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THE POTENTIAL FOR USING BIOLOGICAL CONTROL TECHNOLOGIES IN THE MANAGEMENT OF *DREISSENA* SPP.

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ABSTRACT Broadly defined, biological control is the use of one species for the suppression of another. Two groups of organisms have potential as Dreissena control agents: selectively toxic microbes and natural enemies. Selectively toxic microbes are naturally occurring soil and water microorganisms that simply by chance happen to be toxic to *Dreissena.* Applied at artificially high densities to water, the microbial cells *per se* or their released metabolites are selectively lethal to *Dreissena.* In contrast, natural enemies are organisms that, by their evolutionary nature, will debilitate or kill *Dreissena,* including predators, parasites (both multicellular and microbial), and benthic competitors (organisms capable of competitively displacing *Dreissena* from substrates).

Selectively Toxic Microbes: In the short run, these microorganisms represent the most promising candidates as biological control agents, The use of highly-specific, toxic microbes has a clear record of commercial success and environmental safety in the control of invertebrate pests in North America. and strains lethal to *Dreissena* have been already isolated. Considering how quickly a selectively toxic microbe could move from the laboratory to commercialization, continued research to develop this microbial control strategy is a high priority.

Natural Enemies; In North America, as in Eurasia, there will likely be isolated field reports of major impacts by natural enemies, and, on the whole, we will likely see a cumulative effect of a complex of enemies having a constant, but limited, role in naturally suppressing *Dreissena* populations. In the majority of cases, *Dreissena* populations will cause economic and ecological effects at densities well below those that their enemies could *naturally* maintain. This does not mean, however. that certain natural enemies could not be *artificially manipulated* (e.g., mass produced and released in an inundative fashion) to cause major *Dreissena* reductions.

1. *Parasites:* These natural enemies would likely be the most environmentally-safe biocontrol agents, due primarily to their high host specificity. Comprehensive investigations to identify parasites that are strictly specific to *Dreissena* and that can be economically mass produced are a key research priority. Parasites from *Dreissena's* native Eurasian range should be studied to identify species that would be "nearly risk free" candidates for importation into North America. Research to uncover parasites of *Dreissena* that are already present in North America should be intensified.
2. *Predators:* Although organisms, such as fish and birds, have sometimes been documented to consume *Dreissena* at high rates, this does not necessarily mean that they would be effective candidates for use in control programs. Predators are typically not specific enough in their prey choices. A predator introduced to a waterbody from outside its natural range may highly prefer *Dreissena* as a prey item, but will also consume other aquatic organisms. The consumption of such nontarget prey could potentially have serious, adverse, ecological impacts.
3. *Benthic Competitors;* In addition to being micro/macrofouling organisms themselves, the lack of specificity of species that can competitively displace *Dreissena* from substrates (e.g., sponges) significantly reduces their potential as biocontrol agents.

KEY WORDS: Zebra mussels, quagga mussels, selectively toxic microorganisms, natural enemies, predators, parasites, benthic competitors

INTRODUCTION

The introduction of zebra mussels, *Dreissena polymorpha,* and quagga mussels, *Dreissena bugensis,* into North America just over a decade ago and their spread through inland waters have resulted in a variety of serious, adverse impacts. Because of their ability to colonize hard substrates, these mussels can be a major macrofouler for raw water-dependent infrastructures, causing damage and increased operating expenses worth hundreds of millions of dollars (O'Neill 1996, O'Neill 1997). The following passage provides an overview of the types of problems encountered in raw water systems (U.S. Army Engineer Waterways Experiment Station 1995):

> "Zebra mussels could render inoperable miter gates on locks, fire prevention systems..., reservoir release structures, navigation dams, pumping stations, water-intake structures, dredges, and commercial and recreational vessels. Materials and equipment, such as small-diameter pipes, seals, valves, gears, air vents, weep holes, screens, trash racks, chains, pulleys, and wire ropes are vulnerable."

