Biological Control xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Invasive quagga mussels can be attenuated by redear sunfish (*Lepomis microlophus*) in the Southwestern United States

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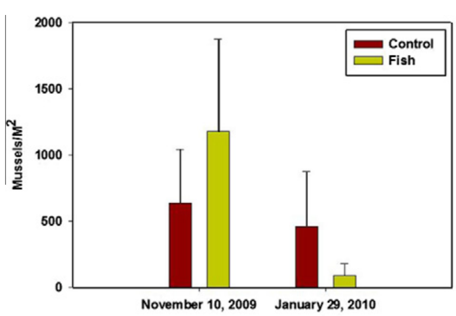
HIGHLIGHTS

- We demonstrate that redear sunfish can remove adult quagga mussels efficiently.
- Redear sunfish can suppress the growth and recruitment of invasive mussels.
- Redear sunfish can be used as a biological control fish species on quagga mussels.
- Targeted stocking of redear sunfish can be an efficient approach to mitigate mussels.

GRAPHICAL ABSTRACT

The degree to which invasive quagga mussels have spread across the Southwestern United States is unprecedented, and until now, none of the controls currently available is risk-free to the environment or human health. Here we demonstrate that stocking high-density (0.42 fish/m^3 or 1.90 fish/m^2) redear sunfish (*Lepomis microlophus*) in an infested lake enclosure removed adult quagga mussels efficiently and appeared to suppress their growth and recruitment. Redear sunfish is a species native to the Southeastern United States that has become a popular, stocked sportfish in the Southwest. Targeted stocking of redear sunfish may be an efficient and environmentally friendly approach to mitigate the colonization of invasive quagga mussels in suitable open water ecosystems, especially those with new dreissenid infestations or those threatened by invasion.



Quagga mussel densities in the boulder area of Sweetwater Reservoir before (November 10, 2009) and after (January 29, 2010) redear sunfish were stocked

ARTICLE INFO

Article history:
Received 11 July 2012
Accepted 26 November 2012
Available online xxxx

Keywords:
Biological control
Invasive quagga mussels
Dreissena rostriformis bugensis
Redear sunfish
Lepomis microlophus
Fish stocking

ABSTRACT

The degree to which invasive quagga mussels have spread across the Southwestern United States is unprecedented, and until now, none of the controls currently available is risk-free to the environment or human health. Here we demonstrate that stocking high-density (0.42 fish/m^3 or 1.90 fish/m^2) redear sunfish (*Lepomis microlophus*) in an infested lake enclosure removed adult quagga mussels efficiently and appeared to suppress their growth and recruitment. However, mussels were not eradicated during the short term experimental course. Long-term study needs to be conducted to determine whether mussels can be completely eliminated by redear sunfish and what optimum density would be required for balancing high efficacy mussel control with cost-effectiveness. Redear sunfish is a species native to the Southeastern United States that has become a popular, stocked sportfish in the Southwest. Targeted stocking of redear sunfish may be an efficient and environmentally friendly approach to mitigate the

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1049-9644/$ - see front matter
http://dx.doi.org/10.1016/j.biocontrol.2012.11.006

colonization of invasive quagga mussels in suitable open water ecosystems, especially those with new dreissenid infestations or those threatened by invasion.

1. Introduction

Biological invasions by nonindigenous species is a global environmental issue threatening the health of ecosystem and safety of many artificial water ways (Connelly et al. 2007; Holeck et al. 2004; Karatayev et al. 2007; Nalepa and Schloesser 1993; Strayer 2009). Invasive dreissenid mussels [zebra mussel (*Dreissena polymorpha*) and quagga mussel (*Dreissena rostriformis bugensis*)] in North America were first discovered in the Laurentian Great Lakes in the 1980s (Hebert et al. 1989; May and Marsden 1992; Mills et al. 1993; Nalepa and Schloesser 1993). They rapidly spread to other major basins such as the Illinois River, Mississippi River, and Hudson River (Ram and McMahon 1996). The detection of quagga mussels in Lake Mead and Lake Havasu in January 2007 was the first confirmed introduction of a dreissenid species in the western United States (LaBounty and Roefer 2007; Stokstad 2007). In the same year, quagga mussels colonized the lower Colorado River, as well as lakes and reservoirs in Arizona, California, and Nevada (Benson 2009), due to the transportation of quagga mussel veligers through waterways along the Colorado River Aqueduct. The speed at which this species has spread in the West is unprecedented (Wong and Gerstenberger 2011).

