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Effectiveness of EarthTec® for killing invasive quagga mussels (Dreissena rostriformis bugensis) and preventing their colonization in the Western United States

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Effectiveness of EarthTec® for killing invasive quagga mussels (*Dreissena rostriformis bugensis*) and preventing their colonization in the Western United States

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Quagga mussels (*Dreissena rostriformis bugensis*) have created economic and ecological impacts in the western United States since their discovery in 2007. This study focuses on chemical control for preventing the spread of these mussels. The effectiveness of EarthTec® in killing quagga mussels (adults, juveniles, and veligers) in Lake Mead, Nevada-Arizona, was evaluated over time across six concentrations: 0, 1, 5, 10, 17, and 83 ppm. One hundred percent mortality of adult and juvenile mussels was achieved after 96 h with 17 ppm and 5 ppm (respectively), and 100% veliger mortality occurred within 30 min at 3 ppm. From December 2010 to February 2011, the effectiveness of EarthTec® in preventing veliger colonization was also evaluated and the results showed that 2.8 ppm was effective in preventing veliger colonization on fiberglass panels. This study indicates that EarthTec® has the potential to be an effective control agent against the invasive quagga mussel, and more specifically, in preventing the colonization of veligers.

Keywords: *Dreissena rostriformis bugensis*; quagga mussel; EarthTec®; copper sulfate; molluscicide; chemical control; biofouling

Introduction

The zebra (*Dreissena polymorpha*) and the quagga mussel (*Dreissena rostriformis bugensis*) have become arguably the most serious nonindigenous biofouling pests introduced into North American freshwater systems (LaBounty & Roefer 2007). The economic impact of zebra and quagga mussels in North America has been estimated at $1 billion a year (United States Army Corps of Engineers 2002). The speed at which the quagga mussel has spread throughout the southwestern United States is unprecedented (Benson 2011; Wong & Gerstenberger 2011). In addition to invading the Great Lakes region, the quagga mussel was subsequently discovered in Lake Mead in 2007 (LaBounty & Roefer 2007), and following establishment has resulted in significant economic impacts. For example, the mussels clog water intake pipes and disrupt water filtration in electric generating plants and water treatment facilities. They also affect boat motors, damage recreational equipment, and once established in the lake, routine maintenance is necessary to avoid additional impairment. The cost in the western United States will be significant with the further spread to uninfested bodies of water (Turner et al. 2011). Quagga mussels also alter the ecosystem by increasing water clarity and bioaccumulating contaminants. With their efficient filtering capabilities, quagga mussels remove suspended food particles from the water column, including detritus, phytoplankton and bacterioplankton, reducing availability for native filter-feeding aquatic species (Claudi & Mackie 1994; Strayer et al. 1999; Karatayev et al. 2007; Nalepa et al. 2009).

Chemical means are the most commonly used methodology in both the United States and Europe to control zebra and quagga mussel macrofouling (Claudi & Mackie 1994). Following the introduction of nonindigenous zebra and quagga mussels to North America, a number of chemicals with unknown and known molluscicidal properties were proposed for use in controlling invasive molluscs (Sprecher & Getsinger 2000). The most popular and least expensive chemical used for control of invasive mussels is chlorine, where it is added as chlorine gas or as liquid sodium hypochlorite (Claudi & Mackie 1994; Rajagopal et al. 1996; Sprecher & Getsinger 2000). Chlorine is beneficial because it is effective at low concentrations and efficient against all fouling categories ranging from bacteria to molluscs. It not only kills adult quagga mussels, but is effective in preventing embryonic forms (ie veligers) from settling in raw water piping systems

