reproduction (mean pH 7.7, calcium content of 10-20 ppm) (Sincock *et al.*, 1966), but the presence of *Rangia* infers that other species of bivalves, such as *Dreissena*, could survive there. Once established, *Dreissena* would survive high-salinity periods by persisting in freshwater tributaries.

The Dismal Swamp and the Dismal Swamp Canal, in contrast to Back Bay, have very low pH (maximum 6.7 in July) and calcium (7.2 ppm) (Lichtler and Marshall, 1979), probably much too low for the reproduction or even extended survival of *Dreissena*. The Dismal Swamp Canal therefore is unlikely to be invaded by, or serve as, a route for natural dispersal of *Dreissena*, but it remains a ready passage for dispersal by fouling on the hulls of vessels passing between the Elizabeth River, in the Chesapeake Bay system, and the Pasquotank River, in the Albemarle/Pamlico Sound system.

Urban development in southeast Virginia has lead to the creation of many small lakes, most of which are connected by ditches or pipes to other waterways. Water quality and chemistry are unknown for most of these, but it is probable that at least some will have ideal conditions for *Dreissena*. For example, Smith and Whitehurst Lakes, in the Little Creek drainage adjacent to the Norfolk International Airport, are both modally alkaline with sufficient calcium for *Dreissena* reproduction (Virginia Department of Game and Inland Fisheries, unpubl. data). If *Dreissena* is introduced, therefore, the probability that it could become established in some part of the system is high.

Table 1 summarizes the information for estuaries discussed above. The relative chance of inoculation, or "Risk," is given as "high," "moderate," or "low," based on factors discussed above. Using available water chemistry data and published data on *Dreissena* physiological requirements, the relative threat of establishment of large populations of *Dreissena* following inoculation, or "susceptibility" is also given as "high," "moderate," or "low," "High" predicts that if *Dreissena* becomes established, it will rapidly attain high population levels, and stay at those levels at least until the ecological community adjusts to the invasion. "Moderate" predicts that if *Dreissena* becomes established, it will reproduce successfully only during certain, favorable periods, and will attain pest proportions only occasionally. "Low" indicates that *Dreissena* is unlikely be able to reproduce successfully.

Lakes and Reservoirs

All major rivers and many small rivers in the mid-Atlantic region have large artificial impoundments. It is unlikely that *Dreissena* could become established in a river system by a single inoculation into the river itself, but once they become established in a reservoir, they would then spread to downstream reservoirs and freshwater portions of estuaries. Only unfavorable water quality, such as low pH and low calcium concentrations, would then limit *Dreissena* population levels.

Water chemistry data were available for some Virginia lakes, discussed in alphabetical order hereafter, except where two or more adjacent reservoirs are discussed together. Water chemistry data, especially calcium levels, are incomplete for most lakes, and while risks have been assessed based on known data, it is possible that the known data are not representative of common conditions. The role of water chemistry in *Dreissena* survival and reproduction are discussed in *Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region.*

TABLE 1. PREDICTED INVASION SUCCESS IN FRESHWATER ESTUARIES

Estuaries are listed approximately from north to south. *Risk* refers to the relative chance that *Dreissena* will be introduced, and *susceptibility* refers to the relative chance that *Dreissena* will attain high population levels.

Estuary	Risk	Susceptibility
Pocomoke River, MD & VA	low	low
Potomac River, MD & VA	high	high
Rappahannock River, VA	moderate	moderate
Piankatank River, VA	low	low
Mattaponi River/ Pamunkey River, VA	moderate	low
James River, VA	high	high
Elizabeth River, VA/ Albemarle Sound, VA & NC	high	high

Claytor Lake

The risk of inoculation by *Dreissena* to Claytor Lake, is high, relative to other lakes, but its susceptibility to the establishment of large populations is only moderate. Claytor Lake is a multi-purpose reservoir (recreation, hydropower) on the New River (Kanawha River), a tributary of the Ohio River. It receives heavy recreational use, with eight improved public boat ramps, as well as eight more on the New River upstream (DeLorme Mapping Co., 1989). There are thus many opportunities for accidental inoculation of *Dreissena* via the hulls of small recreational vessels. Fields Dam impounds the New River upstream of Claytor Lake, but the reservoir is probably too small (flushing rate too high) to act as a reproductive refuge for *Dreissena*. Although *Dreissena* is already present in other portions of the Ohio River basin (New York Sea Grant, 1993), the probability of its dispersing naturally upstream to Claytor Lake is low, relative to the risk posed by human-mediated invasion. Surface waters are normally quite alkaline (7.3-9.3 in June), but calcium is generally low (9-10 ppm). In some years, however, calcium levels can attain 30 ppm (Virginia State Water Control Board, unpubl. data), so the question of *Dreissena* success in Lake Claytor, should it be inoculated, would depend on the varying water chemistry.

Flannagan Reservoir

John W. Flannagan Reservoir is at high risk of inoculation by *Dreissena*, but its susceptibility to establishment of large populations is only moderate. Flannagan Reservoir is on the Pound River, a tributary of the Ohio River via the Big Sandy River. The reservoir has three improved public access boat ramps; there are two more just upstream on tributaries, and three more are on North Fork Pound River Lake, also upstream (DeLorme Mapping Co., 1989). There are thus many opportunities for inoculation via the hulls of small recreational vessels. Although *Dreissena* is present in other portions of the Ohio River basin (New York Sea Grant, 1993), the probability of its dispersing naturally upstream to Flannagan Reservoir is low, relative to the risk posed by human-mediated invasion. The surface waters are alkaline (pH 7.6-8.9 in June), with low to moderate levels of calcium (9-29 ppm) (Virginia State Water Control Board, unpubl. data). *Dreissena* would survive, if released into Flannagan Reservoir, but in some years reproduction may be calcium-limited.

Harwood Mills Reservoir

Harwood Mills Reservoir is one of many small multi-use (fishing, municipal water storage) reservoirs in urbanized southeast Virginia. The risk of inoculation by *Dreissena* is low, but the lake is highly susceptible to establishment of this species, should it become introduced. Harwood Mills, on the headwaters of the Poquoson River, in Newport News, has a single public boat ramp, limited to craft without internal-combustion engines. This reduces but does not eliminate the possibility of *Dreissena* inoculation via the hulls of recreational vessels. Like the majority of small municipal reservoirs in southeast Virginia, it is modally alkaline (pH 8.1 in June), with moderate levels of calcium (25 ppm) (Virginia Dept. Game and Inland Fisheries, unpubl. data). These conditions are favorable for *Dreissena* reproduction.

Of ten similar small reservoirs in that area surveyed by Virginia Department of Game and Inland Fisheries, six have water chemistry that would support high populations of *Dreissena*, three have chemistry that would support at least moderate populations, and only one (Kilby Reservoir) has water chemistry that would be unlikely to support *Dreissena* populations.

Kerr Reservoir and Lake Gaston

John H. Kerr Reservoir, and Lake Gaston, just downstseam, are at high risk of inoculation by *Dreissena*, and at least portions of both lakes are highly susceptible to establishment of large populations of this species. Both reservoirs are large multi-use (recreation, hydropower) impoundments on the Roanoke River, astride the Virginia/North Carolina Reservoir. Just below Lake Gaston in North Carolina is the Roanoke Rapids dam and reservoir, and the Roanoke ends in Albemarle Sound, North Carolina, which has an extensive freshwater portion. Kerr Reservoir and Lake Gaston are heavily used by recreational boaters and fishermen, with a total of about 50 public boat ramps. In addition, both are downstream of a variety of public-access reservoirs, including Philpott Reservoir, Banister Lake, Smith Mountain Lake, and Leesville Lake in Virginia, and Hyco Lake, Mayo Reservoir, and After Bay Reservoir in North Carolina, with over 80 public access boat ramps (Alexandria Drafting Co., 1981; DeLorme Mapping Co., 1989). Water chemistry in both Kerr Reservoir and Lake Gaston varies between stations, and on the basis of this McMahon (1992) considered the susceptibility of Lake Gaston to be relatively low. Both lakes, however, have semi-enclosed branches in which water chemistry may differ, and in both lakes there are modally alkaline regions (pH 6.9-9.3). Calcium levels for Kerr Reservoir were unavailable, but calcium content of the alkaline stations in Lake Gaston are about 24-44 ppm (Virginia State Water Control Board unpubl. data), and because of the proximity of the two lakes, it is safest to assume that Kerr Reservoir, more complex even than Lake Gaston, also has regions of modally high calcium.

Lake Anna

Lake Anna is at high risk of inoculation by *Dreissena*, but its susceptibility to subsequent establishment of this species is low. It is on the North Anna River, a tributary of the Pamunkey, and is the largest reservoir in the Pamunkey River drainage. Lake Anna is used heavily by recreational boaters and fishermen, and is the water source for the North Anna Nuclear Power Plant. Downstream is the freshwater tidal portion of the Pamunkey River. There are 9 improved public access boat ramps on Lake Anna. Upstream of Lake Anna are Lake Orange, with one public boat ramp, and Lake Louisa, which is surrounded by a housing development (DeLorme Mapping Co., 1989). McMahon (1992) considers Lake Anna to be highly susceptible to the establishment of large *Dreissena* populations, but based on unpublished water chemistry data provided by Virginia Power (Innsbrook Technical Center, Glen Allen, VA), this seems unlikely. Although pH often rises as high as 7.9 in some branches of Lake Anna during the summer, most of the lake is modally acidic, and even where waters are alkaline, the calcium content remains too low (maximum about 6.0 ppm) for *Dreissena* reproduction.

Lake Chesdin

Lake Chesdin is at relatively high risk of inoculation by *Dreissena*, but its susceptibility to establishment of this species is low. On the Appomattox River (a tributary of the James), it has several public-access boat ramps, and receives heavy recreational use from the nearby Richmond area. It has a water chemistry unsuited for *Dreissena*, however; the pH is variable (6.4-8.7), but modally acid in summer in shallow water, and calcium levels are very low (about 5-10 ppm) (Virginia State Water Control Board, unpubl. data).

Lake Gaston (See Kerr Reservoir)

Lake Moomaw

Lake Moomaw is a rarity in Virginia; a large reservoir at relatively low risk of inoculation by *Dreissena*. If *Dreissena* were introduced, however, Lake Moomaw is moderately susceptible to establishment of a large population. It is on the Jackson River, in the headwaters of the James River, within a state wildlife management area, where recreational use is limited. DeLorme Mapping Co. (1989) shows no public-access boat ramps on or upstream of Lake Moomaw. The pH is modally alkaline (7.6-8.4) in shallow water in summer, with calcium levels of about 13-17 ppm (Virginia State Water Control Board, unpubl. data); marginal conditions for *Dreissena* reproduction.

Leesville Reservoir (See Smith Mountain Lake)

Philpott Reservoir

Philpott Reservoir is at relatively high risk of *Dreissena* inoculation, but its susceptibility to establishment of this species is low. It is on the Smith River, a tributary of the Roanoke River via the Dan River, and has 11 improved, public access boat ramps. The water is modally alkaline (pH 7.2-8.7), but available calcium data indicates very low levels (4-5 ppm) (Virginia State Water Control Board, unpubl. data), which would inhibit *Dreissena* reproduction. If it does become established, however, it will spread to Kerr Reservoir and Lake Gaston, downstream, which have more benign water chemistry.

Smith Mountain Lake and Leesville Lake

Smith Mountain Lake is a large reservoir on the headwaters of the Roanoke River, and Leesville Lake is directly below it. Both are at high risk from inoculation by *Dreissena*, although the susceptibility of both lakes to establishment of large populations is only moderate. There are only two improved public access boat ramps into Leesville Lake, but there are more than 17 into Smith Mountain Lake, upstream. Smith Mountain Lake is also the site of a large, annual professional bass fishing tournament. The pH of both lakes in shallow water during the summer is normally high (7.6-9.1), and calcium levels are about 15-17 ppm (Virginia State Water Control Board, unpubl. data). These conditions permit reproduction of *Dreissena*, although in some years calcium content may limit population levels. Downstream of these lakes are John H. Kerr Reservoir and Lake Gaston.