The ecological, recreational, and economic impacts of dreissenid mussels are profound. They are efficient ecosystem engineers that impact different ecosystems in different ways. These mussels cause a variety of changes such as alteration of phytoplankton species composition and nutrient dynamics and affect other organisms by direct colonization or indirect competition for food and/or space and increase water clarity by removing suspended particles (e.g., phytoplankton, debris, silt, and microzooplankton) in the water column. Benthic algae and plants benefit from increased water clarity (light transmittance) and reactive inorganic nutrients. Mussels can also alter morphological and physical properties of their habitat areas and affect availability of resources (Nalepa and Schloesser 1993; Holeck et al. 2004; Karatayev et al. 2007). Mussels biofoul available substrates and clog water pipes, boat intakes, and water delivery systems. Billions of dollars have been spent in North America, especially in the Great Lakes, to control and monitor dreissenid mussels (Aldridge et al. 2006; Connelly et al. 2007). In the arid Southwest, where there is a vast infrastructure of water conveyance systems, impact may be even more severe with the complete reliance of 27 million people in Arizona, California, and Nevada on lower Colorado River water delivery. The regular operations of water transportation, hydraulic power plants, fisheries, and boating activities have been impacted. At Hoover Dam, these invasive pests clog water lines that are used to cool the 17 massive hydropower turbines, and dam operators have been forced to temporarily shut down the power plant that supplies electricity to 1.6 million people in southern Nevada, Arizona, and California (Streater 2009). The control and prevention of infestation by dreissenid mussels are a major concern to managers of any type of water delivery system. For example, the Metropolitan Water District of Southern California expects to spend between $10 million and $15 million per year to address quagga mussel infestations in its 390-km Colorado River aqueduct and reservoir system (Fonseca 2009). The quagga mussel has become an increasingly problematic pest that threatens the economy and environmental health in the Southwest. The mussels' high fecundity, their passively dispersed planktonic veliger larval stage, and their ability to attach to submerged objects with byssal threads make dreissenid mussels arguably the most destructive non-indigenous biofouling pest introduced into North American freshwater systems (LaBounty and Roefer 2007) and one of the world's most economically and ecologically important pests (Aldridge et al. 2006).

Tools for effective, cost-efficient, and ecologically sound quagga and zebra mussel control are limited. Many methods have been tested or being developed for dreissenid mussel control, such as chemical treatment, physical killing, mechanical removal, and biological control. Chemical control option, especially chlorination, remains the only widespread and licensed option (Aldridge et al. 2006; Claudi and Mackie 1994). However, chlorination poses a number of problems for industry and regulators. When chlorine combines with organic compounds in water, potentially carcinogenic substances such as trihalomethanes and dioxins are formed (United States Environmental Protection Agency 1999). This issue greatly restricts the chlorine doses that can be applied in treating infested waters. Dreissenid mussels respond to unfavorable environmental conditions by closing their valves for prolonged periods, which is temperature-dependent, i.e., the lower the temperature, the longer time they survived (Johnson and McMahon 1998). Control agents, such as chlorine in the form of sodium hypochlorite, must be dosed continuously for up to three weeks (Aldridge et al. 2006). Chlorine cannot be applied to open waters housing other valuable aquatic living resources (i.e., sports fisheries) or dosed into pipelines that exit into open ecosystems, because of its toxicity to non-target biota in the recipient waters (Waller et al. 1993). Containment and control technologies (i.e., chemical treatment and mechanical removal) are primarily developed for closed-water systems and are only effective for a short period.

Natural resource interest groups and regulatory agencies have made it clear that safe and non-chemical alternatives for controlling mussel fouling are preferred. Biological control of invasive dreissenid mussels is more desirable at some degree, because it is less damaging to the environment and, potentially, to human health. Molloy (1998) reported that selectively toxic microbes and many natural enemies of dreissenid mussels, such as predators, parasites, and benthic competitors are potential biological control candidates. *Pseudomonas fluorescens* is a bacteria that has the potential of being used as a biological control agent on the dreissenid mussel (Molloy 1998), but its effectiveness in the field needs to be addressed. Regarding predatory fish, it has been suggested that freshwater drum, redear sunfish, and pumpkinseed sunfish are more likely to consume more dreissenid mussels than other fish in eastern North America because they possess both upper and lower pharyngeal teeth (French 1993). The evidence is clear that these fish species can consume dreissenid mussels, and it has been documented that they can consume them at high rates; however, field experiments (usually cage or other artificial substrates studies) show that major impacts by dreissenid mussels' natural enemies, while constant, are limited in naturally suppressing *Dreissena* populations (Bartsch et al. 2005; Magoulick and Lewis 2002; Martin and Corkum 1994; Molloy 1998; Thorp et al. 1998). There are no field trials that demonstrate successful control of natural wild populations of dreissenid mussels by biological agents. There had appeared to be no grounds to expect the development of a practicable molluscivore fish control method because field evidence attests that predation by natural fish populations are insufficient to control or reduce mussel densities (Bartsch et al. 2005; Magoulick and Lewis 2002; Thorp et al. 1998). Herein we test the hypothesis that artificially stocking redear sunfish, one of the most

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efficient dreissenid mussel predators, could significantly reduce the colonization of invasive natural quagga mussel population in Sweetwater Reservoir, a drinking water source reservoir in San Diego, California.

2. Materials and methods

Quagga mussel veligers were detected in December 2007, and juveniles and adults found in early 2009 in Sweetwater Reservoir, California (Hatcher 2008). The Colorado Aqueduct is a water source for this reservoir that receives water from the Colorado River where mussel veligers were originally found in the Western United States (Stokstad 2007). There was no redear sunfish in this reservoir before. Therefore, this reservoir provides an ideal location to test our hypothesis using an enclosure.