In open waters, *Dreissena* has also caused significant ecological impacts, including increased transparency, decreased seston, decreased chlorophyll, decreased primary phytoplankton productivity, increased macrophytes, increased native bivalve mortality, and restructured benthic communities (MacIsaac 1996, Karatayev et al. 1997).

People sometimes speak of the quest for the "silver bullet" for *Dreissena* control- a single, economical, environmentally-safe, and effective control method. Of course, this is unrealistic since no single control method will be the practical solution in all situations. Solving *Dreissena* problems requires implementation of a wide range of integrated pest management strategies. A variety of approaches (e.g., filtration, mechanical cleaning, coatings, selective pesticides, etc.) must be used separately and in combination to achieve effective and environmentally-compatible control in raw water-dependent infrastructures (Claudi and Mackie 1994). The potential use of biological control methods in this integrated pest management effort in such infrastructures, as well as in open waters, is the focus of this paper.

BIOLOGICAL CONTROL APPROACHES

A successful pest control method is one that is effective, affordable, and safe. Although broad-spectrum, synthetic chemicals have been the traditional approach to pest management, their affects on human health and the environment have fostered the development of optional control approaches. One such alternative is biological control-a method that has proven to be an economical and environmentally acceptable tool in the integrated management of many pest species (Debach and Rosen 1991, Crawley 1992a, Rodgers 1993).

Broadly defined, biological control is the use of one species for the suppression of another. Two groups of organisms have potential as *Dreissena* control agents: selectively toxic microbes and natural enemies.

Selectively Toxic Microbes

These are not parasites of *Dreissena,* but rather naturally occurring soil and water microbes that simply by chance happen to be toxic to *Dreissena.* Applied at artificially high densities to water, these microbial cells *per se* or their released metabolites are selectively lethal to *Dreissena.* Commercial products based on such toxic microbes have the potential to be effective irrespective of whether they contain dead or live cells (Gaertner et al. 1993).

Natural Enemies

These are organisms that by their evolutionary nature will debilitate or kill *Dreissena,* including predators, parasites (both multicellular and microbial), and benthic competitors (i.e., organisms capable of competitively displacing *Dreissena* from substrates). The vast majority of species that are natural enemies in Eurasia are not present in North America, but ecologically similar organisms do exist, particularly among the predators (Molloy et al. 1997). *Dreissena* is a novel and abundant organism for these North American species, and they have become the new natural enemies of *Dreissena.*

SELECTIVELY TOXIC MICROBES

Why would one look to naturally occurring, nonparasitic microbes as a novel strategy for *Dreissena* management? It is widely accepted that screening of the diverse biochemicals found in tropical plant species is a worthwhile activity because of the discovery of drugs that can prevent or cure animal diseases, particularly cancers. Production of these biochemicals, however, did not evolve in these plants for this purpose, and the effect of these plant substances on animal diseases is purely coincidental. Using the same logic, we can also look to microorganisms for unique biochemicals that have potential as highly selective pesticides. The use of selectively toxic microbes has a clear record of commercial success and environmental safety in the control of invertebrate pests in North America, as well as globally. Sales of the selectively toxic bacterium *Bacillus thuringiensis* for insect control represent over 90% of the current international biocontrol market (Rodgers 1993). Individual subspecies of *B. thuringiensis* are highly specific to targeted pests. The use of one subspecies, *B. thuringiensis israelensis (Bti),* has become the most environmentally-safe and effective method ever developed for the control of two aquatic invertebrate pests-blackflies (Simuliidae) and mosquitoes (Culicidae) (Molloy 1990, Entwistle et al. 1993). The toxic activity of *Bti* to blackfly and mosquito larvae is caused by particulate, proteinaceous crystals that are formed during bacterial sporulation. *Bti,* although a highly lethal bacterium to larval blackflies and mosquitoes, does not kill them in nature because it is very rare. Applied at artificially high densities to waters in which these fly larvae live, however, these filter-feeding invertebrates concentrate the bacterial protein particles from the water column and typically die within 24 h. Like chemical pesticides, *Bti* and other selectively toxic microbes give only short-term control and require periodic reapplication. In stark contrast to chemical pesticides, however, selectively toxic microbes pose no problems with biomagnification of any toxic residues along the food chain and are significantly more difficult for pests to develop resistance to.