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which can increase the efficiency of the water facility (Jenner & Janssen-Mommen 1993). Chlorine controls mussels through an oxidation process either directly on the adults or through inhibition of settlement and growth of the veligers. Adult mussels can sense the presence of chlorine in low doses to which they respond by shutting their valves resulting in cessation of filter-feeding and dependence on anaerobic metabolism (Rajagopal et al. 1997, 2002). Because mussels try to avoid the chemical, they may die from asphyxiation or metabolic acidosis induced by anaerobic metabolism over a prolonged period (Van Benschoten et al. 1995). Trihalomethanes (THMs) are formed as by-products of chlorination when it is used to disinfect drinking water. These byproducts are formed when chlorine reacts with organic or inorganic material already present in the water being treated. THMs are linked to adverse health effects and can be carcinogenic to animals (Cotruvo & Regelski 1989). The US Environmental Protection Agency (US EPA) set a standard for the maximum allowable annual average concentration level of total THMs of 80 ppb (US EPA 2010). Water treatment facilities that use chlorine as a preventative measure against veliger colonization must monitor total THM production to avoid hazardous limits. In cases where THM exceeds the US EPA's limit, an alternative form of chemical control needs to be implemented.

EarthTec® is a proprietary copper chemical that may be used as a chemical control method for quagga and zebra mussels. It is formulated by blending copper sulfate pentahydrate with Earth Science Laboratory's base acid. EarthTec® is registered with the US EPA as an algicide/bactericide and certified as a drinking water additive. It is commonly used in lakes, ponds, reservoirs, and municipal drinking and wastewater systems. The biologically active ingredient in EarthTec® is the cupric ion form of copper (Cu^{2+}).

Quagga mussels have been threatening the local ecosystem and environments since their introduction, and currently there is not a single method that will eliminate the problem. The objective of the present study was to determine the lethal dose of EarthTec® for quagga mussels, and to test the effectiveness of this agent in preventing settlement by quagga mussel veligers. This information will be useful as an added option for the management of quagga mussel biofouling.

Materials and methods

Lethal effects of EarthTec® on quagga mussels

Specimen collection and holding conditions

In November, December, and January 2010–2011, adult, juvenile, and veliger specimens of *D. rostriformis bugensis* were collected from Lake Mead, Nevada-Arizona, USA (36°1′50.69′N; 114°46′12.95′W). Adults and juveniles were collected from rope substrata at depths of 10–20 m, and veligers were collected at 30 m using a 64 μm pore size plankton net (Gerstenberger et al. 2011). A National Park Service permit was obtained, granting permission to collect quagga mussels. Immediately following collection, the samples were brought back to the Nevada Department of Wildlife's (NDOW) hatchery in Boulder City, NV to acclimate for 5 days, in 10 gallon (=37.9 l) tanks. The aquaria used to acclimate adult and juvenile mussels contained water taken from a flow through system carrying water pumped directly from Lake Mead. The water in the aquaria was continuously aerated with air stones and the temperature was recorded daily. Adults (>11 mm) and juveniles (<11 mm) were divided and placed into twenty four, 800 μm fine media mesh bags with 12–15 mussels per bag. Veligers were divided into small, glass Petri dishes for the toxicity experiment, or divided into the 10 gallon tanks for the colonization experiment. Twelve tanks equipped with air stones were used and filled with 25 l of raw Lake Mead water.

Adult, juvenile, and veliger toxicity tests

Six concentrations of EarthTec® solution were tested for the adult, juvenile, and veliger toxicity: 0 (control), 1, 5, 10, 17, and 83 ppm with corresponding Cu^{2+} concentrations of 0 (control), 0.06, 0.3, 0.6, 1, and 5 ppm, respectively. Only healthy mussels in the fine media mesh bags were used for experimentation. The duration of both the adult and juvenile portions of the toxicity tests was 7 days (168 h). Four replicates of the six treatment groups (including controls) were used for the toxicity tests. In total, for each adult and juvenile test, 240 mussels of roughly equal size ($\sim$11 mm $-$23 mm) were used for the toxicity experiments (10 mussels $\times$ 6 treatment groups $\times$ 4 replicates = 240 total mussels). Each replicate was placed in a 800 μm mesh bag and immersed in a beaker with raw Lake Mead water and the appropriate dose of EarthTec®. Each beaker was aerated with an air stone and kept in a 22°C water bath to mimic the epilimnion water temperature of Lake Mead. Each group was fed daily with 0.1 ml of Instant Algae® *Isochrysis* 1800 (Reed Mariculture, Campbell, CA) at a concentration of 1×10^6 cells ml^{-1}.