2.1. Enclosure area

Quagga mussel veligers were detected in Sweetwater Reservoir (San Diego, CA) in December 2007, and juveniles and adults were found in early 2009. Sweetwater Reservoir provides water service to approximately 187,000 people in National City, Bonita and the western and central portions of Chula Vista, CA. One of Sweetwater Reservoir's sources is the Colorado Aqueduct, which, in turn, receives water from the Colorado River where mussel veligers were originally found in the Western United States (Stokstad 2007). This study focused on Sweetwater Reservoir's boulder area, which receives Colorado River water delivered by the San Diego County Water Authority. Juvenile and adult mussels were first found in the boulder area due to its rocky nature and hard sediment substrate composition (Hatcher 2008). An experimental enclosure ($L \times W \times D$ = 13.7 m × 7.6 m × 4.6 m) was netted on November 10, 2009 just offshore at the entry point of raw aqueduct water inflow. A block net (1.59 cm holes) was purchased from Christensen Networks (Everson, WA). The net was fabricated from black knotless nylon netting and equipped with floats every 0.45 m across the top, and a 95/100 lead line along the bottom. Anchor weights were attached to plastic rings at the bottom of the net. The temperature and dissolved oxygen concentration at different depths of the experimental area (0, 2, 3, 5, and 6 m) were monitored with a YSI Model 600QS (SM 4500-G, Membrane Electrode Method).

2.2. Redear sunfish stocking and stomach-content analysis

Redear sunfish were obtained from the International Bait and Supply (San Diego, CA). On December 1, 2009, approximately 200 healthy fish were stocked into the netted study area with a density of 0.42 fish/m^3 or 1.90 fish/m^2. This density corresponds to just slightly higher than the highest end of the natural range observed for sunfish (0.04–1.77 fish/m^2) (Osenberg et al. 1992). An additional net was placed on top of the area to prevent birds from eating the fish. Just prior to stocking, 10 fish were randomly selected, frozen, and transported overnight on ice to the Environmental Health Laboratory at the University of Nevada, Las Vegas (UNLV). Standard length and wet weight were immediately recorded upon arrival for the specimens, which were then stored at −30 °C until further analysis. Stomach-content analysis was completed within 7–10 days under a dissecting microscope with cross-polarized light illumination (Carl Zeiss SteREO Discovery.V8, Toronto, Ontario, Canada). On January 29, 2010, eight fish were caught with a line and hook baited with worms. Standard length, wet weight, and stomach contents were recorded.

2.3. Quagga mussel sampling and analysis

On November 10, 2009, PVC quadrats (0.25 × 0.25 m) were used by divers to collect quagga mussels by pushing the quadrat with force until the frame was firmly in contact with the substrate. Using a paint scraper, mussels, algae, mud, and sand located inside the frame were removed from the boulder field. Mussels could be individually attached to a rock or in a colony form. Each collected sample was put into a mesh bag (mesh size 500 μm) then brought to surface and transferred into a plastic bag that was placed inside a cooler containing dry ice. Each bag was labeled with date and location. Five samples were collected randomly from inside the experimental enclosure, and five samples were collected from the control area. This resulted in a sampling of 48 samples/km^2 that is within the standard range of benthic sampling (Abadie and Poirrier 2000). Note the control sampling area was located in close proximity to the experimental enclosure and contained the same substrates as those inside the enclosure. The collected samples were frozen in a freezer and transported on ice to the UNLV Environmental Health Laboratory via FedEx overnight delivery. The samples were analyzed within a month. The numbers of mussels in each sample and shell length of each individual mussel were recorded. The density of mussels in each location was calculated. Subsequently, on January 29, 2010, additional samples were collected from the experimental and control areas (five samples from each area) nearby those previous sampling locations. Growth of the initial cohorts and recruitment of new cohort were estimated using the modal progression of Fish Stock Assessment Tool II (FiSAT II). FiSAT II applies the maximum likelihood concept to separate the normally distributed components of size–frequency samples, allowing accurate demarcation of the component cohorts from the composite polymodal population size of fish or shellfish (http://www.fao.org/fi/statist/fisoft/fisat). For each cohort identified, mean lengths with standard deviations and group sizes (in numbers) were identified to calculate growth of the same cohort. A T-test was used to determine if there was any significant difference in density between the control and experimental areas. The level of significance was set at $\alpha = 0.05$.

3. Results

From November 2009 to January 2010, water temperature at different depths decreased gradually while dissolved oxygen concentration increased with time; surface water was always warmer with higher concentration of dissolved oxygen (Fig. 1). On November 10, 2009, the density of quagga mussels in the study area (with fish) and control area (without fish) did not differ significantly (Fig. 2, $P > 0.05$). On January 29, 2010, mussel density in the study area was only 8% of the initial density (Fig. 2) and the difference between these two sampling events in the study area is significant ($P < 0.01$). In the control area, the mussel density between these two sampling dates was not significantly different ($P > 0.05$). The density of mussels in the control area was significantly higher than that in the study area ($P < 0.05$) on January 29, 2010. Based on the size frequency of mussel populations (analyzed by FiSAT II), recruitment appeared reduced in the enclosure (Fig. 3) where the redear sunfish was stocked. Apart from the new cohort in the control area, the growth of the initial cohort on November 10, 2009 appeared obvious while no growth of the mussels living with redear sunfish inside the experimental enclosure was observed (Fig. 3).