In North American blackfly control programs, chemical pesticides have been essentially replaced by *Bti,* as for example, in the Adirondack Mountains of New York State, where *Bti* is annually applied to streams and rivers in over 3,000 km^2. The State of Pennsylvania has the largest North American Bti-blackfly control program, with an annual operational budget of ca. 4 million dollars (D. Arbogast, pers. comm.). Both *Dreissena* and larval blackflies are lotic, filter-feeding invertebrates, and thus, the protocols for the control of *Dreissena* with selectively toxic microbes could someday be adapted from those currently used for blackfly control with *Bti.*

Unreliable and inconsistent performance of biological control agents has often resulted from insufficient knowledge of the parameters affecting their performance, including both environmental (e.g., pH, temperature, etc.) and ecological (e.g., relative susceptibility of pest life stages) variables. In this regard, the relative insensitivity of toxic-microbe preparations to these variables has been one of the keys to their commercial success (Rodgers 1993). *Bti* applications, for example, are capable of killing blackflies of all larval instars and at all water temperature and pH values.

Use of selectively toxic microbes is a small, but growing, portion of the pest control business. Sales of biocontrol agents (primarily selectively toxic microbes) account for about 1% ($120 million) of all global pesticide sales (Powell 1993) but are annually increasing at a rate of 10-25%, whereas the world chemical pesticide market is static-to-shrinking (Rodgers 1993). One major reason is the relatively high expense of a chemical pesticide's research and development. Due primarily to the costs of nontarget safety testing, the average budget of bringing a single chemical pesticide to market is about $20-40 million (Marrone and MacIntosh 1993) versus $2 million (Rodgers 1993) for a biocontrol agent. Thus, the relatively low cost of biocontrol research and development is a plus for commercial development.

Shortly after the discovery of *Dreissena* in North America, it was hypothesized that microorganisms existed in nature that could be selectively toxic to this new bivalve invader (Molloy 1991). Over the last 8 years, several North American laboratories have been actively involved in the screening of hundreds of microorganisms (primarily bacteria) to find strains useful for *Dreissena* control. Gu et al. (1997) have explored the incorporation of selectively toxic bacterial metabolites into coatings to deter attachment. Other North American scientists have focused more on applying such bacteria directly to water for *Dreissena* control (Molloy and Griffin 1992, Singer et al. 1997, Genthner et al. 1997). In this regard, recent trials with bacterial strain CL0145A, an isolate from a North American river, have been particularly encouraging (Molloy, unpublished data). Treatment of *Dreissena* with strain CL0145A routinely achieved 80-100% kill in the laboratory, yet without any mortality to unionid mussels. To test for field effectiveness, a small-scale trial was conducted under once-through conditions within a hydroelectric station on the Mohawk River in New York State. This trial achieved a 94% kill and represented the first, successful demonstration of the feasibility of using a biological agent for *Dreissena* control within a raw-water dependent infrastructure. As a result of these successful laboratory and field trials, a patent application for the use of strain CL0145A has been filed. Because of the commercial success of using selectively toxic microbes for the environmentally safe control of other invertebrates, the potential of this approach for *Dreissena* control should not be underestimated.

NATURAL ENEMIES

Predators, parasites, and benthic competitors are well documented for *Dreissena.* In their review of the international literature on natural enemies of *Dreissena,* Molloy et al. (1997) cited q76 species involved in predation, 34 in parasitism, and 10 in competitive exclusion of *Dreissena.* As *Dreissena* increases its geographical range in North America, the number of species that can be listed as natural enemies will constantly increase as organisms make their initial contact with *Dreissena;* this will be particularly true for molluscivores.