For the veliger toxicity portion of the experiment, the Ecological Effects Test Guidelines for bivalve acute toxicity test was followed (US EPA 1996). Unlike the adult and juvenile tests, this portion of the experiment did not exceed 48 h (US EPA 1996). Quagga mussel veligers (n = 10–20) were pipetted into small, glass Petri dishes and examined under a stereo microscope

(Olympus Stereo Zoom, model SZ4045ESD) to assess viability. Both dead and living veligers were counted and documented for each Petri dish.

Adult, juvenile, and veliger mortality

Mortality was checked every 24 h from the beginning of the experiment for adults, and at 6 h and 12 h followed by every 24 h for the juveniles. To test for mortality, gaping mussels were first gently prodded on their shell valves with forceps; those individual mussels that did not respond by immediate shell closure were stimulated in the area of their siphons. Mussels that still did not respond to siphon stimulation, had their shell valves forcibly closed with forceps. The mussel was considered dead if it immediately reopened upon release of the forceps (Harrington et al. 1997; Morse 2009; Comeau et al. 2011). Dead mussels were removed from the beaker, their shell length recorded to the nearest 0.1 mm with digital calipers (Model 62379-531: VWR International, Inc) followed by placement into a different mesh bag. They were then transferred to a flow through system and mortality was confirmed 24 h later. The experiments for both adult and juvenile mussels lasted 7 days (168 h). The shell lengths of mussels that were still alive at 168 h were similarly recorded.

Determination of mortality using cross-polarized light (CPL) microscopy immediately followed the addition of EarthTec® to each Petri dish containing viable veligers. When veligers stopped moving or internal organs appeared to cease movement under a microscope for a 2-min observation period, they were documented as dead (Britton & Dingman 2011). If 100% mortality was not observed within 3 h, the Petri dish was set aside and examined every 12 h thereafter, until 36 h was reached. Prior to each treatment, the control groups were examined to evaluate viability.

The effectiveness of EarthTec® for preventing veliger colonization

The colonization experiment was performed in two phases on veligers that were collected as described previously. Both phases lasted 30 days, with six controls (0 ppm) and six treatments of 1 ppm (0.06 ppm of Cu^{2+}) of EarthTec® in Phase I. Phase II consisted of four controls, four treatment groups of 2 ppm (0.12 ppm of Cu^{2+}), and four treatment groups of 3 ppm (0.18 ppm of Cu^{2+}). Fiberglass panels (79 × 68 × 1.66 mm) were hung in each tank with fishing line from the shelf above. Five days before the experiment, the fiberglass panels soaked in fresh Lake Mead water to form a biofilm. The panels were used to measure colonization of veligers. The veligers were fed twice daily with 0.375 ml of Instant Algae® *Isochrysis* 1800 (Reed Mariculture, Campbell, California) (1.54×10^8 cells). Every week, half the water in the tanks was exchanged and replaced with fresh Lake Mead water. To prevent the loss of the veligers, the water being removed was filtered in the cone portion of the plankton net with 64 μm pore size and the veligers were placed back into the corresponding tank. Each tank received a minimum of 25 veligers l^{-1} of water. After veligers were added to an aquarium, the appropriate amount of Earth Tec® was added to the medium to attain the appropriate test concentration. Because EarthTec® is considered a low pH product, the pH of the water in all tanks was analyzed (YSI EcoSense pH100), and the average pH in the treatment tanks was 8.25 (range = 8.24–8.26).

Panel analysis

After 30 days, the fibreglass panels were removed from all tanks and were brought back to UNLV's Environmental and Occupational Health Laboratory. CPL microscopy was used to assess the colonization status of attached quagga mussel juveniles. Each mussel was then photographed with the Zeiss Discovery V8 stereo microscope (Carl Zeiss, Inc., Peabody, MA). To measure the amount of colonization, all six surfaces of the panel were observed. To determine the number of mussels per m^2, the total number of colonized juveniles was divided by 0.01.