South Holston Lake

South Holston Lake is at relatively high risk of inoculation by *Dreissena*, and its susceptibility to subsequent establishment of large populations of this species is also high. South Holston Lake is a large multipurpose reservoir (recreation, hydropower) on the South Fork Holston River, a tributary of the Tennessee River. It is in southwest Virginia, and the majority of the lake is within Tennessee. The lake is within a few hours' drive of other lakes in the Tennessee River system containing *Dreissena* (New York Sea Grant, 1993). There are 16 public access boat ramps on the lake, and two more upstream on the smaller Hungry Mother Lake. The pH of South Holston Lake is relatively stable and modally alkaline (6.9-8.6 in June and July), with moderately high levels of calcium (18-30 ppm), based upon data collected largely in the 1970s (Tennessee Valley Authority unpubl. data). These conditions are favorable for *Dreissena* growth and reproduction, and once introduced, it would rapidly attain pest proportions.

Western Branch Reservoir, Lake Meade

Western Branch Reservoir, Lake Meade, and some adjacent reservoirs are at moderate risk of inoculation by *Dreissena*, and highly susceptible to establishment of large populations of this species. Western Branch Reservoir is the largest of seven impoundments in the Nansemond River drainage, in southeast Virginia. It is on the Western Branch Nansemond River, while Lake Meade is the largest of four impoundments on the Eastern Branch Nansemond River, but the drainages of these are very close to each other. Other lakes include Lake Prince and Lake Burnt Mills, upstream of Western Branch Reservoir, and Lake Cohoon, Lake Kilby, and Spaetes Run Lake, upstream of Lake Meade. Western Branch Reservoir has two public boat ramps on or upstream of it, and Lake Meade has four. All lakes are used heavily for recreational fishing, but the majority of the users are local (Virginia Dept. Game & Inland Fisheries, pers. comm.). Water chemistry data shows moderately alkaline water (pH 8.2 at 2 m depth, June) with moderate levels of calcium (20-25 ppm) in all of these lakes except Lake Cohoon and Lake Kilby (no data is available for Spaetes Run Lake). Lakes Cohoon and Kilby are often acidic, and their levels of susceptibility are thus moderate or low. (Virginia Dept. Game and Inland Fisheries, unpubl. data). In the remaining four lakes, conditions are favorable for *Dreissena* reproduction. Once invasion occurred in any of those four lakes, *Dreissena* would reach high population levels. Natural dispersal, perhaps by adults attached to turtles or other amphibious organisms, could then spread *Dreissena* to the other impoundments in the Nansemond drainage.

Table 2 summarizes the information for reservoirs discussed above. The definitions for "risk" and "susceptibility" are the same as for Table 1.

Alexandria Drafting Co. 1981. *Freshwater Fishing and Hunting in Virginia.* Alexandria, VA. 84 pp.

Coupe, R.H., Jr. and W.E. Webb. 1984. Water quality of the tidal Potomac River and estuary- hydrologic data reports supplement, 1979 through 1981 water years. U.S. Geological Survey Open File Report 84-132. 355 pp.

DeLorme Mapping Co. 1989. *Virginia Atlas and Gazetteer.* Freeport, ME.

Diaz, R.J. 1977. The effects of pollution on benthic communities of the tidal James River. Ph.D. thesis, University of Virginia, Charlottesville, VA. 149 pp.

Diaz, R.J. 1989. Pollution and tidal benthic communities of the James River estuary, Virginia. *Hydrobiologia* 180:195-211.

TABLE 2. PREDICTED INVASION SUCCESS IN VIRGINIA LAKES AND RESERVOIRS

Reservoirs are listed alphabetically. Invasion *Risk* refers to the relative chance that *Dreissena* will be introduced, and *Susceptibility* refers to the relative chance that *Dreissena* will attain high population levels. See also text for explanation of terms.

Lake	Drainage	Recreational Vessel Use	Other Uses	Risk	Susceptibility
Claytor Lake	Ohio	high	hydroelectric power	high	moderate
Flannagan Res.	Ohio	high		high	moderate
Harwood Mills Res. (Newport News)	Poquoson	moderate	municipal water	low	high
Kerr Reservoir	Roanoke	high	hydroelectric power	high	high
Lake Anna	Pamunkey	high	nuclear power plant	high	low
Lake Chesdin	James	high		high	low
Lake Gaston	Roanoke	high	hydroelectric power	high	high
Lake Meade	Nansemond	high		moderate	high
Lake Moomaw	James	low	wildlife mgmt. area	low	moderate
Leesville Lake	Roanoke	moderate		high	moderate
Philpott Res.	Roanoke	high		high	low
Smith Mtn. Lake	Roanoke	high		high	moderate
S. Holston Lake	Tennesse	high	hydroelectric power	high	high
W. Branch Res.	Nansemond	moderate	municipal water	moderate	high

Griffiths, R.W., D.W. Schloesser, J.H. Leach, and W.P. Kovolak. 1991. Distribution and dispersal of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes region. *Can. J. Fish. Aquat. Sci.* 48:1381-1388.

James, R.W., J.F. Hornlein, R.H. Simmons, and B.F. Strain. 1991. Water Resource Data Maryland and Delaware, Water Year 1991. Vol. 1. Surface Water Data. U.S. Geological Survey Water-Data Report MD-DE-91-1. 592. pp.

Lane, M.F. and D.M. Dauer. 1991. Community structure of the macrobenthos of Back Bay. 99-127. **In** Marshall, H.G. and M.D. Norman (eds.). *Proc. Back Bay Ecological Symposium.* Old Dominion University, Norfolk, VA.

Lange, C.L. and R.K. Cap. 1992. The range extension of the zebra mussel (*Dreissena polymorpha*) in the inland waters of New York State. *J. Shellfish Res.* 11:228-229.

Litchler, W.F., and H.G. Marshall. 1979. Hydrology of the Dismal Swamp, Virginia–North Carolina. 140-168. **In** Kirk, P.W., Jr. (ed.). *The Great Dismal Swamp.* University Press of Virginia, Charlottesville, VA.

McMahon, R.F. 1992. Evaluation of the susceptibility of the raw water resources of Virginia power facilities to zebra mussel (*Dreissena polymorpha*) invasion and colonization. Report to Virginia Power. Macrofouling Consultants, Arlington, TX.

McMahon, R.F. and J.E. Alexander, Jr. 1991. Respiratory responses to temperature, hypoxia and temperature acclimation of the zebra mussel, *Dreissena polymorpha* (Pall.). (Abstract). *Amer. Zool.* 31(5):74A.

Meehan Overseas Terminals, Inc. 1991. Port of Richmond Harbor.

Master Monthly Waterborne Tonnage Reports, January-December, 1991. Meehan Overseas Terminals, Inc., Richmond, VA.

Mellor, G.L., 1986. Physical Oceanography. 29-49. **In** Goodrich, D.M. (ed.). *Delaware Bay: Issues, Resources, Status and Management.* National Oceanic and Atmospheric Administration Estuarine Programs Office, Washington, D.C.

NOAA (National Oceanic and Atmospheric Administration), 1985. *National Estuarine Inventory Data Atlas. Volume 1: Physical and Hydrologic Characteristics.* National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Rockland, MD. 111 pp.

New York Sea Grant. 1993. North American Range of the Zebra Mussel as of 3 January, 1993. *Dreissena polymorpha Information Review* 3(3):8-9.

Norman, M.D. and R. Southwick. 1991. Salinity and secchi disc records for Back Bay (1925-1989). 11-19. **In** Marshall, H.G. and M.D. Norman (eds.). *Proc. Back Bay Ecological Symposium.* Old Dominion University, Norfolk, VA.

Phelps, H.L. 1991. Positive uses of *Corbicula* clams: in polyculture waste management and as food. *(Abstract). Proc. 11th International Estuarine Research Conference, San Francisco, CA: 107.*

Prugh, B.J., Jr., P.E. Herman, and D.L. Belval. 1992. Water Resource Data Virginia, Water Year 1991. Vol. 1. Surface Water and Surface-Water-Quality Records. U.S. Geological Survey Water-Data Report VA-91-1. 592 pp.

Shtegman, B.K. (ed.). 1968. Biology and Control of Dreissena. Israel Program for Scientific Translations, Ltd., Jerusalem, Israel, and U.S. Dept. Commerce, National Technical Information Service, Springfield, VA. 145 pp.

Sincock, J.L., K.H. Johnston, J.L. Coggin, R.E. Wollitz, J.A. Kerwin, and J.G. Grandy, III. 1966. Back Bay-Currituck Sound Data Report: Environmental Factors. U.S. Fish and Wildlife Service, North Carolina Wildlife Research Commission, Virginia Commission of Game and Inland Fisheries, unpubl. rep. 338 pp, including tables and figures.

Sprung, M. 1987. Ecological requirements of developing *Dreissena polymorpha* eggs. *Arch. Hydrobiol./Suppl.* 79:69-86.

Staczykowska, A. 1977. Ecology of *Dreissena polymorpha* (Pall.) (Bivalvia) in lakes. *Pol. Arch. Hydrobiol.* 24:461-530.

Strayer, D.L, 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha* in North America. *Can. J. Fish. Aquat. Sci.* 48:1389-1395.

US Army Corps of Engineers (United States Army Corps of Engineers), 1984. *Chesapeake Bay Low Freshwater Inflow Study. Main Report.* U.S. Army Corps of Engineers, Baltimore District, Baltimore, MD. 83 pp.

Walton, W.C. 1993. The invasion of the Hudson River estuary by the zebra mussel *Dreissena polymorpha*, and its subsequent range overlap with the dark false mussel, *Mytilopsis leucophaeata.* Final Report to Polgar Fellowship Program. 31 pp. (Available from W. Walton, Inst. Marine & Coastal Sciences, Rutgers Univ., New Brunswick, NJ.)

Wolff, W.J. 1969. The Mollusca of the estuarine region of the rivers Rhine, Meuse and Scheldt in relation to the hydrography of the area. II. The Dreissenidae. *Basteria* 33:93-103.

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THE ZEBRA MUSSEL (DREISSENA POLYMORPHA): AN UNWELCOME NORTH AMERICAN INVADER

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INTRODUCTION

A new invader of North American fresh surface waters, *Dreissena polymorpha* (Pallas), commonly known as the "zebra mussel," has the potential to biofoul municipal, electric power generation and industrial water intake facilities; to disrupt food webs and ecosystem balances; and to interfere with sport and commercial fishing, navigation, recreational boating, beach use and agricultural irrigation throughout North American fresh surface waters.

ORIGIN OF THE ZEBRA MUSSEL IN THE GREAT LAKES

The zebra mussel, *Dreissena polymorpha*, native to the drainage basins of the Black, Caspian and Aral Seas, was introduced into several European freshwater ports during the late 1700s. Within 150 years of its introduction, the zebra mussel was found throughout European inland waterways.

Although the actual pathway of the mussel's introduction into North America is unknown, it is believed that ships originating from overseas freshwater ports where the mussel is found carried the mussel in freshwater ballast which was discharged into freshwater ports of the Great Lakes. Although adult mussels are capable of attaching to ships' hulls, their transoceanic transport in this manner is unlikely since the mussels cannot survive the high total salinity in open ocean saltwater for the time required for a transatlantic crossing.

The zebra mussel was first discovered in the Great Lakes Basin in Lake St. Clair in June 1988. Judging from shell size, it was theorized that the mussels were introduced into the lake sometime in 1986. The first confirmed sighting in the western basin of Lake Erie was in July 1988. Extensive colonies of up to 30,000 to 40,000 individuals per square meter were reported in the western basin of Lake Erie in the summer of 1989 by the Ontario Ministry of Natural Resources. By the end of 1989, specimens had been found in water treatment and industrial water systems in the Detroit River below Lake St. Clair, on beaches and in water treatment and industrial facilities along most of the north and south shores of Lake Erie. Adult mussels were first reported in Lake Ontario in Port Weller at the mouth of the Welland Canal in November 1989 and on a navigation buoy four miles off the Niagara Bar in December 1989.