Natural enemies in North America, particularly predators, undoubtedly are exerting a suppressive influence on *Dreissena* population densities, but to what extent is unclear. While seasonal and localized reductions of *Dreissena* densities by natural enemies have been documented, the high recruitment rate typical of *Dreissena* populations inherently makes them very difficult for natural enemies to control over the long term. One theory holds that *Dreissena,* being a nonindigenous pest, quickly reached high population densities in the Great Lakes and elsewhere primarily because of the absence of an established natural enemy complex. The ability of natural enemies to regulate prey populations, however, depends on the prey's rate of increase. If the net rate of increase is too great, then the prey population can escape control. No matter what functional and numerical responses are mounted by natural enemies, they simple cannot keep up with prey reproduction (Crawley 1992b). Molloy et al. (1997) concluded that in North America, as in Eurasia, there will likely be isolated reports of major impacts by natural enemies, and on the whole, we will likely see a cumulative effect of a complex of enemies having a constant, but limited, role *in* suppressing *Dreissena* populations.

The classical biological control approach involves the release of a nonindigenous pest's imported natural enemy and assumes that this natural enemy will proliferate on its own and, in the long term, lower pest densities to levels below economic and/or ecological thresholds (Debach and Rosen 1991). Such a classical approach is not likely to work for the control of *Dreissena* in North America. This approach certainly has a successful track record for other nonindigenous pests (both animals and plants)-specifically those which have little to no adverse ecological or economic impact in their native range since their densities there are kept "low" by their natural enemy complex. Evidence to date suggests that this is *not* the case with *Dreissena* spp. in their Eurasian range. Because of the relative lack of "complaints" from overseas raw-water users about *Dreissena* problems, there is a misconception among North Americans that *Dreissena* densities are naturally "low" in Eurasia. This is not the case. Complaints about *Dreissena* are infrequent in Eurasia because raw-water users have had over a century to find solutions to these macrofouling bivalves. In reality, *Dreissena* population dynamics, densities, and biomass in Eurasian waterbodies are far more similar to those in North American waters than generally thought. Like in North America, when introduced into European freshwaters, is not unusual for *Dreissena* to become enormously abundant in a short time, obtaining a biomass 10 times greater than that of all other native benthic invertebrates (Karatayev et al. 1997). Thus, in the vast majority of Eurasian waterbodies. it does not appear that *Dreissena's* natural enemies keep their densities low enough to avoid ecological or industrial problems. Thus, until a natural enemy can be identified from Eurasia that naturally suppresses *Dreissena* populations to levels below economic or ecological impact thresholds, it would not be worthwhile to attempt a classical biocontrol release in North America. The question remains, however, as to whether certain natural enemies could, both in Europe and North America, be *artificially manipulated* to give satisfactory control of *Dreissena.* This will be discussed below for each type of natural enemy.

Predators

What types of organisms prey on *Dreissena?* Combining North American and Eurasian records, birds (36 species) and fish (15 species eating veligers and 38 species eating attached mussels) have been the most commonly reported predators (Molloy et al. 1997). The number of fish and bird species that have been documented as predators can be misleading, however, since most literature references contain records of only occasionally finding a few *Dreissena* in the stomachs of the predators listed. Records of field-documented predation also include copepod and coelenterate consumption of pelagic larvae, and observations of leeches, crabs, crayfish, and mammals eating attached mussels (Molloy et al. 1997).

Birds have been the most intensively studied natural enemies of *Dreissena* (Molloy et al. 1997). Consumption of attached *Dreissena* has been recorded for at least 21 species in Eurasia and 20 in North America. Only five species-Greater Scaup[1] *(Aythya marila),* Goldeneye (Bucephala *clangula),* Oldsquaw *(Clangula hyemalis),* Herring Gull *(Larus argentatus),* and White-Winged Scoter *(Melanitta fusca)* -have been observed eating *Dreissena* both in Eurasia and North America. Five diving ducks-Tufted Duck *(Aythya fuligula),* Pochard *(Aythya ferina),* Greater Scaup *(Aythya marila),* Lesser Scaup *(Aythya affinis),* and Goldeneye *(B. clangula)*- and one diving-rail, the Coot *(Fulica atra),* are the most well documented avian predators of *Dreissena* (Molloy et al. 1997).