Statistics and data interpretation

Analysis of covariance (ANCOVA) was used to examine the effectiveness of different doses of EarthTec® on killing mussels at different time intervals (Zar 1996). Analysis of variance (ANOVA) was used to evaluate if there was any significant difference in minutes to reach 100% veliger mortality among different treatment groups in the veliger toxicity test. Student-Newman-Keuls *post hoc* multiple comparisons test was conducted to determine if the difference was significant. For the colonization experiment, *t*-test and ANOVA were used to determine if there was significant difference among treatments in Phase I and Phase II, respectively. Linear regression was performed to estimate the concentration of EarthTec® at which a zero colonization rate was reached. The significance criterion was set at $\alpha = 0.05$. All statistical analyses above were performed using SAS® Software (version 9.2, SAS Institute Inc. Cary, NC).

Results

The concentration of EarthTec® significantly affected the survival of adult mussels with time as a significant

covariant ($p < 0.0001$). Higher concentrations of and increased exposure times to Earth Tec® resulted in greater levels of mussel mortality. No mortality occurred in control groups of adult mussels. The time to 100% mortality of adult quagga mussels decreased with increasing EarthTec® concentration (Figure 1A). Similar results were found among juvenile mussels (Figure 1B): higher concentrations of Earth Tec® and/or increased time of exposure led to higher levels of mortality (ANCOVA, $p < 0.0001$).

In the adult and juvenile toxicity tests, the control groups and the 1 ppm of EarthTec® groups showed no or little mortality. In the adult toxicity test, 50% of the mussels in the 83 ppm group of EarthTec® were dead by 30 h. By 96 h, >50% of the mussels in the group with 5 ppm were dead, >50% of the mussels in the group with 10 ppm were dead, and all the mussels in the 17 and 83 ppm groups were also dead. By 168 h, 95% of the mussels in the 5 ppm group were dead and 92.5% in the 10 ppm group were also dead (Figure 1A).

In the juvenile toxicity test, 98% of the mussels in the 5 ppm group were dead by 72 h, and 3% were dead in the 1 ppm group. Mortality was confirmed by 96 h for all the mussels except the controls and the 1 ppm group (Figure 1B).

Based on the acute toxicity of EarthTec® to adult and juvenile quagga mussels, their 96 h LC_{50} values were estimated to be 3.42 ppm and 1.40 ppm, respectively.

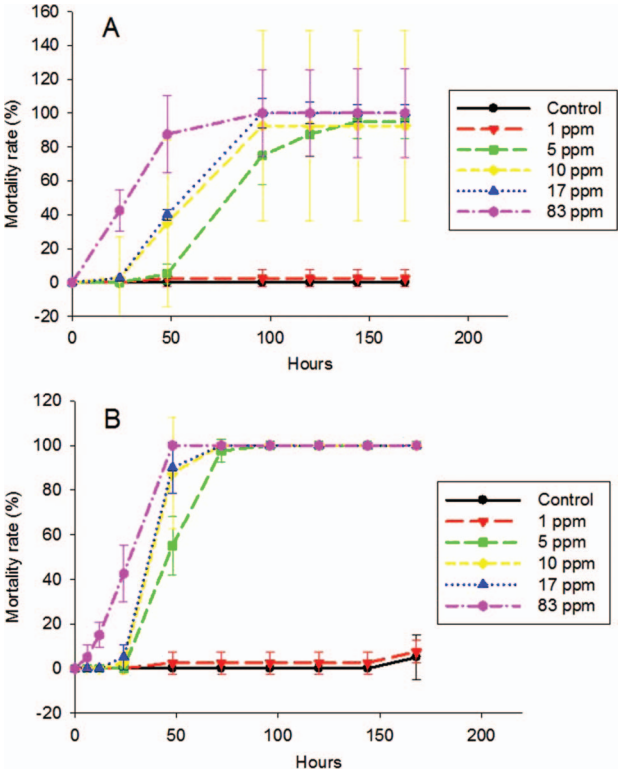

Figure 1. Cumulative mortality of quagga mussel adults (A) and juveniles (B) at different EarthTec® concentrations. n = 240, mean ± 1 SD.