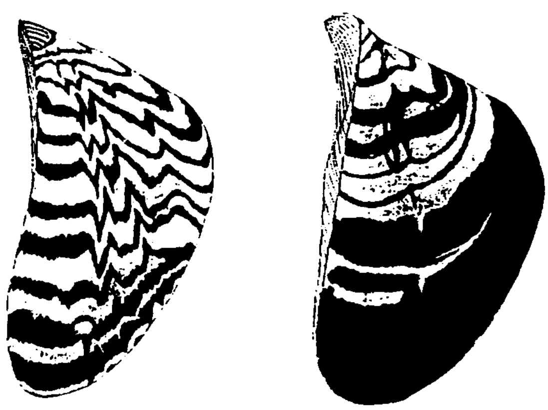
By September 1991, the mussel was found in all five of the Great Lakes; their connecting waterways; the St. Lawrence River; the western two-thirds of the Erie Canal; the eastern end of the Mohawk River; Cayuga and Seneca Lakes (in New York's Finger Lakes); the headwaters of the Susquehanna River in Johnson City, New York; the Hudson River between Albany and Red Hook, New York; the Illinois River; the Mississippi River between its confluence with the Illinois River and St. Louis, Missouri; the upper Mississippi River near La Crosse, Wisconsin; the Tennessee River near the Kentucky border; and the Ohio River near Mound City, Illinois.

Biologists believe that interbasin transport of the zebra mussel from the Great Lakes system into inland fresh surface waters is taking place via natural and human influenced dispersal vectors, and that the mussels will ultimately infest most areas of North America south of central Canada and north of the Florida Panhandle. This prediction seems to be borne out by sightings in the Illinois, Susquehanna, Mississippi, Tennessee, and Hudson Rivers. (See map for the zebra mussel's range in North America.)

Such dispersal will likely be greatly enhanced by interlake transport of veligers (larvae) in ship ballast and adult and juvenile mussels attached to ship and recreational boat hulls. The discovery of zebra mussels in Duluth Harbor (Lake Superior) may be evidence of such transport. There is concern that the range expansion of the zebra mussel will be further facilitated by transport of veligers by commercial bait transport, in anglers' bait bucket water and recreational boat engine cooling water, transport of juveniles and adults by waterfowl and by attachment to crayfish and turtles.

BIOLOGY OF THE ZEBRA MUSSEL

Zebra mussels are small (5 cm and smaller) bivalve mollusks (relatives of clams and oysters) with elongated shells typically marked by alternating light and dark bands (Fig. 1). As its scientific name *polymorpha* implies, the species shows considerable genetic and morphological plasticity, particularly in its marking and coloration patterns. Specimens with few markings, with a herringbone pattern, with stippled patterns or radial striping are quite common. Soviet studies suggest the presence of discrete morphological and physiological ecotypes or "phenes" (races) of *Dreissena* (Smirnova 1990). Early Soviet studies described at least five species (Andrussov, 1898).



[From: Morton (1969)]

Figure 1. The origin of the name *polymorpha* can readily be seen in the variations in the light and dark banded markings on Zebra mussels.

Zebra mussels secrete durable elastic strands, called byssal fibers, by which they can securely attach to nearly any surface, forming barnacle-like encrustations (Fig. 2). Because of an affinity for water currents, zebra mussels extensively colonize water pipelines and canals, often severely reducing the flow of water and, upon death, imparting a foul taste to drinking water (serious impacts in Europe since the late 1800s).

Zebra mussels will colonize lakeshores and riverbanks where they attach to rock or gravel substrates, forming broad reef-like mats (Fig. 3). In some European lakes, colony densities exceeding 100,000 per square meter have been reported with 15 cm deep shell accumulations from dead mussels on the lake bottom within two years.

[Photo: Ontario Ministry of Environment]

Figure 2. Zebra mussels can attach to nearly any surface. This car, retrieved from the bottom of Erieau Harbor, Ontario, had mussels growing on every surface including sheet metal, tires, fiberglass, glass, even cloth seats.

The mussels are generally found within 2 to 7 meters of the water surface but may colonize to depths up to 50 meters (Walz, 1978). Colonization depths vary from lake to lake, but appear to be determined by light intensity, water temperature and availability of food. Zebra mussels can tolerate a fairly wide range of environmental conditions. They prefer water temperatures between 20° and 25°C (68° and 77°F) and water currents 0.15 to 0.5 meters per second for proper growth. While normally considered a freshwater species, the zebra mussel can adapt to and inhabit brackish areas ranging from 0.2 to 2.5 ppt (parts per thousand) total salinity in estuarine locales. European reports indicate occasional sightings of zebra mussels in total salinities exceeding 12 ppt (Benthem Jutting, 1943).

In Europe, mussel densities tend to be higher in large lakes (surface areas greater than 485 hectares) with depths exceeding 35 meters, which are not overly enriched but which have a high calcium content, generally greater than 12 ppm (parts per million). Conditions generally considered as unsuitable for growth are water temperatures below 7°C (45°F) or above 32°C (90°F), water currents greater than 2 meters per second or rapid water level fluctuations. Zebra mussels can withstand dessication for two to three days, depending upon atmospheric humidity.

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Figure 3 Zebra mussels attached to rock or gravel substrates can reach colony densities greater than 100,000 per square meter with shell accumulations reaching 15 cm or more on the lake bottom.

The zebra mussel has a reproductive strategy unique to freshwater mussels which is responsible for its rapid population expansion in Europe and the Great Lakes. Sexual maturity is typically reached at age two but may occur in the first year at a size of 3 to 5 mm. Zebra mussels are separately sexed, but some hermaphroditism has been reported. Mature female mussels can produce 30,000 to 40,000 eggs per year, as the water temperatures reach 12°C (54°F). At least one European study has indicated that a 30 mm female can produce, on average, up to 1 million eggs per year. Precocious young-of-the-year mussels as small as 3 mm may produce as many as 6,000 eggs per year (Walz, 1978). Egg production can occur in either asynchronous or synchronous batches enabling individuals to spawn several times during the spawning season. Spawning activity may extend throughout the year in warm, productive waters.

Although poorly understood, the reproductive cycle is apparently influenced by environmental cues such as water temperature, phytoplankton abundance and species composition, and mussel population density. Evidence from Lake Erie suggests that reproductive activity may be cued by such seasonal phytoplankton dynamics as blooms and algal species succession. Spawning patterns may show considerable year-to-year variations. Recent studies from Lake Erie suggest that cool water temperatures, storm events, elevated turbidity, and increased population densities can delay spawning, resulting in possible synchronous spawning activity. Spawning may also be induced by the presence of mussel gametes (sex products) in the water.

In Europe, fertilized eggs are 40 to 70 microns long and become planktonic larvae (veligers) in 2 to 3 days when water temperatures reach 14° to 16°C (57° to 61°F). In Lake Erie 11°C (52°F) is the norm, with the Ontario Ministry of Natural Resources reporting veligers in water as cold as 8.0°C (46°F). Veligers are capable of active swimming for 1 to 2 weeks, and are also transported by water currents, enabling them to disperse considerable distances from their parent colonies. Nocturnal vertical migrations of veligers have been reported in European lakes.

Within 3 weeks of hatching, the young mussels reach the "settling stage," where they can attach to bedrock, cobble, bottom debris or such manmade objects as boat hulls, breakwaters and water intake cribs. At this life-cycle phase, the settling larvae can experience mortalities exceeding 99%, primarily from hypoxia, temperature shock, and failure to locate a suitable attachment substrate (which could result in larvae sinking into bottom sediments or into deeper, colder water with lower productivity).

During the first year of life, young mussels are capable of active crawling along the substrate at speeds over 3.8 cm per hour until they find a suitable location to attach with small, temporary byssal fibers. With age, the mussels develop extensive byssal fibers and, for the most part, become sessile. Younger, overwintering mussels can detach from their temporary byssal fibers and migrate to deeper (warmer) waters to escape from cold temperatures and ice scour. During the first growing season, young zebra mussels may reach 5 to 10 mm in length.

The lifespan of a zebra mussel is highly variable depending on a number of environmental conditions. Lifespans average around 3.5 years but can reach 8 to 10 years in some less productive European systems.

Typically, when the zebra mussel is introduced outside its native range, the relocated population undergoes a rapid increase in number, often by a factor of 2 to 3, lasting for several years after the initial introduction, followed by a marked reduction in population size and subsequent population oscillations. However, in Sweden the population of zebra mussels has not yet crashed after more than 11 years. The zebra mussel population expansion in Lake Erie appears to be more aggressive than in Europe, most likely due to the lake's highly suitable chemical, biological and thermal regimes.

USE OF THE ZEBRA MUSSEL AS FOOD: NATURAL PREDATION

Although larval and adult zebra mussels (which offer a high nutritional value to predators) are regularly consumed in Europe by several species of fish, the overall impact upon mussel populations is believed to be insignificant in many instances. Veliger and post-veliger larvae are also preyed upon by young fish and zooplankton, but to what extent this predation contributes to mussel mortality is unknown, although some researchers estimate this loss can reach five percent (Piesek, 1974). In some European lakes, crayfish predation on mussels 1 to 5 mm long is considerable, with adult crayfish (90 mm) consuming over 100 mussels per day (about 6,000 mussels per summer). Crayfish, however, are believed to be ineffective predators in deeper lakes due to cooler water temperatures. Some studies indicate that over 90% of the diets of the roach, a Eurasian fish species, is composed of zebra mussels. In the Great Lakes, the role of coarse fish species such as carp, eels and sheepshead may become increasingly important as a biological control agent; sheepshead are already reportedly feeding extensively upon zebra mussels in inshore areas of Lake Erie.

In Europe, studies indicate that waterfowl predation rates on zebra mussel populations are variable, ranging from insignificant to as high as 32% during the summer months and greater than 90% during the winter in some lakes. In the littoral zone (water depths of 0 to 5 meters) waterfowl are considered to be the prime controller of zebra mussels. For example, Lake IJssel, in the Netherlands, supports a large population of diving ducks feeding on zebra mussels.

The value of zebra mussels as a human food source is doubtful. It appears that they may not be a viable human food because of their small size, a strong byssal attachment which would make them difficult to harvest, and a possible tendency to serve as a parasite vector (transmitter) to humans. Furthermore, the mussel's filter feeding process may cause bioaccumulation of toxic contaminants, making the mussels unfit for human consumption.

BIOLOGICAL IMPACTS

Using siphons and a ciliated gill system, zebra mussels filter small particles such as phytoplankton (microscopic plants and many forms of algae), small zooplankton (microscopic animals) such as rotifers, and detritus (bits of organic debris) out of water drawn into the mussel's mantle cavity. Laboratory studies indicate that the mussels can efficiently filter food particles down to 0.7 microns, but preferentially select those particles between 15 to 40 microns as food. Rotifers as large as 450 microns can be retained and eaten. Zebra mussels can also filter and consume their own veligers. Particles of unsuitable size or chemical composition that are not ingested are coalesced into a mucus bolus (pseudofeces) and subsequently discharged.

Filtration rates (volume of water filtered per unit of time) are determined by food particle concentration and sizes, water temperatures, hunger state and mussel body size. On average, a 25 mm long zebra mussel can filter 1 liter of water per day. Filtration rates up to 2 liters per day under optimal conditions have been observed. European studies indicate that the filtration ability of the mussels can dramatically increase lake water clarity. Since the introduction of zebra mussels into the western basin of Lake Erie, Canadian researchers have observed a two- to three-fold increase in water clarity and a significant reduction in chlorophyll a content (chlorophyll a analysis provides an index of the open water food chain production available for the aquatic plants and animals in a waterbody). The extent that changes in the lake's clarity and productivity can be attributed directly to zebra mussel filtration activity is unknown. It is suspected that the zebra mussel has played a role. Lake Erie has also experienced an effective phosphate abatement program, which may be responsible in part for these observed trends in increased water clarity and decreased chlorophyll a content.

Since phytoplankton and detritus are major food sources for pelagic (open water) lake and riverine food webs respectively, fisheries-related impacts could result from zebra mussel filtration activity. Excessive removal of phytoplankton and detritus from the water column could cause a decline in zooplankton species which feed upon those food particles. Small zooplankton are also eaten by zebra mussels. Larger zooplankton species and larval fish of all species preying on smaller zooplankton could face reduced survival as mussel populations expand, suggesting other potential food web impacts. In addition, extensive deposition of mussel pseudofeces on the lake bottom could favor the proliferation of benthic (bottom-dwelling) fish and invertebrate species, especially in littoral areas. The changes in water transparency and the selective survival of benthic algae in mussel pseudofeces could favor a shift towards increased importance of primary production of benthic algae in the Great Lakes.