Molloy et al. (1997) indicated that 10 Eurasian and 5 North American fish species within five families have been field-documented as containing planktonic *Dreissena* larvae in their alimentary tracts: Cyprinidae (7 species), Clupeidae (3 species), Osmeridae (2 species), Percidae (2 species), and Percichthyidae (1 species). Consumption of *Dreissena* attached to substrates has been recorded for at least 13 fish families, including 14 species within 10 families in North America and 27 species within 9

[1] Common names of individual bird species are capitalized in this paper as is the traditional practice in scientific literature.

families in Eurasia. Only three species-the common carp *(Cyprinus carpio),* pumpkinseed *(Lepomis gibbosus),* and round goby *(Neogobius melanostomus)*- have been field-documented as predators on both continents. Another 13 North American fish species have been mentioned in the literature as potential predators, based primarily on their documented feeding on other bivalve species in the field (Molloy et al. 1997).

Although predators, particularly fish and birds, have been documented on occasion to consume *Dreissena* at high rates (Molloy et al. 1997) this does not necessarily mean that they would be effective biocontrol agents. Practical constraints and ecological considerations are essential to implementation of a successful biocontrol project. Past biocontrol failures have made it very clear that extreme care must be exercised not to introduce a natural enemy that is not relatively host specific. In this regard, generalist natural enemies with wide host ranges can not be seriously considered. Predators are typically not highly specific in their prey choices. There is, for example, no known predator (nor does one likely exist) that consumes only *Dreissena* (Molloy et al. 1997). Thus, a fish introduced to a waterbody from outside its natural range may prefer *Dreissena* as a prey item, but will also consume other aquatic organisms (likely other molluscs). Such predators may reduce *Dreissena* population densities, but their consumption of nontarget prey could potentially cause serious, adverse ecological impacts. After their introduction, these predators would likely successfully reproduce and spread to other waterbodies where their presence might be undesirable. If technically and economically feasible, blocking reproduction among such introduced predators (e.g., stocking with sterile animals or those of a single sex) might possibly make their use acceptable in limited situations.

Besides their lack of prey specificity, predators have other characteristics which are likely to severely limit their usefulness as biocontrol agents. Predators would not likely provide the quick mussel kill typically desired in the infrastructures of raw water users. The financial cost of obtaining large numbers of predators (mass production?, mass harvesting from other areas?, etc.) to treat Dreissena-infested waterbodies would likely be economically prohibitive. In addition, all currently known predators would be completely impractical for use in reducing mussel densities in the majority of confined *Dreissena* habitats within raw water infrastructures (e.g., pipes).

Could existing, indigenous predator populations be managed in their present habitats to maximize the role they naturally play in *Dreissena* control? French (1993) suggested that resource agencies should manage populations of drum, sunfish, and redhorse to improve their habitats and to reduce exploitation of large individual fish (i.e., the size that preys most intensively on *Dreissena).* Similarly, McMahon et al. (1994) also suggested improving habitat conditions for desired predators so that their populations would increase at a gradual rate and would be sustained through periods of reduced food. The technical and economic feasibilities of these ideas remain to be tested.

Parasites

A wide diversity of endosymbiotic organisms can be found within the mantle cavity or within the organs/tissues of *Dreissena,* but which have potential as biocontrol agents? Molloy et al. (1997) discussed 34 species as parasites-all of which were reported from attached mussels (i.e., none from pelagic larvae). Their definition of "parasites," however, was intentionally broad and included a number of organisms whose symbiotic relationships with *Dreissena* still remain unclear (e.g., possibly mutualism or commensalism).