Veliger toxicity

Doses of 3, 5, 10, 17, and 83 ppm of EarthTec® were effective for killing 100% of the veligers within minutes. Mortality occurred in <10 min for mussels treated with 83, 17, and 10 ppm. For mussels treated with 5 ppm and 3 ppm, mortality occurred in <30 and 20 min, respectively (Table 1). The experiment was completed after 36 h, and all the controls and individuals in the groups with 1 ppm were still alive. The time required for 100% mortality to occur varied significantly between treatments (ANOVA, $p < 0.001$; $F_{6,23} = 372{,}022$). As anticipated, Student-Newman-Keuls multiple comparisons showed that the time to 100% mortality was significantly longer when treated with 3 ppm and 5 ppm than with higher doses such as 10 ppm, 17 ppm, and 83 ppm (Table 1).

Colonization experiment

For data obtained in Phase I of the colonization experiment, a pooled *t*-test was performed. The groups with 1 ppm of EarthTec® had a lower colonization rate compared to the control group ($p < 0.01$) (Figure 2A). In Phase II of the colonization experiment, the treatments with 3 ppm of EarthTec® had a zero colonization rate (Figure 2B). The groups treated with 2 ppm and 3 ppm were less colonized than the control group (ANOVA, $p < 0.01$) (Figure 2B) while there was no significant difference between 2 ppm and 3 ppm ($p > 0.05$).

Assuming the control (0 ppm) treatment had a 100% colonization rate in Phase I, an average 32% colonization rate was found for 1 ppm. The same assumption was applied for the Phase II experiment where the colonization rates for 0 ppm, 2 ppm, and

Table 1. Time for quagga mussel veligers to reach 100% mortality at different doses of EarthTec®.

EarthTec®	Minutes (Mean ± SD)	Replicates
0 ppm	Mortality was 0	8
1 ppm	Mortality was 0	6
3 ppm	27.5 ± 7.5	4
5 ppm	20.3 ± 8.1	3
10 ppm	6.0 ± 2.0	3
17 ppm	6.0 ± 1.0	3
83 ppm	5.7 ± 4.5	3

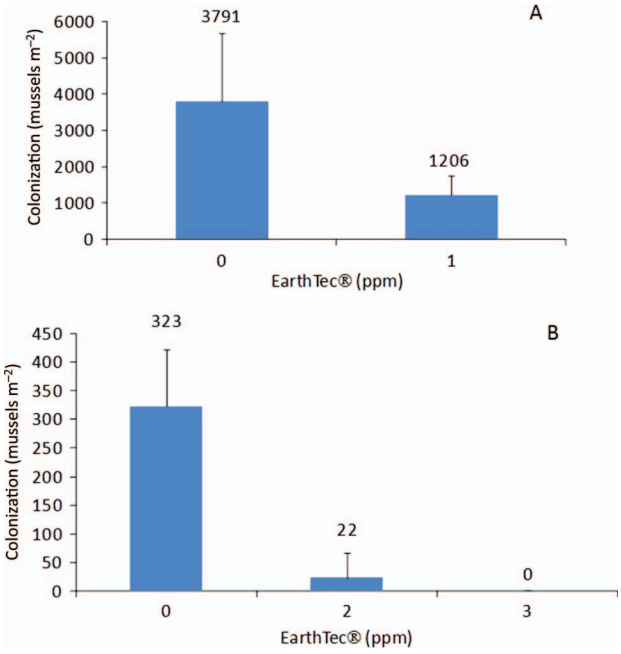

Figure 2. Colonization density of quagga mussels treated with 0 and 1 ppm (A) and 0, 2, and 3 ppm (B) of EarthTec®. Mean ± 1 SD; values shown on top of the bars are means.