Because zebra mussels settle on rock cobble as an attachment substrate, there is concern that extensive colonization of shoal areas could impair reproduction of species of fish (such as walleye and lake trout) which spawn only on rocky-bottomed areas. Some biologists are concerned that decomposing mussel pseudofeces could reduce water quality in and around fish egg masses on shoals, reducing egg survival. Data collected by the Ohio Department of Natural Resources in 1990-91, however, indicated good year classes of walleyes produced from mussel-encrusted shoals in western Lake Erie. Apparently, mussels were scoured from some spawning areas by ice prior to 1990 walleye spawning. Wave action also helped by sweeping shoal areas clear of mussel pseudofeces. Continued monitoring of spawning areas is necessary to quantify any future mussel impacts. Furthermore, increased water clarity may reduce the ability of larval fish to avoid predation. This also makes zooplankton more visible to fish predators.

In general, freshwater mollusks are important vectors of parasites (digenetic trematodes) in waterfowl, fish, wildlife, and, occasionally humans (in tropical areas). The typical life cycle of digenetic trematodes involves the development of the parasite within the bodies of mollusks, which serve as intermediate hosts. Although zebra mussels are not considered as common parasitic vectors in Europe, they could potentially increase the spread of certain parasites, particularly as the mussel colonizes rapidly throughout North America. Zebra mussels themselves show little effects from parasites.

Native mussel populations may be adversely impacted by competition for food and space by the sheer numbers of zebra mussel colonies reported in areas of the Great Lakes. There are already early signs that native unionid clam populations in Lake St. Clair are disappearing rapidly coincident with zebra mussel colonization. Numerous live and dead unionids have been observed covered with extensive growths of zebra mussels. Many unionids appear to die as zebra mussel colonies interfere with host shell movements or cause damage to the shell edges.

THE ZEBRA MUSSEL AS A BIOFOULER IN RAW WATER SUPPLIES

A major impact of zebra mussel infestations is the fouling of raw water intakes such as those at drinking water, electric generation and industrial facilities. Water intake structures (intake cribs, trash racks, pipelines and tunnels) serve as excellent habitat for mussel colonization. The continuous flow of water into intakes carries with it a continuous source of food and oxygen to the mussels and carries away wastes, while the structures themselves protect the mussels from predation and ice scour. This makes water intakes ideal mussel habitat.

The zebra mussel is capable of attaching to firm substrates at water flow velocities below 2.5 meters per second on horizontal surfaces or 2.0 meters per second on vertical surfaces. Researchers in the Netherlands have reported that flows of 1.0 to 1.5 meters per second are sufficient to preclude settling under some conditions (Jenner, 1989). The presence of zebra mussels in a raw water main is usually first detected by the discharge of shells into the facility's raw well or forebay, possibly accompanied by a noticeable decrease in head, as the mussels line the pipeline or tunnel, eliminating the laminar flow along the walls of the conduit. In some cases, layers up to 0.3 meters or more in thickness are formed in intake mains.

Once in a drinking water treatment facility, zebra mussels may colonize any surface within the distribution system up to the first oxidation or filtration stage, including intake mains, raw wells, screen house walls, traveling or stationary screens, strainers and settling tanks. The main impacts associated with colonization are: loss of intake head, obstruction of valves, putrefactive decay of highly proteinaceous mussel flesh, obnoxious methane gas production, and increased electrocorrosion of steel and cast iron pipelines.

A similar fouling problem can occur in power plants and industrial water systems which use an infested waterbody as their raw water supply. Condenser and heat exchanger tubing can become clogged, leading to loss of heat exchange efficiency and overheating. Service water (fire protection, bearing lubrication/cooling, transformer cooling, etc.) lines can also become clogged, resulting in potential damage to vital plant components and possible safety hazards if sprinkler systems fail to deliver sufficient fire fighting water.

The rate of overgrowth of zebra mussels from intake cribs and trash racks to internal distribution systems is dependent upon chemical and physical characteristics of the raw water supply, flow velocity within the system, the three-dimensional position of the surface of the overgrowth, and the surface structure of the substrate. One Great Lakes utility has reported mussel densities as high as 750,000 per square meter in its intake canal.

IMPACTS ON NAVIGATION AND RECREATIONAL BOATING

Zebra mussels can impact commercial navigation and recreational boating. As with any organism capable of attaching to hulls, zebra mussels increase the amount of drag, reduce a boat's speed, and increase fuel consumption. Growth of larval mussels drawn into a boat's engine cooling water intake may occlude the cooling system, leading to overheating and possible damage to the engine. If shells are drawn into the engine, abrasion of cooling system parts, especially impellers, could result.

Commercial and recreational navigation can also be impacted if marker buoys sink under the weight of mussel encrustations on the submerged portions of the navigation aids. There is concern that navigation canals can also be negatively impacted by mussel colonization in lock systems.

The zebra mussel can also negatively affect docks and piers. Large colonies can encrust pilings and ladders, making them difficult to tie up to and speeding corrosion as a result of the mussels' waste excretions. On floating dock systems, each square meter of adult mussels on the bottom and sides of floats can add as much as 20 to 30 pounds. Dock systems that are left in the water year-round could be destabilized or sunk by mussel colonization. Bubbler or flow developer systems which are used to prevent ice damage to dock systems could be colonized, decreasing the systems' ice minimization effectiveness.

IMPACTS ON RECREATION

Recreational use of beaches in infested areas may be impacted by colonization of cobble in shallow nearshore areas by the mussels and by littering of beaches by shells washed up from submerged colonies by storm waves. Bathers on some Great Lakes beaches are reportedly adopting the use of beach/bathing footgear to prevent cuts from zebra mussel shells. Obnoxious smells from the decomposition of mussels also detract from the enjoyment of shoreline recreational activities.

PHYSICAL AND MECHANICAL CONTROL ALTERNATIVES

The European and Soviet experiences indicate that it is best to eliminate the zebra mussel in water pipelines at the veliger stage or before the most rapidly growing post-veliger specimens are able to pass unhindered through the pipeline. Control can be continuous or periodic with the time schedule for elimination based upon the mussel's growth rate for the specific waterbody and the minimum openings in the pipeline through which dead or living specimens can pass.

The first, and most evident, method for controlling zebra mussel infestation of raw water use facilities is to prevent entry of the mussel into such water systems (exclusion). This is accomplished by the use of strainers and filters to prevent the entry of larval, juvenile and adult mussels. The effectiveness of exclusion depends upon the mesh size of traveling and stationary screens and the size of the mussel.

The common traveling screen mesh used in water supply systems is 9 to 13 mm. The effectiveness of screens can be increased by reducing the mesh size (some newer power plants use traveling screens with openings as small as 1 mm). This method is effective in excluding only those mussels which originate upstream of the screens or filters. Mussel colonization downstream of the screens (as a result of the passage of veligers through the screens) is not impacted. Additional service water strainers can exclude adult and juvenile mussels that were not excluded by the initial screening. Centrifugal separation debris filters or backflushable bag filters can be used to exclude most sizes of zebra mussels but may result in a loss of head in distribution lines.

Unfortunately, veligers pass easily through both screens and service water strainers and perhaps filters, as well, and need to be eliminated in some other manner before they have an opportunity to settle and colonize within the distribution system. The possibility does exist to use microstraining fabrics or filters with an aperture of 60-70 microns or smaller to keep veligers out of very sensitive portions of distribution systems. However, this is not practical on systems requiring large amounts or high velocities of water.

A different approach is filtration of intake water at the source, before the water enters the pipeline. This can be accomplished through the use of several different forms of buried intakes or sand filters. These types of filters are suitable for low flow requirements, up to a maximum of about 25,000-30,000 gallons per minute. These types of intake filters are either drilled vertically and laterally into a good sand and gravel aquifer near a lake or river (Ranney wells); consist of porous intake pipes laid in trenches excavated into the bed of a lake or river and backfilled with a graded sand and gravel media (infiltration galleries); or are comprised of a flowing water source entering a surface trench or basin filled with a graded sand/gravel media with the pumping conduit either beneath the trench/basin, in the center, or at the outflow end (surface sand filter). Some modified form of sand filtration may also be suitable for use in single family homes or cottages using raw lake or stream water.

Since zebra mussels do not attach in high velocity current areas, another control method is to maintain intake and distribution system flows exceeding the rates stated earlier in this paper. This may not be possible in existing facilities due to pipe and pump size, pipeline configuration, or other factors, but should be taken into consideration in the design of new facilities in infested areas. Anything that causes either a significant drop in flow velocity or an eddying effect (such as changes in pipe diameter, short radius bends, square wall intersections in pumping wells, etc.) which would allow for increased mussel settlement and subsequent colonization, should be avoided. Also, rough pipe walls caused by scale, pitting, or poor welds should be corrected, as these areas create turbulence which allows the mussels an improved chance of reaching conduit walls through the laminar layer and increasing rates of attachment.

Physically scraping mussels from water systems (removal) is also a viable method of control. The desirability and effectiveness of scraping depends upon the design and operational characteristics of the impacted system. Scraping is most effective in large conduits where mussels are found in high concentrations, where access for personnel and equipment is available, and where the conduit can be taken out of service for long enough periods of time that divers (or non-dive personnel, in the case of dewatered systems) can remove the accumulated mussels. This alternative is, however, very expensive in terms of labor and lost production.

In smaller pipes or in pipelines where the configuration does not allow for direct access by workers, scraping may be accomplished by "pigging." The effectiveness of this method depends upon the design of the system and the intensity of the infestation. Pigging is not effective in systems with sharp, short radius bends in the pipeline or where the infestation is so great that the large amount of dislodged mussels might obstruct the progress of the pig or cannot be effectively removed from the conduit. Pigging can be designed into new systems constructed in infested areas.

Attachment of zebra mussels on open surfaces (i.e. trash racks and gates) may be discouraged through the use of electrically charged surfaces using industrial-frequency currents. Care should be taken to ensure that humans cannot come in contact with the charged surfaces. Potential impact on fish, ducks and other animals should also be considered.

It may be possible to control veliger settling in pipelines by the use of electrostatic filters placed in a pipeline cross section. In this case, exposure time depends upon water flow rates. Soviet research indicates that veliger death can be achieved by exposure to high voltage for 0.1 second. For such short exposures, 225 to 250 volts per centimeter would be needed for specimens with open shell valves or 380 to 400 volts per centimeter for those with closed valves (Morton, 1969), making this alternative impractical for most situations. At higher temperatures and voltages, specimens die proportionately more quickly. It should be noted that preliminary testing in the U.S. indicates that even greater charges may be required to ensure 100% mortality.

A "last resort" mechanical control for extreme situations is the removal and replacement of clogged tubing.

AVOIDANCE CONTROL ALTERNATIVES

For facilities that place marker buoys to locate intake cribs, it would be advisable to keep the buoy anchors well away from the intake structures to prevent veligers from settling on the anchor cable and spreading down the cable to the cribs. Periodic scraping of the bottoms of buoys is advised to avoid possible sinking under the weight of attached mussels.

The use of acoustic vibrations (>20kHz) is also being researched as an avoidance methodology. Preliminary data indicate that certain frequencies and intensities may be effective in "deactivating" veligers, that is, rendering them unable to attach to available substrates. Ultraviolet B radiation may also prove to have some effectiveness at killing veligers entering low flow conduits.

OXYGEN DEPRIVATION CONTROL

Since zebra mussels "breathe" oxygen as they draw water over their gills, oxygen deprivation, accomplished by hermetically sealing water intakes and

WATER TEMP °C	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	CRITERIA STUDIED
17-18	7.5 0		0.7 0	0.03 0		0 90	0 100	D.O. (mg/l) % Dead
20-21	9.6 0	0.08 0	0 10.0		0 100			D.O. (mg/l) % Dead
23-24	7.1 0	0.33 0	0 48.0	0 100				D.O. (mg/l) % Dead

Table 1 Zebra mussel mortality rates at differing water temperatures and dissolved oxygen concentrations (Mikheev, 1968).

isolated internal distribution lines, can be used as a control method. Because the mussels utilize oxygen most efficiently at 20°C (68°F), oxygen deprivation tends to work best in summer. Two to three days exposure to anaerobic water at 23° to 24°C (73.5° to 75°F) will result in 100% mortality (Mikheev, 1968; see Table 1). Oxygen can be eliminated from a sealed conduit using sodium metabisulfite with cobalt chloride as a catalyst. Hydrogen sulfide gas may be added to increase the effectiveness of the treatment.