For redear sunfish collected on January 29, 2010, fish stomach content analysis revealed broken shells of quagga mussels, in addition to the presence of zooplankton, benthic organisms, and microalgae (Fig. 4). Broken mussel shell material was also found in sediment sampled within the experimental enclosure. This finding

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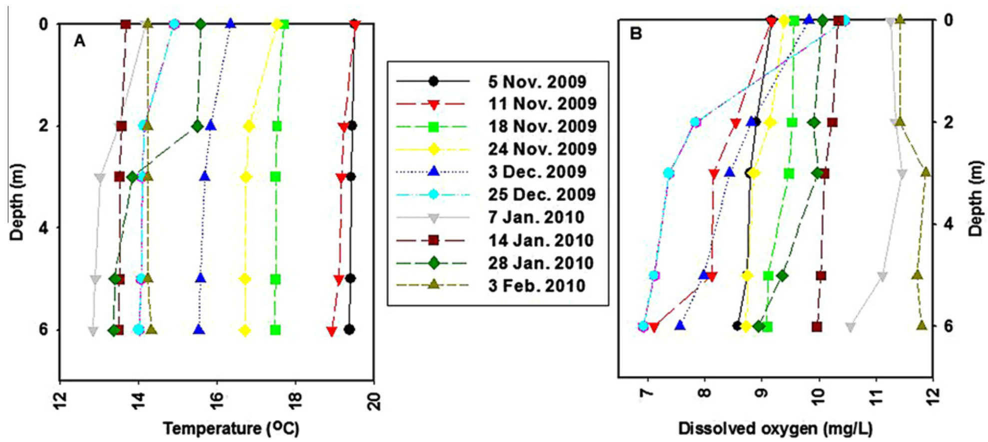

Fig. 1. Water temperature and dissolved oxygen concentration in the experimental area (A: water temperature; B: dissolved oxygen concentration).

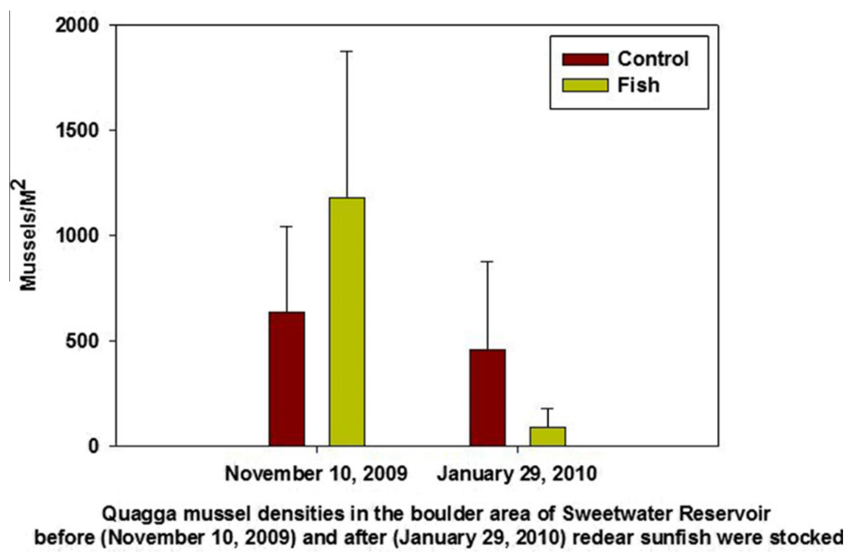

Fig. 2. Quagga mussel densities ($n = 5$, Mean ± SD) in the boulder area of Sweetwater Reservoir, CA before (November 10, 2009) and after (January 29, 2010) redear sunfish were stocked.

confirms that redear sunfish did consume quagga mussels in the natural field environment. The size of mussels inside and outside the enclosure did not show any significant difference on November 10, 2009 (*T*-test, $P > 0.05$). The original fish length and weight were 8.22 ± 1.22 cm and 17.33 ± 8.86 g ($N = 10$, Mean ± SD), respectively; approximately two months later, they were 9.54 ± 1.34 cm and 29.31 ± 10.21 g ($N = 8$, Mean ± SD), respectively.

4. Discussion

For the first time, it is shown that a wild population of dreissenid mussels can be attenuated by a fish species, such as redear sunfish, in their native habitat under controlled conditions. Previous studies have shown that fish, including redear sunfish, can suppress dreissenid mussel colonization by predation, but are ultimately unlikely to limit natural population density (Bartsch et al. 2005; Magoulick and Lewis 2002; Molloy 1998; Thorp et al. 1998; Watzin et al. 2008). The most encouraging result among prior experiments is that natural fish population predation contributed 64% of the reduction of zebra mussel biomass attached to the experimental concrete-blocks in the Upper Mississippi River (uncaged blocks vs. caged); however, colonization of mussels on uncaged blocks with fish predation increased from 0 to 27,023 mussels/m^2 during the experimental course (Bartsch et al. 2005). However, it is found recently that native predators may need time to adapt to feed effectively on invasive mussels. For example, in the Hudson River, predation from blue crab (*Callinectes sapidus*) and other potential predators apparently led to increased mortality and altered population structure in the invasive zebra mussels over time (Carlsson et al. 2011).

The present study is the first field trial demonstrating that a predatory fish has the ability to reduce the density of adult mussels, recruitment of new juveniles, and the growth of mussel cohorts. The redear sunfish is an efficient predator because it has upper and lower pharyngeal teeth and molariform teeth. Occluding mastication mechanisms enable them to close their upper and lower teeth together to crush shells and mollusks, which usually comprise 50–100% of their total food volume (French 1993). Zebra mussels were the primary prey of 100% of adult redear sunfish (Magoulick and Lewis 2002) in one study. Fish with molariform pharyngeal teeth, such as redear sunfish, were shown to shift their main diet to consume zebra mussels that colonized new habitats in eastern North America, outside the Great Lakes (French and Bur