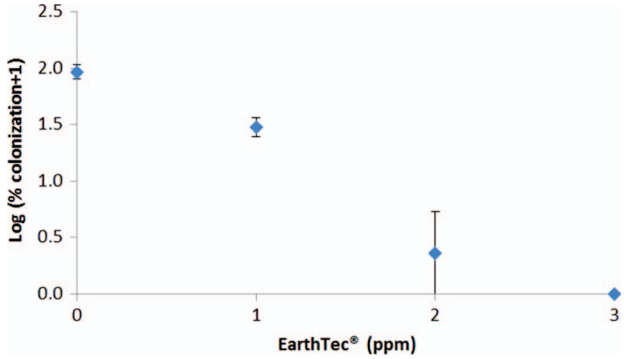

Figure 3. Relationship between the percentage colonization rates and EarthTec® dose in quagga mussel colonization. Mean ± 1 SD. Note that the data on y-axis are log (y + 1) transformed.

3 ppm treatments were 100%, 7%, and 0%, respectively. Therefore, EarthTec® with 1 ppm, 2 ppm, and 3 ppm had reduced colonization rates of 68%, 93%, and 100%, respectively. Because both control treatments had a 100% colonization rate, least square fit regression was used to determine the relationship between colonization rate (%) and dose (ppm). Because of zero values in both dependent variable (colonization rate) and independent variable (dose), an exponential curve is not developed. Therefore, the colonization data were log(y + 1) transformed and this also addresses the heteroscedasticity of limited data (Zuur et al. 2007). A linear regression was produced to elucidate the dose-response relationship (Figure 3). The following relationship was found: Log (Colonization Rate% + 1) = −0.70 × Dose + 2.00 ($R = 0.98$, $p < 0.01$). Therefore, to result in zero colonization, it is estimated that 2.8 ppm (95% confidence level: 1.0–3.0 ppm) of EarthTec® is necessary for winter months (December to February). The corresponding Cu^{2+} concentration is 0.17 ppm (95% confidence level: 0.06–0.18 ppm).

Discussion

The first portion of the study showed that EarthTec® was lethal to quagga mussels. Higher concentrations of EarthTec® and longer exposures were required for 100% mortality in adult mussels compared to juveniles or veligers. To kill >50% of the mussels by 96 h, at least 5 ppm of EarthTec® (0.30 ppm Cu^{2+}) was needed. For 100% mortality of adult mussels, 5 ppm was administered over 168 h. Depending on the location and the current amount of copper already in the water source, 5 ppm (0.3 ppm of Cu^{2+}) of EarthTec® may be too high to use in a facility that treats drinking water. Therefore, control methods may be better targeted towards veligers compared to adult or juvenile mussels.

The results of this study suggest that EarthTec® is more effective for killing adult and juvenile quagga mussels than another algicide/bactericide/cyanobactericide, Cutrine®-Ultra. Cutrine®-Ultra is a chelated copper formulation that is effective in penetrating thick cell walled algae and vascular aquatic plants (Applied Biochemists 2002). When adult zebra mussels (*D. polymorpha*) were exposed to 1,214 μg Cu l^{-1} (1.2 ppm Cu) for 48 h, 50% mortality was achieved (Kennedy et al. 2006). This amount of copper is below the US EPA's maximum containment level (MCL) of 1.3 ppm. After continuous exposure for 96 h, it took almost two times the maximum allowable dosage of Cutrine®-Ultra to kill most of the adult zebra mussels. Another study examined the toxic effects of copper sulfate ($CuSO_4$) on adult zebra mussels, and found them to be resistant to copper, resulting in a 48 h LC_{50} of 5.3 ppm Cu l^{-1}, but the LC_{50} fell to 2.5 ppm Cu l^{-1} after continued assessment of survival (Waller et al. 1993).