A relationship also exists between mussel size and susceptibility to oxygen deprivation. Small specimens die first because smaller mussels consume more oxygen than larger ones (Table 2). Unfortunately, however, since zebra mussels can survive several days of anaerobic conditions, any pipeline treated in this manner must be capable of being shut down and sealed for a number of days, a major drawback for most applications. It should be noted that many European water systems are designed with dual intakes, often quite short, to enable one to be shut down for cleaning while the other carries on the business of the facility.

Length (mm)	% Mortality
1.0-4.9	100
5.0-9.9	61
10.0-14.9	34
15.0-19.9	2
20.0-24.9	0

TABLE 2 Relationship of zebra mussel size and mortality under anaerobic conditions for 37 hours at 22° (Mikheev, 1968).

When eliminating zebra mussels through oxygen deprivation, it should be noted that mussels in closed vessels die more rapidly when dead specimens are already present. There are several explanations for this: the appearance of disintegration products in water, extensive development of bacterial flora, and the rapid uptake of any remaining oxygen for oxidation (decomposition) and bacterial respiration.

THERMAL CONTROL

Experience in Europe and the Soviet Union indicates that one of the most efficient, environmentally sound and cost effective methods of controlling zebra mussel encrustations is the systematic, periodic flushing of water systems with heated water. Water temperatures must exceed 37°C (98.6°F) for approximately 1 hour to ensure 100% mortality for mussels acclimated to 10°C (50°F) water temperatures (Ontario Hydro, 1990). Water temperatures in excess of 55°C (131°F) will result in rapid death of the most mussels of the widest size (life stage) range. In this temperature range, mussels tend to die with their shells slightly opened, promoting exposure and degeneration of byssal threads, followed by detachment of many specimens from the substrate (the smallest mussels, <7.0 mm, detach first). Lower temperatures, or thermal shocking applied to mussels acclimated to warmer water temperatures, will take longer periods of time to achieve 100% mortality (Figure 4). Mussels which remain attached must be mechanically scraped from the attachment areas or may be allowed to decompose. Treatments at temperatures greater than 60°C (140°F) result in immediate 100% mortality. However, many mussels may die with closed shells and may remain attached for several days.

When utilizing thermal control, it is often necessary to treat as many as three or more times annually to remove adults and to target the more vulnerable

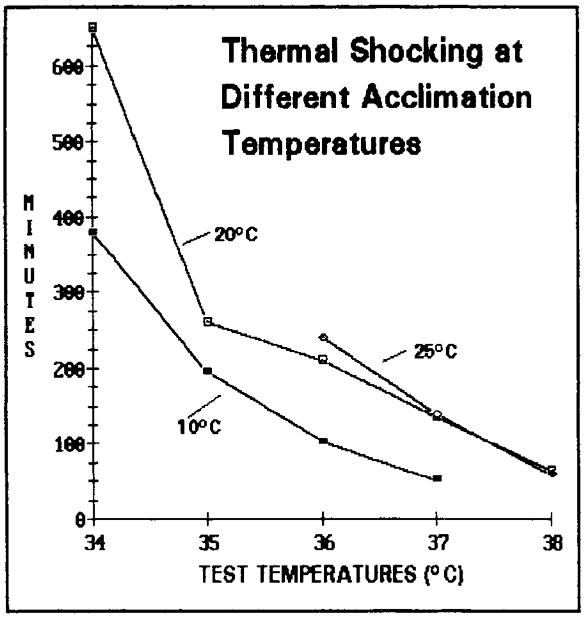

Figure 4 The time required to kill zebra mussels by thermal shocking varies dependent upon the temperature to which the mussels are acclimated and the temperature of the water used for the treatment.

early life stages of the mussel. The suggested annual treatment regime is early summer (June) to eliminate overwintered post-veliger specimens of the previous year, followed by second and third treatments in late summer (August) and fall (late October or November) to eliminate the current year's post-veligers. Each thermal treatment may have to be repeated several times during each of the three annual treatments to eliminate the greatest number of mussels. Mechanical scraping and cold-water flushing can be used after each hot water treatment to remove debris from major encrustations, much of which can be flushed from the system under high flow conditions. It should be noted that byssal threads will remain attached to substrate for considerable lengths of time, possibly disrupting laminar flow long after mussel shells have been removed.

CHEMICAL CONTROL ALTERNATIVES

Chemical control strategies generally fall into two categories: compounds which oxidize the mussels' organic material rather than acting in a toxic manner (e.g. chlorine, chlorine dioxide, ozone, potassium permanganate, hydrogen peroxide, chloramine) and chemicals which have a toxic effect on the mussels (e.g. molluscicides, copper sulfate, some metallic ions).

Chemical control strategies may be applied **once per year** at the end of the mussel spawning season (to kill all mussels of all ages which have been allowed to grow in a system since the end of the last spawning season); **periodically** throughout the spawning season (allowing some colonization but killing the mussels before densities get too great for efficient operation of the system; this allows less colonization than seasonal treatment); frequent **intermittent** treatment with relatively high concentrations of chemical (generally once or twice per day to purge the system of recently settled post-veligers, preventing growth to the more troublesome adult stage); and **continuously** with lower concentrations of chemical throughout the spawning season to prevent all settlement and colonization within the system.

Commercially available **molluscicides** lend themselves more to seasonal or periodic treatment of nonpotable water systems in which some colonization can be tolerated. **Oxidizing chemicals** may be used for short-term seasonal or periodic usage in systems with an immediate discharge to the environment. In potable water systems where little or no colonization can be tolerated because of potential human health impacts (mainly bacterial growth in rotting mussel flesh and taste and/or odor problems), oxidizing chemicals may be suitable for intermittent or continuous treatment.

Experiments in the Soviet Union have indicated that **electrolytically dissolved metal ions** in water may be used in low discharge pipelines and in underground and other inaccessible conduits to eliminate zebra mussels. When using metallic ions, larger mussels can be expected to exhibit a greater negative

ION	mg/l	% MORTALITY	TEST CONDITIONS
SILVER	2.5 5.0 7.5+	40.0 71.5 100	20°C 24 hour[1]
MERCURY	5.0	57.2	20°C, 24 hour[1]
ZINC*	5.0	4.8	20°C, 24 hour[1]
COPPER	4.0	100	20°C, 24 hour[1]
COPPER	3.9	8.0	10°C, 20 hour[2]
COPPER	3.9	93.0	20°-22°C, 20 hr[2]

Table 3 The effects of metal ions on zebra mussels. *Surviving mussels filter water but do not attach to substrate. [1] Static water test. [2] Flowing water test. (Dudnikov and Mikheev, 1968)

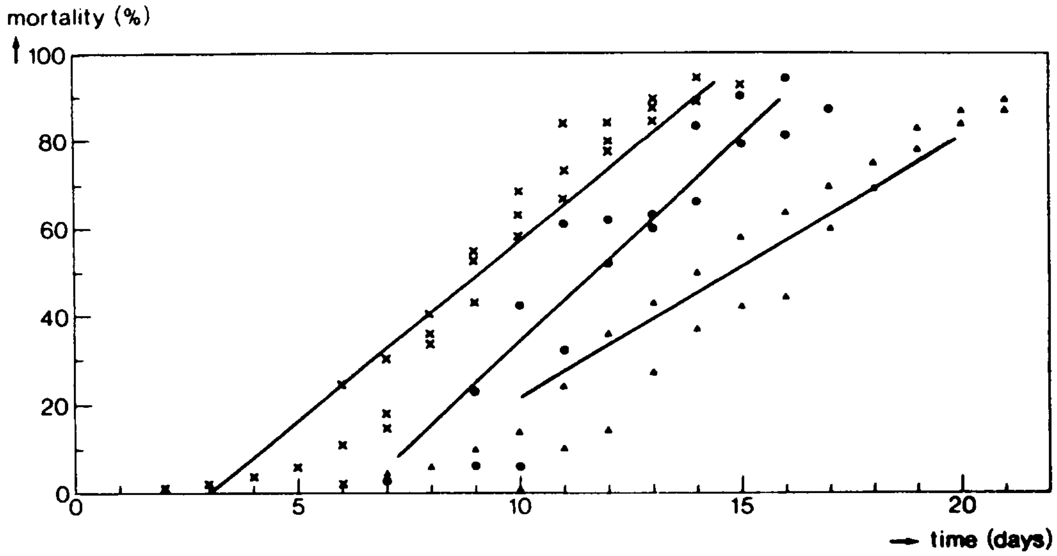

TABLE 4 Mortality rate of zebra mussels in laboratory experiments at varying chlorine concentrations. The lines represent linear correlations. Experiments were run at water temperatures of 12°-15°C.

x = 1.0 mg/l Total Residual Chlorine (TRC); 3 experiments in duplicate; r = 0.972
o = 0.5 mg/l Total Residual Chlorine (TRC); 2 experiments in duplicate; r = 0.988
▲ = 0.25 mg/l Total Residual Chlorine (TRC); 2 experiments in duplicate; r = 0.956

response due to incomplete hermetic sealing of their shells. While discharge of many of these metals into the natural environment (receiving waters) would not be permissible under state and federal regulations, some metallic ions might be applicable for use in closed water systems. Another factor which could limit use of metallic ions as a zebra mussel control measure is the potential corrosion of metal system components.

The use of copper sulfate has been shown in Soviet experiments to be an effective zebra mussel control. However, at temperatures below 22.5°C (72.5°F), lethal doses of copper sulfate are so high (i.e., 300 mg/l at 17.5°C for 5 hours results in 60% mortality [Lukanin, 1968]) as to be impractical, considering corrosion of metal pipes caused by the copper. At temperatures above 27.5°C (81.5°F), lethal concentrations decrease to more practical values (e.g., 11.0 mg/l at 27.5°C for 5 hours yields 88% mortality), perhaps making water pre-heating combined with copper sulfate a feasible control alternative in some situations.

Treatment at the point of raw water intake or within the system with various oxidizing chemicals has been proven in Europe, the Soviet Union, Canada, and the United States to be effective in controlling zebra mussels. Concentrations in the range of 0.25 mg/l to 1.0 mg/l total residual chlorine (TRC) for 2 to 3 weeks has been found to be effective in killing 95%-100% of zebra mussels (Jenner, 1989; see Table 4). Continuous treatment at concentrations of 0.25 mg/l to 0.5 mg/l during that period of the year when veligers and post-veligers are present in source waters has been shown to be effective in preventing settlement and growth of mussels in water treatment facility intakes. Chlorine treatment is more effective at warmer water temperatures than cold.

In power generation and industrial settings, continuous chlorination is feasible only for limited portions of water systems that are highly vulnerable to infestation and/or are part of safety-related systems. This is not a problem in water treatment facilities where oxidizing chemicals are commonly used during most, if not all, of the year for taste and odor control as well as disinfection purposes.

There is concern for negative effects of chlorine on nontarget species in discharge receiving waters. Therefore, dechlorination at the point of discharge is usually required.

There is also the risk that too high concentrations of chlorine may result in harm to the biological character of slow sand filters, thereby requiring dechlorination prior to filtration. In addition, an excessive rate of mussel killing can result in the putrefactive decay of the highly proteinaceous mussels, production of obnoxious or dangerous methane gas, and concentrated deposition of detached shells with a subsequent blockage of conduits when pipelines containing significant infestations are "shock treated."

Chlorination of organic-rich water at the intake end of pipes may cause the formation of trihalomethanes (THMs), suspected carcinogens, and may therefore not be practical for public water treatment facilities which already have THM production problems. In these situations, other oxidizing compounds (e.g., chlorine dioxide, ozone, potassium permanganate, hydrogen peroxide) may be alternatives to chlorine.

Molluscicides may also be effective in industrial and power plant applications. These are usually short-term applications used periodically throughout the year, similar to periodic thermal treatments.

Before using any chemical treatment method, readers are advised to check with local environmental regulatory agencies to determine legality of use for their situation.

COATINGS

Organometallic antibiofouling coatings such as tributyltin oxide (TBTO) may be effective in preventing zebra mussel attachment to pipes, boat hulls and buoys, but are relatively expensive, difficult to apply, must be reapplied frequently and may result in negative environmental impacts on nontarget species as the coatings ablate off the substrate into the surrounding waters. Many such compounds are currently banned for most uses in the Great Lakes. Since these coatings do ablate into the water, they are unsuitable for use in potable water systems. Other coatings, such as copper paints or epoxies or zinc galvanizing may be useful in minimizing zebra mussel attachment and growth without environmental consequences as great as those caused by TBTO. Silicone-based coatings may also prove to be effective.