Species of obligate, strictly host-specific ciliates in the orders Scuticociliatida *(Conchophthirus acuminatus* and *Conchophthirus klimentinus)* and Rhynchodida *(Hypocomagalma dreissenae, Sphenophrya dreissenae,* and *Sphenophrya naumiana)* are known from the mantle cavity and at least one species in the order Hymenostomatida (suborder Ophryoglenina) from the digestive gland (Molloy et al. 1997). The nature of the symbiotic relationships of these ciliates appears to range from commensalism (scuticociliatid ciliate species) to parasitism (rhynchodid and hymenostomatid ciliate species). In a personal communication from S. Kazubski appearing in Stanczykowska (1977), the hymenostomatid ciliates were reported as naturally causing lethal infections in *Dreissena.* Thus, these host-specific parasitic ciliates may well have potential as biocontrol agents if they can be economically mass produced.

Seven genera of trematodes have been reported as parasites of *Dreissena* spp. (Molloy et al. 1997). In their life cycles, *Dreissena* can serve as the first intermediate host (e.g., for *Bucephalus poly morphus* and *Phyllodistomum* spp.), second intermediate host (e.g., for *Echinoparlyphium recurvatum),* or the only host (e.g., for *Aspidogaster* spp.). Those trematode species that use *Dreissena* as an intermediate host, usually subsequently develop in fish or waterfowl. Because of the potential adverse impact on these subsequent hosts, these trematode species have little potential as biocontrol candidates.

Whereas ciliates and trematodes are the most commonly reported parasites, a variety of other pathogenic organisms have been recorded from field samples, including suspected bacterial and ascetosporan infections (Molloy et al. 1997). Mites, nematodes, leeches, chironomids, and oligochaetes have also been observed to be associated symbiotically within the mantle cavity, but with little to no adverse effect. In laboratory trials, Toews et al. (1993) reported initiating lethal infections in *D. polymorpha* with Gram-negative bacteria.

Host specificity of a parasite is a key feature for selection of a biocontrol candidate. In nature, some parasites exhibit a broad host range, and thus it was expected that some indigenous North American parasites would be capable of infecting *Dreissena.* This appears to be occurring, as the few obligate parasites that have been found thus far in North American *Dreissena* are indigenous organisms whose hosts are native bivalves (i.e., aspidogastrid and plagiorchiid trematodes, Toews et al. 1993). The broad host range of these parasites essentially eliminates them from consideration as biocontrol agents. In contrast, many other parasites could be particularly safe control agents since they have been fine-tuned through evolution to be strictly host specific. But such host-specific parasites, however, can also have limitations as control agents. They often have complex growth requirements and elaborate life cycles, and these characteristics could represent obstacles toward their economical, *in vitro* mass production *(in vivo* mass production of parasites would likely be more expensive, thereby hindering commercialization).

High host pathogenicity is another feature desirable in a parasitic biocontrol agent. The Eurasian trematode *Bucephalus polymorphus* has been well documented as being seriously debilitating to *Dreissena* (i.e., it sterilizes them by destroying their gonads), but its use is out of the question since fish are also infected as part of its life cycle. A putatively lethal infection with ascetosporan protozoans has been reported from *D. polymorpha* populations in the Netherlands (Bowmer and van der Meer 1991; de Kock and Bowmer 1993). Infections were noted over a 3-year period in several rivers. The entire blood system-including the blood spaces of the digestive gland and gonad, the filamentary blood vessels of the gills, and the mantle-were observed to contain plasmodia, sporocysts, and spores. Infection often resulted in little or no remaining functional tissue in the digestive gland. Compared with the wide diversity of virulent parasites known from other bivalves, particularly commercially valuable marine species (Lauckner 1983, Sparks 1985, Sindermann 1990) the list of seriously debilitating *Dreissena* parasites is currently a short one. Before their arrival in North America, however, relatively little attention was paid to their diseases (Molloy 1992). Eurasian parasite records were almost all reports of "large" organisms easily detected during dissection (trematodes, ciliates, etc.). An intensive research effort employing histological techniques to detect diseases at the cellular level is now underway both in Europe and North America (Molloy, unpublished data), and this is likely to reveal a much broader assemblage of parasites, particularly pathogenic, intracellular, microbial species. Using parasites to debilitate *Dreissena* in its veliger stage (i.e., before settlement) would be an ideal control strategy, and a special effort should be made to detect the parasites (likely all intracellular) present in these pelagic larvae.