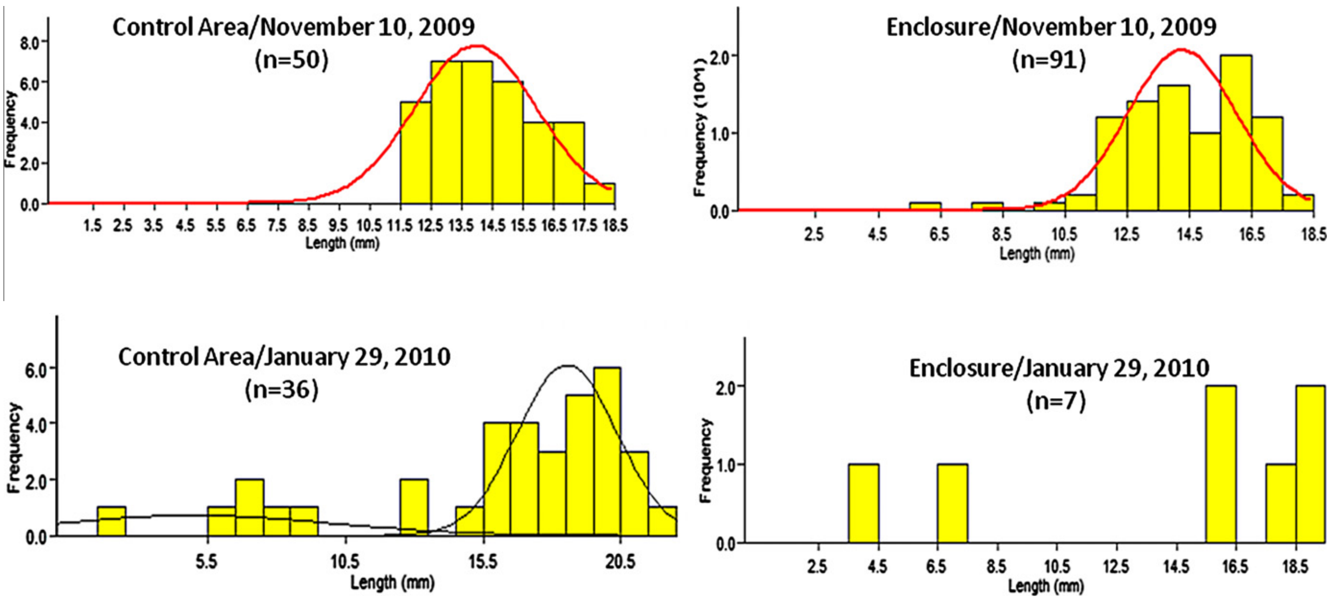

Fig. 3. Frequency of quagga mussel shell length (mussels data in each panel were collected from five locations).

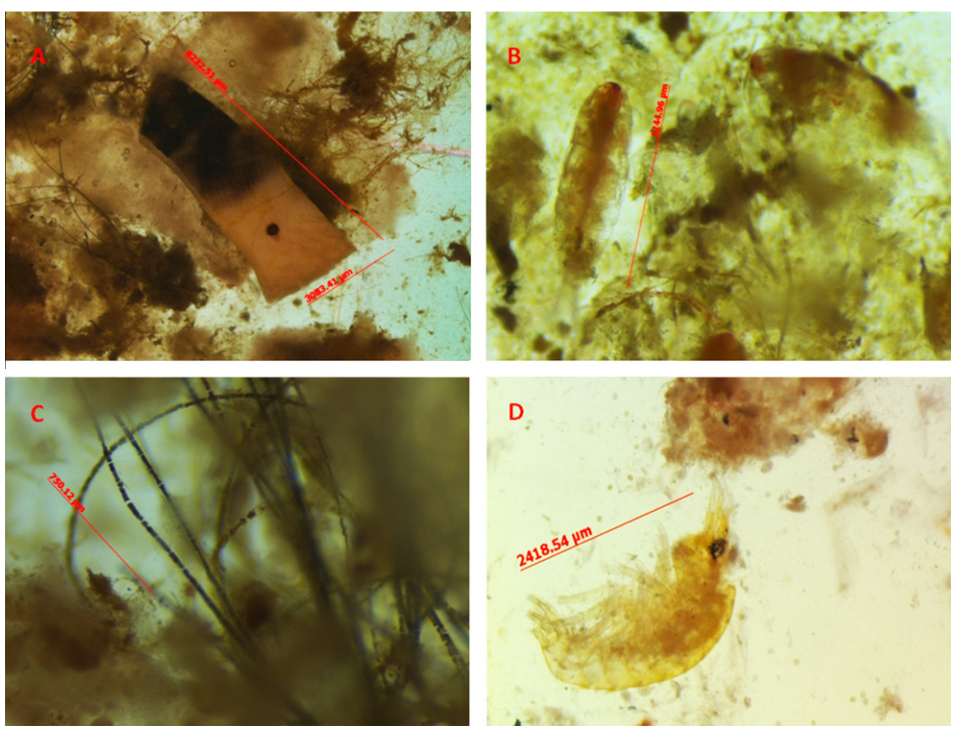

Fig. 4. Broken quagga mussel shell (A), Zooplankton (B; copepod), Microalgae (C), and Benthic organism (D; amphipod) in redear sunfish stomach contents.