SUMMARY AND CONCLUSIONS

The zebra mussel, *Dreissena polymorpha*, is now well established throughout the Great Lakes and their connecting channels, as well as in numerous inland river systems in North America. There is no way to eliminate the mollusk in these water bodies without harming other life forms, so we must assume that the mussel is here to stay and that it will eventually be found throughout most inland waterbodies throughout North America. The task now is to control its impacts on ecosystems and water uses.

The control methods cited above will give readers an introduction to the mussel and its control. Note that new control alternatives will most likely be developed as a result of the invasion of the zebra mussel into the Great Lakes. Readers should augment this fact sheet by referring to research reports available from Sea Grant, federal, state and provincial environmental management/regulatory agencies, and researchers.

REFERENCES

Andrussov, N. (1898). Fossile unde lebende Dreisseniidae Eurasiens. Trudy St. Petersburgkago Obschchestva Estestvoispitatelei (Otdyelenie Gelogii i Mineralogii), 25. 25 plates + text. 798 p.

Clarke, K. B. 1952. The Infestation of waterworks by *Dreissena polymorpha*, a fresh water mussel. Journal of the Institution of Water Engineers, 6(5): 370-379.

Dudnikov, V. F. and V. P. Mikheev. 1968. The effect of certain metal ions on *Dreissena*. In: Shtegman, B. K. (Ed.). Biology and Control of *Dreissena* (translated from Russian), 60-64.

Greenshields, F., and J. E. Ridley. 1957. Some researches on the control of mussels in water pipes. Journal of the Institution of Water Engineers, 11: 300-306.

Jenner, H. A., and J. P. M. Janssen-Mommen. Control of the zebra mussel in power plants and industrial settings. Presented at the Second International Conference on the Zebra Mussel in the Great Lakes. Rochester, NY. 1989.

Kirpichenko, M. Y., V. P. Mikheev and E. P. Shtern (1962). Control of *Dreissena polymorpha* fouling at hydro-electric power stations (translated from Russian). Elektr. Stat., (5): 30-32.

Lukanin, V. S. 1968. Survival of adult *Dreissena* in copper sulfate solutions of different concentration and temperature. In: Shtegman, B. K. (Ed.). Biology and Control of *Dreissena* (translated from Russian), 69-70.

Lyakhov, S. M. 1968. Work of the Institute of Biology of Inland Waters, Academy of Sciences of the U.S.S.R. In: Shtegman, B. K. (Ed.). Biology and Control of *Dreissena* (translated from Russian), 54-59.

Lyakhov, S. M. 1962. Protection of underwater structures from encrustation of *Dreissena* (translated from Russian). Priroda, (51): 106-108.

Mikheev, V. P. 1968. Mortality rate of *Dreissena* in anaerobic conditions. In: Shtegman, B. K. (Ed.). Biology and Control of *Dreissena* (translated from Russian), 65-68.

Morton, B. S. 1969. Studies on the biology of *Dreissena polymorpha*. Habits, habitats, distribution and control. Water Treatment and Examination, 18: 233-241.

Ontario Hydro. 1990. Thermal shocking. Unpublished research results as reported in *Dreissena polymorpha* Information Review, 1(1): 6. Zebra Mussel Information Clearinghouse. New York Sea Grant. Brockport, NY.

Piesik, Z. 1983. Biology of *Dreissena polymorpha* (Pall.) settling on stylon nets and the role of this mollusc in eliminating the seston and the nutrients from the water-course. Polskie Archiwum Hydrobiologii, 30(4): 353-361.

Smirnova, N. F. and G. A. Vinogradov. 1990. Biology and ecology of *Dreissena polymorpha* from the European USSR. Presented at the workshop Introduced species in the Great Lakes: ecology and management. Saginaw, MI, 26-28 September 90.

Walz, Norbert. 1978c. The energy balance of the freshwater mussel *Dreissena polymorpha* (Pallas) in laboratory experiments and in Lake Constance: 2. Reproduction. Archiv fur Hydrobiologie/Supplementbande, 55(1): 106-119.

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New York Sea Grant Extension is a state and federal program designed to help people solve coastal problems along New York's Great Lakes, St. Lawrence, Niagara, and Lower Hudson Rivers, the New York City waterfront, Long Island Sound, and the State's Atlantic Ocean coast. It is administered through the State University of New York and Cornell University. Sea Grant funds research projects and conducts educational programs on issues ranging from off-shore mining and erosion control to commercial fisheries, coastal tourism, and aquaculture.

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Mid-Atlantic Contacts for Zebra Mussel Information

Delaware

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Marine Communications Office
263 East Main Street
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Virginia Polytechnic Institute and State University
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(703) 231-5059

Invasion of an Exotic Species: Stop the Zebra Mussel!

Activities and Resources For Grades 8 - 12

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INTRODUCTION

Invasion of an Exotic Species: Stop the Zebra Mussel!

Activities and Resources For Grades 8 - 12

Thousands of exotic plants, animals, and microbes have been introduced into the United States. Some of these organisms were intentionally imported for use in agriculture, the pet industry, and fish and wildlife management. Others accidentally found their way to the United States in ships' ballast water, in packing materials, or as hitchhikers on other plants and animals. Many exotic species, such as soybeans and wheat, have been beneficial. Others, such as the Japanese beetle and kudzu, have had a negative impact. In addition, plant and animal species from the Americas have been exported to other parts of the world, with similar effects. Many exotic species displace native plants and animals, alter ecosystems, cause disease, and interfere with human activities in industry, agriculture, and recreation.

The zebra mussel is an exotic freshwater mollusk from Europe which was accidentally introduced into the United States in the Great Lakes area in 1985 or 1986. The mussel larvae were most likely transported in the ballast water of a ship and released into Lake St. Clair. The mussels reproduce rapidly in suitable habitats and have created serious environmental and economic problems in many parts of the country. Zebra mussels are spreading toward the mid-Atlantic states. Where and how will they be most likely to invade Virginia? How can the zebra mussel invasion be controlled?

The activities and resources presented in this packet will guide students in a study of the zebra mussel and the possibilities of its invasion of Virginia. Actual scientific research data are introduced as a critical part of group problem-solving activities. Students are challenged to use the scientific data and other information to design action plans to help prevent the introduction and spread of zebra mussels into the state. Additional follow-up activities extend the study of zebra mussels and encourage the investigation of the impact of other exotic plants and animals.

Acknowledgments

The information used to develop the data cards in the activity "Where Will the Zebra Mussel Invade?" was obtained from personal communications with Patrick Baker, a graduate student at the Virginia Institute of Marine Science, and from the following research reports:

Baker, Patrick, Shirley Baker, and Roger Mann. 1993. Criteria for predicting zebra mussel invasions in the mid-Atlantic region. Virginia Sea Grant College Program, Virginia Institute of Marine Science, VSG-93-03.

Baker, Patrick, Shirley Baker, and Roger Mann. 1993. Potential range of the zebra mussel, *Dreissena polymorpha*, in and near Virginia. Virginia Sea Grant College Program, Virginia Institute of Marine Science, VSG-93-04.

Supplementary materials:

North Carolina Sea Grant
Ohio Sea Grant
Virginia Sea Grant
Virginia Department of Game and Inland Fisheries
Zebra Mussel Information Clearinghouse, New York Sea Grant

Editorial Review:

Bland Crowder
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Zebra mussel art work: Carol Allaire, Michigan Sea Grant

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Activity Instructions

Where Will the Zebra Mussel Invade?

Objective

Students will work in small groups to communicate and analyze scientific data on zebra mussels and water quality. Using this information, each group will predict the likelihood of zebra mussels becoming introduced and established in various aquatic sites in Virginia.

Student Preparation

Students should have a basic understanding of pH, temperature, and calcium content as measurable characteristics of the water in aquatic habitats. They should understand that "parts per thousand" and "parts per million" refer to the concentration of chemical substances present in a body of water.

Time Needed

1 class period (45 - 50 minutes)

Materials Needed (for each group of 4 - 6 students)

From the "Student Activities" section:
- Zebra Mussel Biology
- Zebra Mussel Critical Habitat Needs
- Zebra Mussel Impacts
- Zebra Mussel Study Site Data Cards (one set of 6 data cards per group)
- Zebra Mussel Study Site Report

Optional: Virginia highway map (one per group)

Teacher Preparation

1. Read the information in the "Student Activities" section and the supplementary reference materials provided in the packet to familiarize yourself with zebra mussels and their impact.

2. Duplicate the Zebra Mussel Study Site Data Card sheets. (You will need one set of 6 cards for each student group.) Cut the data cards apart and put each set of six in a separate envelope, or paper clip them together. (If the cards become mixed up, the small number at the bottom of each card will help you put the sets back together.)

3. For each group, duplicate one copy of the other four pages ("Zebra Mussel Biology," "Zebra Mussel Critical Habitat Needs," "Zebra Mussel Impacts," and "Zebra Mussel Study Site Report"). If you wish, give the "Biology" sheet to each student to read before class. You may want to make overhead transparencies of the "Critical Habitat Needs" and "Impacts" sheets and display them for reference during the activity.

4. If students are not already familiar with the concept of exotic species, decide how you will relate the zebra mussel issue to other concepts that they have studied, such as animal adaptation, species competition, impact of human activities on ecosystems, etc.

Conducting the Activity

1. Divide the class into groups of four to six students each. Assign roles within the groups as follows:

   Materials Manager: Obtains activity materials from teacher, distributes them to group, and returns all materials to teacher in good order after activity is finished.

   Recorder: Keeps written notes on group discussions and observations. Records group responses to questions on activity worksheets. Reads written information back to rest of group for their approval.

   Reporter: Gives verbal report to the class summarizing the group's conclusions, using the activity worksheets and other notes from the Recorder.

   Research Technician(s): Provide(s) additional information to the group during the problem-solving activities by consulting supplementary handouts and reference materials.

2. Introduce students to the information from the "Zebra Mussel Impacts," "Zebra Mussel Biology," and "Critical Habitat Needs" sheets. You may lead a class discussion, or each small group may read and discuss the information and review it with the teacher and the rest of the class. Explain that they will be working in groups to analyze scientific information in order to predict whether or not various places in Virginia are suitable habitat for zebra mussels.

3. Give each Materials Manager a set of Zebra Mussel Study Site data cards and a copy of the Zebra Mussel Study Site Report form. The Materials Manager should distribute the data cards one at a time to all group members (some students may get more than one card if groups have fewer than six students). In turn, the students read aloud the information on their data cards to the other group members. The Recorder reads the Study Site Report form to the group.

4. Based on this information, each group develops a prediction about the likelihood that its study site will be affected by zebra mussels. The questions on the

Study Site Report form will guide their discussion. The Recorder writes the predictions and supporting information on this form.

5. Once all groups have completed their report forms, each group's Reporter shares the results with the rest of the class. To facilitate discussion as the class compares the sites, the Recorders can post on a chart or the chalkboard the predictions for their sites, along with water quality data and other important facts.

6. If you plan to follow this activity with "Developing a Zebra Mussel Action Plan," have the Recorders keep their Site Report forms to use as reference.

Summary and Evaluation

1. Based on the information known about each study site, did each group make a reasonable prediction about the zebra mussel's introduction and establishment? (See chart below for scientists' predictions.) If students disagree, remember that all of the facts are not yet known, and that there is some room for debate.

Study Site	Chances for Introduction	Chances for Establishment
1. James River	high	high
2. Potomac River	high	high
3. Smith Mountain Lake	high	moderate
4. Rappahannock River	moderate	moderate
5. Kerr Reservoir and Lake Gaston	high	high
6. Mattaponi and Pamunkey Rivers	moderate	low
7. Lake Anna	high	low
8. Claytor Lake	high	moderate
9. South Holston Lake	high	high

2. Rank the study sites from "lowest risk" to "highest risk" for the successful establishment of a zebra mussel population. Which site is closest to your school?

3. Overall, what human activity might be most likely to contribute to the introduction of zebra mussels in Virginia?

4. Locate the study sites on a Virginia highway map. How could the location and geography of each study site contribute to the introduction of zebra mussels? Once the zebra mussel becomes established, how far away from each study site do you think the mussel could spread?

5. At which study site might zebra mussels have the most serious economic impact?

Activity Instructions

Developing a Zebra Mussel Action Plan

Objective

Students work in small groups to design and communicate action plans to help prevent the introduction and spread of zebra mussels in areas which are at risk.