Comprehensive investigations to identify host-specific, quick-killing parasites suitable for *in vitro* mass production are also a research priority. Research to date has confirmed that many of the organisms living within the bodies of *Dreissena* do tend to be extremely host specific. The above-mentioned six species of ciliates, for example, have never been found in any other bivalve other than *Dreissena*. Research leading to the commercial development of a parasite as a control agent is typically a long-term process requiring exhaustive experimentation to verify host specificity prior to parasite release for control purposes. Commercially available parasite products, although a small component of global pesticides, do exist for control of other invertebrate pests, primarily insects, and include bacteria, fungi, nematodes, protozoans, and viruses (Rodgers 1993). Because many *Dreissena* parasites are strictly host-specific, the future use of parasites as biocontrol agents is not an unrealistic possibility.

The most effective use of parasites as biocontrol agents may be in an inundative fashion (Debach and Rosen 1991) where *Dreissena* spp. are simply overwhelmed by exposure to abnormally high concentrations of a parasite. The effect of a disease on a host (i.e., ranging from benign to lethal) is governed by a complex of factors, such as host physiological state, environmental stress, and parasite density within the host (Lauckner 1983). A parasite which normally causes a disease of low pathogenicity could actually induce a lethal infection if, for example, its density within the host was abnormally high. Thus, if parasites that are strictly host specific can be economically mass produced, they could be used to induce artificially high, intense infections, resulting in serious host debilitation and death. For this reason, parasites that are strictly host specific to *Dreissena,* yet which in nature have low pathogenicity, should not be excluded from consideration as potential biocontrol agents.

Benthic Competitors

Dreissena spp. tend to be the dominant invertebrates both in numbers and biomass in benthic communities, with their introduction often leading to the displacement of indigenous species (Karatayev et al. 1997). Attachment to a suitable substrate is essential to completion of their life cycle, but other organisms, however, have been reported to be capable of excluding *Dreissena* from substrates. Sponges, especially on vertical surfaces, can overgrow and kill *Dreissena* spp. by impairing normal mussel feeding and respiration (Ricciardi et al. 1995). Other benthic organisms recorded to successfully outcomplete dreissenids include amphipods, algae, bryozoans, hydrozoan coelenterates, and other bivalves (Molloy et al. 1997). None of these organisms, however, seem to have potential for use as a biocontrol agent, because of their lack of specificity and their own micro/macrofouling nature.

Benefits and Limitations of Biological Control with Natural Enemies

Not everyone, however, agrees that biological control using natural enemies (whether indigenous or not) is an attractive pest management approach. Its potential usefulness is often underestimated and its successes ignored by advocates of other control approaches. Biocontrol enthusiasts, however, can also lack objectivity and be unrealistic in their assessment of its potential, frequently overlooking its limitations. Compared with conventional, chemical pesticides, however, biocontrol with natural enemies does have some clear advantages (Debach and Rosen 1991):

- Natural enemies are generally less damaging to the environment since they are typically more specific to the target pest; chemical pesticides are typically broad spectrum, adversely affecting far more nontarget organisms; natural enemies of the pest may be some of the nontargets killed by chemical pesticides, potentially leading to increased pest densities;
- With natural enemies, there is less chance that a pest will develop resistance to the control agent;
- Research and development are typically less expensive with natural enemies and long-term pest control is sometimes possible from a single application.