1992). Redear sunfish prefer living in vegetated littoral zones of ponds; streams with sluggish to slow-flowing waters; and sheltered areas in rivers and lakes (French 1993). In vegetated habitats, where gastropods are abundant, the redear sunfish may not be an effective predator of zebra mussels, because the fish prefers gastropods over mussels for prey (French and Morgan 1995). This is the reason redear sunfish were proposed to control snails, the intermediate hosts for digenetic trematodes, in aquaculture ponds (Ledford and Kelly 2006). In many Southwest lakes and reservoirs, vegetated habitats are rare and gastropods are not abundant. For samples taken from the enclosure boulder area of Sweetwater Reservoir, no gastropod was found and no such vegetated littoral zone exists. Redear sunfish grew well by feeding on many kinds of food sources (Fig. 4) while still effectively controlling quagga mussels located in the boulder area of Sweetwater Reservoir.

Not only has biological control can decrease the likelihood of a pest developing resistance to the control agent, but also, it is more effective in the long term and is less expensive (Molloy 1998). The present study demonstrated that redear sunfish is effective in attenuating satellite populations of invasive quagga mussels. However, it remains to be seen by long-term and whole-lake experimentation whether the attenuation on dreissenid mussels by redear sunfish can be sustained, and ultimately, the invasive mussels can be successfully eradicated in a lake. Although elimination of dreissenid mussels in large open water systems may not be possible, introduction of a predator species to control a population of dreissenid mussels is a more environmentally benign form of integrated pest management. Based on one experiment involving the Asian clam (*Corbicula fluminea*), invasive bivalve populations are not likely be exterminated by fish predation (Robinson and Wellborn 1988); however, the Asian clam study relied on caged studies. The biomass reduction of zebra mussels from wintering waterbirds can be as high as 90% in shallow areas of Lake Constance (Werner et al. 2005). However, the invasive mussels are not eradicated by wintering waterbirds because the veliger larvae were produced by 2–3% of the larger mussels from the previous year, which forms the bulk of zebra mussels in the littoral zones (Werner 2002, but see Werner et al. 2005). In addition, stocking redear sunfish may significantly reduce mussel colonization to a dam, it may not have any effect within an infested water pipe, or fish may not survive in an industrial facility, such as hydropower penstocks. Finally, purposeful introduction of exotic molluscivores, such as black carp and roach, are discouraged in North America because an introduced biological controller usually does not concentrate only on unwanted pests, nor resides only in the preferred habitats of pests (French 1993). Several species of Asian carp were released into the Mississippi River Basin in an attempt to control mollusks, plants, and other biological problems in aquaculture ponds. The carp, originally used as biological control agents, have now become pests themselves by disrupting ecosystem processes and driving native species to localized extinction (Zambrano et al. 2006). Redear sunfish are typically found in the Southeastern United States and are one of the most widely distributed native fish in North America. They have been introduced into many states, such as the Colorado River system and Southern California in the 1950s (Wang 1986). They are wide spread and remain stable in the Southwest (Moyle 2002). They provide sport fishery in the region (Leon 2009). For example, redear sunfish are fairly common in the river below Davis Dam and Lake Havasu, along the Colorado River. People go to these areas specifically to fish for redear sunfish (Doug Nielsen, unpublished data). They are living well with other species and are not expected to have negative ecological consequences to other species with similar behavior and/or sharing the same habitat. In the Southwestern United States, redear sunfish is not listed as an invasive species (http://www.azgfd.gov/h_f/aquatic_invasive_species.shtml). Quagga mussel shells were found in the stomach of redear sunfish in the lower Colorado River (Gerald Hickman, personal communication) which is in agreement with the present study in Sweetwater Reservoir. However, quagga mussels are still proliferating in these waters. In fact, the distribution of redear sunfish in North America overlaps the distribution of dreissenids, there is no published information on the ability of redear sunfish to control the invasive mussels. One of the key reasons is that relatively higher density of redear sunfish were stocked to the enclosure in Sweetwater Reservoir. The optimum stocking density to attenuate quagga mussels needs to be studied for future research. The results of this experiment increase optimism for considering redear sunfish as a potential better approach for preventing and controlling quagga mussel infestation in open water systems in the Western United States deemed suitable. Species introduction or re-introduction has been a historical management tool for restoration and conservation programs. In many instances, invasive species in the new ecosystem has no enemy or existing enemy is not powerful enough to control them (LaBounty and Roefer 2007). Therefore, carefully orchestrated biological control such as using exotic species against invasive species may be the only feasible way to control them (Hoddle 2004).