Time Needed

2 class periods or more, depending on number of groups (students may need additional time outside of class to prepare group presentations)

Materials Needed

Zebra Mussel Action Plan Outline (in "Student Activities" section)
Zebra Mussel Study Site Reports (the same forms which were completed by the groups in the previous activity)
Supplementary zebra mussel publications included in this packet (See "Resources" section for list of titles. You may duplicate these so that each group has a copy, or groups can share materials.)
Posterboard, markers, and other art materials
Optional: Additional zebra mussel articles (See "Resources" for bibliography)

Student Preparation

Students should have already completed the "Where Will the Zebra Mussel Invade?" activity and be divided into small groups.

Teacher Preparation

1. Read the "Zebra Mussel Action Plan Outline" for information on how the activity is done.

2. For each group, duplicate one copy of the "Zebra Mussel Action Plan Outline" and the supplementary publications. These publications contain background information the students will need to develop their action plans.

3. Divide students into small groups and assign roles, as in the previous activity. Groups may remain the same, or students may rotate into another group. NOTE: You may decide to have the class develop action plans only for those study sites which are at a high or moderate risk. If so, students from "low-risk" groups can be moved into "high-risk" groups.

Conducting the Activity

1. Give each Materials Manager copies of the "Zebra Mussel Action Plan Outline" sheet and the supplementary publications.

2. Briefly introduce the activity, and give students the timeline for the completion of their plans and for their class presentations (5-10 minutes each). Encourage the groups to use charts, posters, and any other creative methods to make their presentations effective.

3. On the day set aside for presentations, assign a timekeeper to help keep the activity on schedule. Each group should allow time for questions and comments from the rest of the class when its presentation is finished.

Summary and Evaluation

1. Have a small group of students serve as an evaluation team, and let them choose which plans are the most creative, comprehensive, practical, effective, etc. Alternatively, have the entire class discuss and evaluate the merits and shortcomings of each plan.

2. How do the groups' action plans compare to the efforts which Virginia and other states are making to control the zebra mussel? Students may want to contact zebra mussel specialists to get their reactions to the student plans. (See "Resources" for contact people.)

Publications Included In This Packet

Baker, Patrick, Shirley Baker, and Roger Mann. 1993. Criteria for predicting zebra mussel invasions in the mid-Atlantic region. Virginia Sea Grant Program, Virginia Institute of Marine Science, VSG-93-03.

Baker, Patrick, Shirley Baker, and Roger Mann. 1993. Potential range of the zebra mussel, *Dreissena polymorpha*, in and near Virginia. Virginia Sea Grant Program, Virginia Institute of Marine Science, VSG-93-04.

Baker, Shirley, Patrick Baker, and Roger Mann. 1993. Zebra mussels in Virginia's future. Virginia Sea Grant Program, Virginia Institute of Marine Science, VSG-93-05.

Doll, Barbara. 1993. Mid-Atlantic zebra mussel fact sheet. University of North Carolina Sea Grant, North Carolina State University.

Heath, Robert T. 1993. Zebra mussel migration to inland lakes and reservoirs: A guide for lake managers. Ohio Sea Grant College Program, OHSU-FS-058.

Kelch, David O. 1994. Boaters: Slow the spread of zebra mussels, and protect your boat too. Ohio Sea Grant College Program, OHSU-FS-054.

McManus, M., N. Schneeberger, R. Reardon, and G. Mason. 1989. Gypsy moth. Forest insect and disease leaflet 162, U.S. Department of Agriculture Forest Service.

Ohio Sea Grant College Program. A Great Lakes Sea Grant resource list on zebra mussels and other nonindigenous species. 1993. Ohio Sea Grant College Program, OHSU-FS-052.

O'Neill, Charles R. Jr., and David B. MacNeill. 1991. The zebra mussel (*Dreissena polymorpha*): An unwelcome North American invader. New York Sea Grant.

Snyder, Fred L., David W. Garton, and Maran Brainard. 1994. Zebra mussels in North America: The invasion and its implications. Ohio Sea Grant College Program, OHSU-FS-045.

Selected Bibliography

For more information on zebra mussels and other exotic species, check local libraries for the following publications:

Bruenderman, Sue, and Lisie Kitchel. 1992. A hitchhiking terror: The zebra mussel. *Virginia Wildlife*, Vol. 53, No. 4, April 1992, pp. 11-13.

Culotta, Elizabeth. 1991. Biological immigrants under fire. *Science*, Vol. 254, No. 5037, 6 December 1991, pp. 1444-1447.

Doll, Barbara, and Jeannie Farris. 1993. Invasion of the killer mussels. *Wildlife in North Carolina*, Vol. 57, No. 3, March 1993, pp. 21-23.

Fleming, C.B. 1991. Unwelcome immigrants: Ballast water stowaways. *Sea Frontiers*, Vol. 37, No. 3, June 1991, pp. 22-25.

Neves, Richard. Brooding over mussels. 1994. *Virginia Wildlife*, Vol. 55, No. 1, Jan. 1994, pp. 4-9.

Raloff, Janet. 1992. From tough ruffe to quagga. *Science News*, Vol. 142, No. 4, pp. 56-58.

Ross, John. 1994. An aquatic invader is running amok in U.S. waterways. *Smithsonian*, Vol. 24, No. 11, Feb. 1994, pp. 40-51.

Stolzenburg, William. 1992. The mussels' message. *Nature Conservancy*, Vol. 42, No. 6, Nov./Dec. 1992, pp. 16-23.

Virginia Sea Grant. 1992. *Dreissena polymorpha*, the unwelcome colonizer. *Virginia Marine Resource Bulletin*, Vol. 24, Nos. 1 and 2, Spring and Summer 1992, pp. 22-23.

Additional curriculum materials may be ordered from the following sources:

"Alien Invaders: A Case Study on Zebra Mussels"
(curriculum unit with student activities)
The Rivers Project
Southern Illinois University
Box 2222
Edwardsville, IL 62026

"Saving America's Pearly Mussels"
(video, script, and poster)
Virginia Tech Extension Distribution Center
112 Landsdowne St.
Blacksburg, VA 24061-0512

Other Zebra Mussel Contacts

Ohio Sea Grant College Program
The Ohio State University
1314 Kinnear Road
Columbus, OH 43212
(614) 292-8949

Michigan Sea Grant College Program
Zebra Mussel Information Office
University of Michigan
20200 Bonisteel Blvd.
Ann Arbor, MI 48109
(313) 764-1138

Minnesota Sea Grant
Zebra Mussel Information Center
208 Washburn Hall
University of Minnesota
Duluth, MN 55812
(218) 726-8712

Tennessee Valley Authority
1101 Market Street
Chattanooga, TN 37402
(800) 538-2526

Student Activities

See "Teacher's Guide" for activity instructions.
Master copies of student activity pages included in this section are as follows:

- **Zebra Mussel Biology**
- **Zebra Mussel Critical Habitat Needs**
- **Zebra Mussel Impacts**
- **Zebra Mussel Site Report**
- **Zebra Mussel Action Plan Outline**
- **Zebra Mussel Study Site Data Cards** (9 pages)
- **Follow-Up Ideas**

NOTE TO TEACHERS AND STUDENTS:
It is against Virginia state law to import live zebra mussels or any other non-indigenous (exotic) species into the state. No activity in this curriculum involves the use of live zebra mussels. Due to the danger of accidental introduction and the strict laboratory controls required for their use, live exotic species are not recommended for student research.

Zebra Mussel Impacts

Zebra mussels can reproduce in large numbers in suitable habitats. Although individual zebra mussels are small, they attach to each other to form large colonies which grow on almost any solid underwater material. These colonies can grow to contain as many as 100,000 mussels per square meter!

Large populations of zebra mussels in many parts of the United States can cause serious problems, such as the following:

- Clog intake pipes in water treatment plants, power generating plants, and industrial facilities, reducing water flow and causing occasional shutdowns
- Attach to pier pilings, navigational buoys and markers, and docks, interfering with navigation and increasing corrosion
- Grow on boat hulls and inside engine systems, decreasing fuel efficiency and damaging engines
- Attach to shells of native freshwater mussels, weakening or killing them by interfering with the mussels' ability to open or close their shells, as well as competing for food
- Filter large amounts of phytoplankton from the water, reducing food available for other filter-feeding organisms and many fish

Zebra Mussel Critical Habitat Needs

water temperature	6 - 28°C (spawn at 12 - 23°C; die above 30°C)
pH	7.4 - 9.4
salinity	less than 5 parts per thousand (ppt)
calcium (from $CaCO_3$)	greater than 20 parts per million (ppm)
substrate	need firm surface for attachment

NOTE: Larval forms are more sensitive than adults, especially to cold water temperatures.

Zebra Mussel Biology

The zebra mussel is a freshwater bivalve mollusk, originally found in Europe in the Caspian, Aral, and Black seas. Adult zebra mussels range from 0.5 to 3.5 cm long. The zebra mussel's scientific name is *Dreissena polymorpha.* The name *polymorpha* refers to the many individual variations in the color and pattern of the shell. Most zebra mussels have striped shells, but some are solid black or brown.

Zebra mussels feed on plankton, including algae, bacteria, larval animals, and other tiny particles of organic matter suspended in the water. The mussel pumps water into its body through a siphon tube and filters out the food. The water is pumped out through a second siphon. An adult zebra mussel filters an average of one liter of water each day.

Although they are freshwater animals, zebra mussels can survive in slightly brackish water (0.5 parts per thousand). Some adult zebra mussels have survived for several days in water with salinities as high as 12 parts per thousand under controlled laboratory conditions.

Zebra mussels grow and reproduce best in water which is 12 to 26°C with a calcium content of at least 20 parts per thousand. The calcium is important for the growth and maintenance of the shell.

Zebra mussels are either male or female. Mature females can produce 30,000 eggs each year.
Some females have produced as many as one million eggs per year. Spawning occurs when water temperatures warm to 12 to 23°C. If the water temperature remains suitable, spawning may occur several times during the season.

A fertilized zebra mussel egg becomes a microscopic, planktonic larva. The larval mussel spends two to three weeks swimming about, feeding on phytoplankton. During this stage, downstream currents can easily transport the larval zebra mussel from one body of water to another.

About two to three weeks after hatching, the larva begins to settle to the bottom. To survive, it must settle on a hard surface. Almost anything will do, including rocks, pier pilings, boats, concrete, or another animal's shell. It attaches to the surface with strong fibers called byssal threads. Zebra mussels frequently grow in large colonies, with hundreds of individuals attached to an object and to each other.

Zebra mussels can crawl from place to place by secreting temporary byssal threads which the mussels attach and detach as they move along.

Zebra Mussel Site Report

Location of zebra mussel study site:

Names of study team members:

1. The chance that zebra mussels will be introduced to this site is (circle one):

   low moderate high

   What specific facts and information about zebra mussels and about the study site led you to this conclusion?

2. If zebra mussels are introduced, the chance that they will survive and successfully reproduce in this site is (circle one):

   low moderate high

   What specific facts and information about zebra mussels and about the study site led you to this conclusion?

3. List three specific actions which your group feels people should take to prevent the introduction of zebra mussels into this site.

Zebra Mussel Action Plan Outline

Names of team members:

Location of zebra mussel study site:

Chance that zebra mussels will become introduced at this site (see your "Zebra Mussel Site Report" form):

low　　　moderate　　　high

Chance that zebra mussels will survive and successfully reproduce in this site:

low　　　moderate　　　high

Your team is responsible for developing an action plan which will help reduce the chances that zebra mussels will be introduced in your study site. As a team, discuss the following questions (be sure to have your team's recorder take notes during the discussion):

What groups of people (your "target audience") will need to know about zebra mussels?

What will each group of people need to do to help keep zebra mussels out of the area?

How will you communicate this information to each group in your target audience?

How will you pay for developing and conducting your activities?

What can you do to find out if your action plan is successful?

Use your answers to these questions to develop your action plan. Prepare a 5 - 10 minute presentation to give to the rest of the class which describes what your group wants to do. Include a written summary of the plan as well as charts, posters, or other items which will help explain your ideas.