In the juvenile toxicity segment of the present study, most of the mussels were dead by 48 h when 5 ppm of EarthTec® was used. These results are similar to those found in the adult toxicity segment. However, time was reduced by 50%. It took 72 h for 100% mortality for juvenile mussels exposed to 5 ppm of EarthTec® (Cu^{2+} 0.3 ppm). Waller et al. (1993) found the LC_{50} for juvenile zebra mussels (shell length

5–8 mm), after continuous exposure for 48 h to be >2 ppm of $CuSO_4$. This amount exceeds the MCL set by the US EPA at 1.3 ppm of copper. EarthTec® was found to be toxic to quagga mussel veligers, presumably because at this early life-stage they do not have a thick protective shell and membrane function is less well developed, therefore making them more susceptible to copper ions. In the present study, 2.8 ppm of EarthTec® (0.16 ppm Cu^{2+}) was found to be effective for killing quagga mussel veligers in minutes. Based on personal observation, EarthTec® was effective on all life stages of veligers, from trochophores to pediveligers. Kennedy et al. (2006) found the highest 24 h LC_{50} value for the early life stages (trochophores) of veligers to Cutrine®-Ultra was 13 μg Cu l^{-1} (0.013 ppm Cu). The study showed that this chemical is effective for killing the earliest life stage, trochophores. However, it did not investigate its toxicity to later, more developed veliger stages.

The second segment of the study examined the effects of EarthTec® on preventing quagga mussel veligers from colonizing fiberglass substrata. In Phase I and Phase II, EarthTec® was effective in preventing veliger colonization. Phase I of the colonization experiment showed that a greater density of mussel colonization occurred in the control groups whereas there was far less colonization in the 1 ppm group ($p < 0.01$). Mussel colonization was successfully deterred when veligers were exposed to 1 ppm of EarthTec® (0.06 Cu^{2+}). Phase II of the colonization study was conducted in January, where water temperatures were lower (range = 9.6°C–13.3°C) compared to Phase I where water temperatures were warmer (range = 12.3°C–13.3°C). It was found that there was very little colonization in the 2 ppm groups compared to the control groups, while no colonization occurred in the 3 ppm groups. The data are in agreement with the previous experiment that showed 3 ppm was lethal to quagga mussel veligers (Table 1). The 3 ppm experimental value is also very close to the statistically predicted value of 2.8 ppm (Figure 3). Therefore, it is recommended that 2.8 ppm of Earthtec® can prevent quagga mussel colonization.

Presently, chlorine is the most commonly used chemical for prevention of veliger mussel colonization. One study that was conducted in a field laboratory found that an intermittent 2 h daily treatment with 1 mg l^{-1} chlorine reduced mussel settlement by 91% compared with the controls. Although, chlorine is effective in preventing quagga mussel veligers from settling, densities of up to 6000 m^2 still occurred compared to the control settlement monitors which reached 147,100 m^2 (Bidwell et al. 1999). The same study also looked at using half the amount of chlorine (0.5 mg l^{-1}) for 4 h day^{-1}, and similar reductions in mussel colonization were found. The 2 to 4 h chlorine treatments did cause a reduction in settling, but the breaks in treatment were sufficient for the veligers to feed and grow (Bidwell et al. 1999). The intermittent chlorine schedule in this study may work for a short time; however, it will not prevent 100% of mussels from fouling.

Recommendations for further study

Chemical management strategies targeting early larval stages of quagga mussels are more likely to be cost efficient and less prone to non-target environmental impact than strategies aimed at controlling adults and juveniles. The toxicity experiment was conducted from late November to early February when the veligers are competent in colonization in Lake Mead (Gerstenberger et al. 2011). Therefore, a lower dose, such as 1 ppm, may still be effective in preventing colonization in other seasons when veligers were less competent. Since veliger dynamics in Lake Mead vary by season, further studies on the impacts of different seasonal temperature regimes on the effectiveness of Earth Tec® in preventing quagga mussel settlement may be required to determine the lowest effective dose required to prevent any mussel settlement or fouling.