It is very costly and difficult to prevent the spread of mussels through large water distribution systems that exist in the West, including trans-mountain diversions that move water across the continental divide. The introduction of redear sunfish can provide a potential efficient and effective method for reducing quagga mussel populations and recruitments in Sweetwater Reservoir that may serve as a regional model for additional study to benefit local, state, federal, and tribal governments with water resource management responsibilities, in addition to private industry in controlling infestations. For waters infested with quagga mussels in the Southwestern United States, especially in the early stage of invasion, redear sunfish might play a significant mitigatory role. Redear sunfish may also be applicable as a tool to prevent invasive mussel movement through water delivery systems and in certain open water systems. For Southwest waters with an existing redear sunfish, populations should be managed in their present habitats to maximize the role they naturally play in *Dreissena* control. Management options include improving redear sunfish habitat and reducing exploitation of large individual fish (i.e., the size class that preys most intensively on *Dreissena)* (French 1993). Intentional fish stocking can also be applied to these waters to increase the redear sunfish population to optimal levels for quagga mussel control. For waters in Southwestern states without redear sunfish present, stocking at densities determined optimum should be considered. Compared to the damage incurred from the use of traditional, broad-spectrum pesticides, the introduction of redear sunfish is a more effective approach in terms of mitigating environmental risks and its long-term effectiveness for controlling the spread of dreissenid mussels. Stocking redear sunfish to waterway systems in the Southwest, whether or not invaded by quagga mussels, will prevent or assist in reducing the severity of the invasion. For waters infested with quagga mussels, redear sunfish can play a significant mitigatory role. For waters without an existing redear sunfish population, stocking of this species should be considered as a valid prevention tool as long as there is, at the particular site, no ecological (e.g., presence of endangered mollusk species) or legal basis to preclude it. Existing redear sunfish populations should be managed to maximize their role in *Dreissena* control. At the very least, biological control of dreissenid mussels by redear sunfish can be considered as an option for integrated pest management in North America. The risk of introducing redear sunfish to a new system, or increasing its density in an existing system, may not be as significant of an introduction as other fish species, such as carp in the Mississippi River Basin (Zambrano et al. 2006). However, the potentially negative impact to the food web in a large ecosystem by stocking high densities of redear sunfish needs to be assessed. This mitigation strategy can be practically applied in affected systems, such as phased implementation, and monitoring should be established before large-scale implementation begins. Above all, stocking redear sunfish to waterway systems in the Southwest or many regions in North America can assist in reducing the severity of any future dreissenid mussel invasion.

5. Conclusion

We have experimentally shown that redear sunfish can be an efficient predator for reducing the size of a wild quagga mussel population in an environmental closure of the boulder area of Sweetwater Reservoir. This demonstrates that redear sunfish can control the population of invasive quagga mussels; however, mussels were not eradicated during the experimental course. Long-term experimentation must be conducted to determine whether mussels can be completely eliminated by redear sunfish, and what optimum density would be required for balancing high efficacy mussel control with cost-effectiveness. This experiment suggests that stocking redear sunfish in open waters could be an efficient and environmentally friendly tool to mitigate the colonization and potential ecological impacts caused by invasive quagga

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mussels in the Southwest. Based on the results of this present study, it is recommended that this workable and effective strategy be further studied for implementation in open waters to prevent and control invasive quagga mussels in the Southwestern United States. A detailed, long-term and large-scale study of specific sites must be conducted prior to stocking to determine (1) if it is effective on heavily colonized areas and the attenuation on invasive quagga mussels can be sustained over time; (2) practicality based on waterbody volume and the levels/ratios of all other possible food sources are present to calculate density of redear sunfish is required; (3) whether listed/protected native mollusks are part of the existing ecosystem; (4) if predators of redear sunfish can be a problem for stocking; and (5) impacts to higher and lower trophic levels.

Acknowledgments

We thank Dr. Jennell Miller's comments on an early version of this manuscript. This project is partially funded by National Park Service to University of Nevada, Las Vegas (J8360100020).

References

Abadie, S.W., Poirrier, M.A., 2000. Increased density of large Rangia clams in Lake Pontchartrain after the cessation of shell dredging. Journal of Shellfish Research 19, 481–485.

Aldridge, D.C., Elliott, P., Moggridge, G.D., 2006. Microencapsulated BioBullets for the control of biofouling zebra mussels. Environmental Science and Technolgy 40, 975–979.

Bartsch, M.R., Bartsch, L.A., Gutreuter, S., 2005. Strong effects of predation by fishes on an invasive macroinvertebrate in a large floodplain river. Journal of the North American Benthological Society 24, 168–177.

Benson, A.J., 2009. Quagga mussel sightings distribution. Available from: http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/quaggamusseldistribution.asp on November 20.

Carlsson, N.O.L., Bustamante, H., Strayer, D.L., Pace, M.L., 2011. Biotic resistance on the increase: native predators structure invasive zebra mussel populations. Freashwater Biology 56, 1630–1637.

Claudi, R., Mackie, G.L., 1994. Practical Manual for Zebra Mussel Monitoring and Control. Lewis, Publishers, Boca Raton, Florida, pp. 227.

Connelly, N.A., O'Neill, C.R., Knuth, B.A., Brown, T.L., 2007. Economic impacts of zebra mussels on drinking water treatment and electric power generation facilities. Environmental Management 40, 105–112.

Fonseca, F., 2009. Invasive Mussels Imperil Western Water System. New York Daily News, New York.

French, J.R.P., 1993. How well can fishes prey on zebra mussels in eastern North America? Fisheries 18, 13–19.

French, J.R.P., Bur, M.T., 1992. Predation of the zebra mussel (*Dreissena polymorpha*) by freshwater drum in Western Lake Erie. In: Nalepa, T.F., Schloesser, D.W. (Eds.), Zebra Mussels: Biology, Impacts, and Control. Lewis Publishers, Boca Raton, FL, USA, pp. 453–464.

French, J.R.P., Morgan, M.N., 1995. Preference of redear sunfish on zebra mussels and rams-horn snails. Journal of Freshwater Ecology 10, 49–55.

Hatcher, M.D., 2008. Sweetwater Authority dreissenid mussel monitoring, response, and control plan. In: Lab SAWQ (Ed.), Sweetwater Authority, p 21.

Hebert, P.D.N., Muncaster, B.W., Mackie, G.L., 1989. Ecological and genetic studies on *Dreissena polymorpha* (Pallas) - a new mollusk in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 46, 1587–1591.