Why have some biocontrol projects using natural enemies been failures, and what have we learned from these past mistakes? Overly expedient forays, for example, in the eighteenth and nineteenth centuries into the control of vertebrate pests with vertebrate predators were truly disastrous (Waage and Mills 1992). The introduction of mongooses onto islands to control rats resulted in these predators becoming pests themselves and clearly demonstrated that biological control agents would only be effective and safe if they were relatively specific to the target pest. Other biocontrol failures stemmed from erroneous taxonomic identifications of pests and/or their natural enemies (Waage and Mills 1992). These errors of the past are lessons for the future.

Importation of Natural Enemies

Although controversial, the possibility of importing nonindigenous organisms into North America should not be dismissed completely. Laboratory and field research to identify Eurasian parasites that are virtually 100% host-specific to *Dreissena* should be pursued. Before any natural enemy would ever be considered for actual use as a biocontrol agent in North America, research (both laboratory and field trials) within the Eurasian native range would have to be *intensively* performed to confirm that the natural enemy is, for all practical purposes, specific to *Dreissena.* Such overseas investigations are long-term, requiring years of research to ensure that the environmental risk of importing any natural enemy would be acceptable to North American regulatory agencies. In the interim, research to define the natural enemies of *Dreissena* that are already present in North America and might be useful as biocontrol agents should be conducted concurrently. It is not known, for example, if *D. polymorpha* or *D. bugensis* brought any of their parasites with them during their voyage to North America in ship ballast water. Before a parasite would ever be imported and released, it would be prudent to have exhaustively examined *Dreissena* populations in North America for disease organisms suitable for use as biocontrol agents.

Overseas investigations should include quantitative surveys to assess the full richness of *Dreissena's* natural enemy complex, the potential impact of its component species, and of paramount importance, the degree of host specialization. Current knowledge of the natural enemies of *Dreissena* has recently been summarized (Molloy et al. 1997). and such foreign explorations have been initiated (Molloy et al. 1996; Molloy, unpublished data). In the choice of a potentially useful natural enemy, generalists (e.g., non-host-specific predators or parasites) should be quickly eliminated from consideration since they would pose too great a risk to nontarget species. Importation would be followed by strict quarantine while laboratory safety trials on North American nontargets are conducted. Before any natural enemy could be used to control North American *Dreissena,* it would have to be free of any potentially harmful organisms from its native range. Once used, its possible establishment and impact on both *Dreissena* and nontarget populations would have to be carefully monitored.

CONCLUSIONS

The control of *Dreissena* populations in North America requires an integrated pest management approach, and biological control techniques could play a role in this process. Regulatory agencies, in response to public pressure, are demanding that control techniques have minimal environmental impacts- a factor that strongly argues in favor of target-specific, pest management approaches, such as biological control.

Research is required to understand, develop, enhance, and finally integrate biologically based pest management practices into the overall plan for *Dreissena* control, with the goal of reducing dependency on broad spectrum synthetic pesticides or other environmentally disruptive control methods. Specific recommendations are:

- Research on the development of highly specific, selectively toxic microbes should be continued; of all possible biocontrol agents, they are likely to be the first to be commercialized;
- Among natural enemies, host-specific parasites have the greatest potential for use as effective and environmentally safe control agents; research to identify parasites that have this desired host specificity, but that are also quick-killing and capable of being economically *in vitro* mass produced should be given priority;
- Parasites from *Dreissena's* native Eurasian range should be studied to identify species that would be "nearly risk free" candidates for importation into North America;
- Research to uncover parasites of *Dreissena* that are already present in North America should be intensified.

Biological control is by no means a panacea to all pest problems. It has its inherent disadvantages, and the release of any biocontrol agent has risks, but this is true of all pest control approaches. Opponents of biological control are very quick to point out its past failures, but all of these biocontrol failures combined do not come anywhere near the global damage that has been done, and continues to be done, by chemical pesticides. In regard to *Dreissena* control, do we want to continue relying primarily on broad spectrum, chemical biocides, like chlorine, or do we wish to explore other pest control strategies that have far greater potential to be environmentally safe?

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