EarthTec® may be most effective in the summer time when water temperatures are higher. Copper toxicity increases with an increase in temperature and decreases at lower temperatures. Rao and Khan (2000) examined the toxicity of $CuCl_2$ on zebra mussels (*D. polymorpha*) with increasing water temperatures. The ambient water temperature was set at 15°C, and then tested at 20° and 25°C. A 48 h LC_{50} of 0.78 ppm $CuCl_2$ at 20°C decreased to 0.24 ppm $CuCl_2$ at 25°C. A similar effect occurred during a 96 h exposure to $CuCl_2$. The 20°C 96 h LC50 of 0.5 ppm $CuCl_2$ declined to 0.11 ppm at 25°C. Because summer surface water temperatures in Lake Mead approach 28–30°C, the concentration of Earth Tec® required to prevent mussel fouling may be greatly reduced during warm summer months. Thus, the concentrations of Earth Tec® required to prevent mussel fouling may have to be reevaluated relative to temperature conditions during the application period.

More research needs to be done in Lake Mead to understand better the lethality of EarthTec® to the various larval development stages so the appropriate lethal dose to prevent pediveliger settlement can be determined. Research also needs to examine the lethal doses to different stages of veligers in different seasons when environmental factors, such as temperature and food quantity and quality are a challenge. It has been documented that quagga mussel veligers are present year-round in Lake Mead, with the percentage of

settlement competent veligers peaking at >60% during the fall and declining to <5% in February when surface water temperatures are at their lowest (Gerstenberger et al. 2011). The veliger abundance in Lake Mead was found to be strongly associated with the water temperature in the metalimnion (Gerstenberger et al. 2011). Therefore, experiments need to be designed to examine different chemical doses to prevent settlement over a wide range of seasonal temperatures at which settlement occurs. In that case, chemical control may be implemented in low doses and/or for a reduced amount of time when the water temperature is low in winter time. This would reduce the amount of chemical that is necessary for application; hence, reducing cost and the adverse impact on the surrounding ecosystem. The significantly higher chemical sensitivity of veligers compared to adult and juvenile mussels has pertinent implications in the design and use of the chemical. Application of chemical controls in the environment is dependent on a two major factors. Firstly, the chemical needs to be effective against the target organism (ie quagga mussels) and secondly it must not have adverse effects on non-target species in the environment. Furthermore, chemical control plans need to be safe, practical, easy to implement, and cost effective. Therefore, because of the elevated toxicity of Earth Tec® to quagga mussel larval stages relative to juveniles and adults and its capacity to prevent mussel settlement at relatively low application doses, prevention of mussel settlement and fouling may be the most cost-effective and environmentally acceptable Earth Tec® application technology.

Apart from chemical control, there are other alternative treatment methods in quagga/zebra mussel control and management, such as physical and mechanical cleaning, freezing, desiccation, and biological control. Among these alternative methods, thermal control is an optimistic and more environmentally benign method to control mussel fouling that has been tested and adopted by many water treatment plants and power industry (Perepelizin & Boltvskoy 2011; Grutters et al. 2012 and references therein), as well as agencies that decontaminate boats to prevent the overland dispersal of invasive mussels (Morse 2009; Comeau et al. 2011).

Conclusions

For the toxicity portion of the study, 5 ppm of EarthTec® (Cu^{2+} 0.3 ppm) killed 100% of quagga mussel adults by 168 h and juveniles by 72 h, while for veligers, 3 ppm was effective in <30 min. For the colonization portion of the study, 1 ppm of EarthTec® (Cu^{2+} 0.06 ppm) reduced veliger colonization on fiberglass panels. However, the present study was conducted in a laboratory setting, and it cannot be assumed that the same results would occur if conducted in the field because of uncontrolled conditions. While chemical control of quagga mussels has been proven effective in laboratory studies and closed systems, the recommended higher doses required for adult and juvenile eradication restricts the use of harsh, chemical-based strategies in field studies. The best way to combat this issue with chemical control, is to determine the most sensitive life stage and tailor management techniques to that specific life stage, and in this case, the veliger. This would optimize target efficacy while minimizing chemical release into the environment, risk to non-target species, and cost that would be required.

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