Follow-Up Ideas

Classroom Activities

1. Work with your group to design a method to remove zebra mussels from one of the following areas:

   Small lake used for swimming, fishing, and boating

   Water treatment facility which provides water for an entire community, including homes, schools, businesses, hospitals, and industries

   Stream which supports a population of a freshwater mussel which is important to the local economy (its shells are exported to Japan for use in the cultured pearl industry)

   Consult the supplementary materials in this packet for information on zebra mussel control. As you design your control method, consider the following:

   Some control methods which kill zebra mussels may also be harmful to native freshwater mussels, fish, aquatic plants, and other organisms. How will you make sure your method will not be harmful to other organisms in the area?

   What will you do with the zebra mussels that you destroy?

   If drinking water supplies are affected, how will you avoid contaminating the water with chemicals and with dead zebra mussels?

   Describe your control method in writing, or present a report to the class. You may want to draw diagrams and pictures or build a model to show how your control method will work.

2. Design a poster which educates recreational boaters, fishermen, and other users of lakes and streams about the zebra mussel problem. In addition, develop a bumper sticker or T-shirt design using the zebra mussel theme.

3. Produce a public service announcement for television which informs people about the zebra mussel problem. Videotape or present the announcement live to the rest of the class.

4. Write a short play or skit with a zebra mussel as the main character.

5. If you have access to a computer and a telecommunication network, contact students who live in an area where zebra mussels have become established (see range map in "The Zebra Mussel: An Unwelcome North American Invader"). Find out what people in their community are doing about the problem. If you cannot use a computer to communicate, write letters.

Field Activities

1. Visit your local water treatment facility or electric power plant to find out how the operators keep the water intake areas free of debris, animals, plants, etc. It is usually possible to schedule a tour for a group if you call in advance.

2. Take a walk around your school, a local park, or your yard. List the plants and animals which were introduced from another part of the United States or another country. A horticulture teacher, science teacher, botanist, or garden club member might be able to help you with the survey.

3. Call a local greenhouse or plant nursery and ask if your class can schedule a visit to learn about the types of plants which are grown and sold there. How many of these are native plants? What different parts of the world have provided us with some of our most common house and garden plants? What are the advantages and disadvantages of cultivating native vs. exotic plants?

4. Many exotic animals have been intentionally brought into the United States. These animals may have been imported for pets, for hunting, or for control of other species. Contact state and federal wildlife and agriculture departments for information on regulations which control the importation of exotic animals into your state. Local pet stores should also be able to explain how they are required to follow regulations concerning the sale of exotic species.

5. Many plants which originated in the Americas, including corn, tomatoes, and "Irish" potatoes, have been introduced to Europe and Africa. What impacts have these exotic species had on the economies and ecosystems of these areas?

6. Get involved in a water quality monitoring project to learn how to measure mineral content, pH, temperature, and other water conditions. Many communities have organized groups which monitor water quality in specific sites. Contact the following organizations for information on citizen water quality monitoring:

Jay West
Save Our Streams (SOS)
Izaak Walton League of America
1401 Wilson Blvd., Level B
Arlington, VA 22209
(703) 528-1818

Kathleen Ellett, Monitoring Director
Alliance for the Chesapeake Bay, Inc.
6600 York Road , Suite 100
Baltimore, MD 21212
(410) 377-6270

Global Rivers Environmental Education
Network (GREEN)
721 East Huron
Ann Arbor, MI 48104
(313) 761-8142

Zebra Mussel Study Site No. 1 James River at Richmond, VA

The land area which drains into the James River has many large lakes and reservoirs with heavy recreational use. There are over 90 public boat ramps in the area, mostly on lakes.

1

Zebra Mussel Study Site No. 1 James River at Richmond, VA

Large ships traveling from freshwater ports in Europe frequently dock at the deepwater port in Richmond. There is also heavy barge and boat traffic between the James River and other tributaries of the Chesapeake Bay.

2

Zebra Mussel Study Site No. 1 James River at Richmond, VA

Each year, professional bass fishing tournaments are held near Richmond on the tidal freshwater portions of the James. Most of these fishing boats are brought to the tournaments on trailers. The boats may have been in lakes and rivers throughout the country only a day or two earlier.

3

Zebra Mussel Study Site No. 1 James River at Richmond, VA

The water monitoring site closest to Richmond is near Cartersville. The pH of the James River at this site in August is 8.1. The calcium content of the river near Cartersville is about 22 ppm.

4

Zebra Mussel Study Site No. 1 James River at Richmond, VA

In areas where the mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of water for two to three days under certain environmental conditions.

5

Zebra Mussel Study Site No. 1 James River at Richmond, VA

Free-swimming zebra mussel larvae can survive for several days or even weeks in the ballast water of ships. Under some conditions, they can also survive for days in water contained in bait buckets, live wells, boat trailer frames, and other enclosed areas in boats and ships.

6

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

Large vessels travel regularly into the Potomac River from the Great Lakes area. For example, according to officials at one dock terminal, cargo ships from Quebec City on the St. Lawrence River arrive in Alexandria six or seven times a year.

1

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

The pH of the Potomac River near Alexandria is 8.1 - 8.4 from May to September. Calcium content of the Potomac River near Alexandria is 32 - 40 ppm.

2

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

Many zebra mussels live in the St. Lawrence River near Quebec City in Canada.

3

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

Free-swimming zebra mussel larvae can survive for several days or even weeks in the ballast water of ships. Under some conditions, they can also survive for days in water contained in bait buckets, live wells, boat trailer frames, and other enclosed areas in boats and ships.

4

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

Alexandria is the largest port in the freshwater portion of the Potomac River. No one knows the volume of ballast water dumped by ships in the port at Alexandria. Commercial and recreational traffic into the Potomac estuary from neighboring estuaries is very high.

Zebra Mussel Study Site No. 2
Potomac River at Alexandria, VA

The Potomac is the Virginia estuary which is closest to the Susquehanna River. Zebra mussels are living in the Susquehanna River in the vicinity of Johnson City, NY.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

Smith Mountain Lake is a large reservoir on the headwaters of the Roanoke River near the city of Roanoke.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

The pH of Smith Mountain Lake in the summer ranges from 7.6 to 9.1.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

Smith Mountain Lake is heavily used for recreational boating and fishing. There are 17 public boat ramps and a very popular state park located on the lake.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

The calcium level of Smith Mountain Lake is about 15 - 17 ppm.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

A large professional bass tournament is held annually on Smith Mountain Lake. Participants travel from all over the country to compete, and bring their own boats on trailers.

Zebra Mussel Study Site No. 3
Smith Mountain Lake

In areas where the mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of the water for two to three days under certain environmental conditions.

Zebra Mussel Study Site No. 4
Rappahannock River

Along the Rappahannock there are several reservoirs which are used for recreational boating and fishing. There are 11 public boat ramps in the freshwater portion of the river.

1

Zebra Mussel Study Site No. 4
Rappahannock River

Near Fredericksburg, the Rappahannock River has a pH of 7.8 (measured in August).

2

Zebra Mussel Study Site No. 4
Rappahannock River

Boat traffic into the Rappahannock from other estuaries is low to moderate. Residential development surrounds several large, private reservoirs in the Rappahannock drainage area.

3

Zebra Mussel Study Site No. 4
Rappahannock River

Calcium levels of the Rappahannock in August have been measured at 5.2 ppm.

4

Zebra Mussel Study Site No. 4
Rappahannock River

Free-swimming zebra mussel larvae can survive for several days or even weeks in the ballast water of ships. Under certain conditions, they can also survive for days in water contained in bait buckets, live wells, boat trailer frames, and other enclosed areas in boats and ships.

Zebra Mussel Study Site No. 4
Rappahannock River

Currents moving downstream from one body of water to another can easily transport larval zebra mussels.

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

Kerr Reservoir and Lake Gaston are on the Roanoke River. Both lakes are heavily used for recreational boating and fishing.

1

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

Water chemistry varies from place to place in both Lake Gaston and Kerr Reservoir. Scientists have recorded pH readings of 6.9 - 9.3 in parts of both lakes.

2

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

Currents moving downstream from one body of water to another can easily transport larval zebra mussels.

3

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

Scientists have measured calcium levels in Lake Gaston at 24 - 44 ppm. Data on calcium levels in Kerr Reservoir are not yet available.

4

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

Several public-access reservoirs with a total of 80 public boat ramps are located upstream from both lakes.

Zebra Mussel Study Site No. 5
Kerr Reservoir and Lake Gaston

In areas where the mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of the water for two to three days under certain environmental conditions.

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

The Mattaponi and Pamunkey rivers flow together at West Point to form the York River. The York River has a salinity of about 5 ppt at West Point.

1

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

Free-swimming zebra mussel larvae can survive for several days or even weeks in the ballast water of ships. Under some conditions, they can also survive for days in water contained in bait buckets, live wells, boat trailer frames, and other enclosed areas in boats and ships.

2

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

Large barges and ships travel up and down the York River to and from a large paper mill in West Point. The barges travel between West Point and the Eastern Shore of Virginia. The ships travel from a number of ports in northern Europe, Canada, and South America.

3

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

At the Beulahville monitoring site northeast of Mangohick, scientists measured the pH of the Mattaponi in July at 6.9. Calcium content was 3.7 ppm.

4

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

The Mattaponi River has several freshwater reservoirs upstream from West Point. These reservoirs are used for boating and fishing. Lake Anna, a large freshwater reservoir in the Pamunkey River drainage, is also a popular boating and fishing site.

Zebra Mussel Study Site No. 6
Mattaponi and Pamunkey Rivers

In June at the Hanover monitoring site, scientists recorded pH readings for the Pamunkey at 6.9. Calcium content was 9 ppm.

Zebra Mussel Study Site No. 7
Lake Anna

Lake Anna, the largest reservoir in the Pamunkey River drainage, is a very popular site for recreational fishing and boating. There are nine public access boat ramps on the lake.

1

Zebra Mussel Study Site No. 7
Lake Anna

Larval zebra mussels can easily be transported by currents moving downstream from one body of water to another.

2

Zebra Mussel Study Site No. 7
Lake Anna

The pH of Lake Anna measures 7.9 in some branches of the lake during the summer, but most of the lake has a pH of slightly less than 7.0.

3

Zebra Mussel Study Site No. 7
Lake Anna

There is a nuclear power plant located on Lake Anna which requires large amounts of water for its operation.

4

Zebra Mussel Study Site No. 7
Lake Anna

The greatest calcium content measured in Lake Anna waters is 6.0 ppm.

5

Zebra Mussel Study Site No. 7
Lake Anna

In areas where the mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of the water for two to three days under certain environmental conditions.

6

Zebra Mussel Study Site No. 8
Claytor Lake

Claytor Lake has heavy recreational use. There are eight public boat ramps on the lake, and eight more are located on the New River upstream.

1

Zebra Mussel Study Site No. 8
Claytor Lake

The calcium level in Claytor Lake is usually low, around 9.0 to 10.0 ppm. However, in some years, the calcium has been measured at 30.0 ppm.

2

Zebra Mussel Study Site No. 8
Claytor Lake

Claytor Lake hosts numerous fishing tournaments. Participants travel with their boats to Claytor Lake from many areas outside of Virginia.

3

Zebra Mussel Study Site No. 8
Claytor Lake

Claytor Lake was built as a reservoir to provide water for a hydroelectric power plant.

4

Zebra Mussel Study Site No. 8
Claytor Lake

The pH of surface waters in Claytor Lake in June ranges from 7.3 to 9.3.

Zebra Mussel Study Site No. 8
Claytor Lake

In areas where the mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of the water for two to three days under certain environmental conditions.

Zebra Mussel Study Site No. 9
South Holston Lake

South Holston Lake is located near Abingdon on the South Fork of the Holston River. The Holston is a tributary of the Tennessee River.

1

Zebra Mussel Study Site No. 9
South Holston Lake

The pH of South Holston Lake has been measured at 6.9 to 8.6 in June and July.

2

Zebra Mussel Study Site No. 9
South Holston Lake

South Holston Lake is only a few hundred miles from other lakes in the Tennessee River system. Zebra mussels are living and successfully reproducing in the Tennessee River.

3

Zebra Mussel Study Site No. 9
South Holston Lake

Calcium levels in South Holston Lake range from 18 to 30 ppm.

4

Zebra Mussel Study Site No. 9
South Holston Lake

There are 16 public boat ramps on South Holston Lake and two more upstream on Hungry Mother Lake.

Zebra Mussel Study Site No. 9
South Holston Lake

In areas where mussels thrive, adult zebra mussels frequently attach to boats and trailers. These mussels can live out of the water for two to three days under certain environmental conditions.