Hoddle, M.S., 2004. Restoring balance. Using exotic species to control invasive exotic species. Conservation Biology 18, 38–49.

Holeck, K.T., Mills, E.L., MacIsaac, H.J., Colautti, R.I., Dochoda, M.R., Ricciardi, A., 2004. Bridging troubled waters: Biological invasions, transoceanic shipping, and the Laurentian Great Lakes. BioScience 54, 919–929.

Johnson, P.D., McMahon, R.F., 1998. Effects of temperature and chronic hypoxia on survivorship of the zebra mussel (*Dreissena polymorpha*) and Asian clam (*Corbicula fluminea*). Canadian Journal of Fisheries and Aquatic Sciences 55, 1564–1572.

Karatayev, A.Y., Padilla, D.K., Minchin, D., Boltovskoy, D., Burlakova, L.E., 2007. Changes in global economies and trade: the potential spread of exotic freshwater bivalves. Biological Invasions 9, 161–180.

LaBounty, J.F., Roefer, P., 2007. Quagga mussels invade Lake Mead. Lakeline 27, 17–22.

Ledford, J.J., Kelly, A.M., 2006. A comparison of black carp, redear sunfish, and blue catfish as biological controls of snail populations. North American Journal of Aquaculture 68, 339–347.

Leon, S., 2009. Fish lab study to focus on redear's appetite for tiny mollusks - quagga mussels. The Regional Report. U.S. Bureau of Reclamation, Boulder City, Nevada.

Magoulick, D.D., Lewis, L.C., 2002. Predation on exotic zebra mussels by native fishes: effects on predator and prey. Freshwater Biology 47, 1908–1918.

Martin, G.W., Corkum, L.D., 1994. Predation of zebra mussels by crayfish. Canadian Journal of Zoology 72, 1867–1871.

May, B., Marsden, J.E., 1992. Genetic identification and implications of another invasive species of dreissenid mussel in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 49, 1501–1506.

Mills, E.L., Dermott, R.M., Roseman, E.F., Dustin, D., Mellina, E., Conn, D.B., Spidle, A.P., 1993. Colonization, ecology, and population structure of the quagga mussel (*Bivalvia Dreissenidae*) in the lower Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 50, 2305–2314.

Molloy, D.P., 1998. The potential for using biological control technologies in the management of *Dreissena spp*. Journal Shellfish Research 17, 177–183.

Moyle, P.B., 2002. Inland Fishes of California. University of California Press, Berleley, p. 385.

Nalepa, T.F., Schloesser, D.W., 1993. Zebra mussels: Biology, Impacts, and Control. Lewis Publishers, Boca Raton, Ann Arbor, London, Tokyo, p. 810.

Osenberg, C.W., Mittelbach, G.G., Wainwright, P.C., 1992. 2-Stage life histories in fish - The interaction between juvenile competition and adult performance. Ecology 73, 255–267.

Ram, J.L., McMahon, R.F., 1996. Introduction: The biology, ecology, and physiology of zebra mussels. American Zoologist 36, 239–243.

Robinson, J.V., Wellborn, G.A., 1988. Ecological resistance to the invasion of a freshwater clam, *Corbicula fluminea*: fish predation effects. Oecologia 77, 445–452.

Stokstad, E., 2007. Invasive species - Feared quagga mussel turns up in western United States. Science 315, 453–454.

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

Streater, S., 2009. Tiny Eurasian mussel now threatening mighty Hoover Dam. New York Times, New York.

Thorp, J.H., Delong, M.D., Casper, A.F., 1998. In situ experiments on predatory regulation of a bivalve mollusc (*Dreissena polymorpha*) in the Mississippi and Ohio Rivers. Freshwater Biology 39, 649–661.

United States Environmental Protection Agency, 1999. Wastewater technology fact sheet: Chlorine disinfection. US Environmental Protection Agency, Washington DC, p. 7.

Waller, D.L., Rach, J.J., Cope, W.G., Marking, L.L., Fisher, S.W., Dabrowska, H., 1993. Toxicity of candidate molluscicides to zebra mussels (Dreissena polymorpha) and selected nontarget organisms. Journal of Great Lakes Research 19, 695–702.

Wang, J., 1986. Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A Guide to the Early Life Histories - Redear Sunfish *Lepomism microlophus*. Interagency Ecological Program Technical, Report #9.

Watzin, M.C., Joppe-Mercure, K., Rowder, J., Lancaster, B., Bronson, L., 2008. Significant fish predation on zebra mussels Dreissena polymorpha in Lake Champlain, USA. Journal of Fish Biology 73, 1585–1599.

Werner, S., Mortl, M., Bauer, H.G., Rothhaupt, K.O., 2005. Strong impact of wintering waterbirds on zebra mussel (*Dreissena polymorpha*) populations at Lake Constance, Germany. Freshwater Biology 50, 1412–1426.

Wong, W.H., Gerstenberger, S.L., 2011. Quagga mussels in the Western United States: Monitoring and Management. Aquat Invasions. 6, 125–129.

Zambrano, L., Martinez-Meyer, E., Menezes, N., Peterson, A.T., 2006. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. Canadian Journal of Fisheries and Aquatic Sciences 63, 1903–1910.

Please cite this article in press as: Wong, W.H., et al. Invasive quagga mussels can be attenuated by redear sunfish (*Lepomis microlophus*) in the Southwestern United States. Biological Control (2012), http://dx.doi.org/10.1016/j.biocontrol.2012.11.006