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MANAGEMENT BRIEF

A Comparison of Two Mobile Electrode Arrays for Increasing Mortality of Lake Trout Embryos

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Abstract
Conservation of sport fisheries and populations of several native fishes in the western United States is dependent on sustained success of removal programs targeting invasive Lake Trout *Salvelinus namaycush*. Gill-netting of spawning adults is one strategy used to decrease spawning success; however, additional complementary methods are needed to disrupt Lake Trout reproduction where bycatch in gill nets is unacceptable. We developed and tested two portable electrode arrays designed to increase Lake Trout embryo mortality in known spawning areas. Both arrays were powered by existing commercial electrofishing equipment. However, one array was moved across the substrate to simulate being towed behind a boat (i.e., towed array), while the other array was lowered from a boat and energized when sedentary (i.e., sedentary array). The arrays were tested on embryos placed within substrates of known spawning areas. Both arrays increased mortality of embryos (>90%) at the surface of substrates, but only the sedentary array was able to increase mortality to >90% at deeper burial depths. In contrast, embryos at increasingly deeper depths exhibited progressively lower mortality when exposed to the towed array. Mortality of embryos placed under 20 cm of substrate and exposed to the towed array was not significantly different from that of unexposed embryos in a control group. We suggest that the sedentary array could be used as a viable approach for increasing mortality of Lake Trout embryos buried to 20 cm and that it could be modified to be effective at deeper depths.

Lake Trout *Salvelinus namaycush* have been intentionally or inadvertently introduced into many lakes throughout the western United States and are currently being suppressed in many of these lakes (Martinez et al. 2009). Among other ecosystem effects, the establishment of nonnative Lake Trout may cause declines in the abundance of native species. For example, in Yellowstone Lake, Yellowstone National Park, the abundance of Yellowstone Cutthroat Trout *Oncorhynchus clarkii bouvieri* is negatively influenced by Lake Trout predation (Ruzycki et al. 2003; Syslo et al. 2011). Additionally, Bull Trout *S. confluentus* abundance declined concomitantly with an increase in abundance of Lake Trout in four lakes within Glacier National Park, Montana (Fredenberg 2002). In Swan Lake, Montana, the abundance of Lake Trout has increased since their establishment (Cox 2010; Kalinowski et al. 2010; Rosenthal and Fredenberg 2010). The increase in Lake Trout abundance in Swan Lake is of concern to state, federal, tribal, and private organizations because Swan Lake contains one of the most stable Bull Trout populations in Montana (Rosenthal and Fredenberg 2010).

Lake Trout suppression programs have been initiated in several western lakes in an attempt to reduce negative ecological interactions between Lake Trout and native species (Martinez et al. 2009; Syslo et al. 2011). Suppression programs in Lake Pend Oreille, Idaho; Swan Lake, Montana;

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Quartz Lake, Montana; and Yellowstone Lake, Wyoming, target juvenile and adult Lake Trout for removal using gill nets and trap nets. The efficacy of these programs is being evaluated, but targeting Lake Trout embryos may be a complementary and effective method for suppressing Lake Trout.

Lake Trout generally form spawning aggregates in lakes during the autumn (Muir et al. 2012). Consequently, Lake Trout suppression efforts often target removal of individuals from preidentified spawning sites, where large numbers of adults may be captured (Cox 2010; Syslo et al. 2011). However, other life stages of Lake Trout may also be targeted for removal at spawning sites. For example, Lake Trout embryos are a sessile life stage, and targeted suppression or removal of Lake Trout embryos may complement efforts to remove other Lake Trout life stages. Lake Trout are broadcast spawners that generally spawn at depths from 1 to 80 m in areas with substrates ranging in size from about 65 to 999 mm (Marsden et al. 1995). After fertilization, embryos settle into interstitial spaces within the substrate. The interstitial depth to which they settle is unknown but dictated by substrate shape, size, and size distribution (J. E. Marsden, University of Vermont, personal communication). Therefore, targeted removal or suppression of Lake Trout embryos would have to occur among variable water depths, substrate sizes, and interstitial depths. Embryo suppression would take advantage of life-stage–specific niche separation and increase mortality of the target species without the bycatch observed in gill nets (Cox 2010; Syslo et al. 2013).

Several studies have shown that electrofishing can increase mortality of fish embryos (e.g., Dwyer et al. 1993; Dwyer and Erdahl 1995; Bohl et al. 2010). Most studies on this topic have been aimed at providing methods that reduce mortality of embryos; however, electroshocking embryos may be useful for eradicating unwanted fishes (Bohl et al. 2010; Nutile et al. 2013; Gross et al. 2015; Simpson et al. 2016). Electrofishing equipment has been used as a control measure to remove juvenile and adult fish (Moore et al. 1983; Weidel et al. 2007), but to our knowledge, application of electrofishing techniques as a means to cause mortality of any life stage has not been attempted in situ.

Application of electric fields to cause high rates of embryo mortality requires specialized equipment. Existing electrofishing equipment used to capture juvenile or adult fish is designed to stun fish above the substrate using low power densities (e.g., <1 V/cm). Electric fish barriers (e.g., Smith-Root 2015) use electrodes mounted within concrete that produce similar low-voltage gradients in the water column to deter fish and prevent passage. However, equipment used to cause mortality in salmonid embryos would need to produce a high-density electric field (e.g., >3 V/cm; Bohl et al. 2010) and be able to penetrate into substrate interstices. Although permanent or semipermanent electrode arrays deployed on spawning areas may be able to create high-density electric fields, such an array would need to be extensive in lakes with large or broadly distributed spawning habitats. Conversely, an electrode array that is mobile would allow for transportation among spawning habitats or patches within lakes as well as among different lakes. We developed two mobile electrode arrays that produce a high-density benthic-oriented electric field. The objective of this study was to compare the configuration and deployment (stationary or towed) of electrode arrays for increasing mortality of Lake Trout embryos.

METHODS

Two electrode arrays were tested along a section of the Swan Lake shoreline that had previously been identified as Lake Trout spawning habitat (Cox 2010); this section was located along the eastern shoreline with a northern boundary of 47.940347°N, 113.870968°W (decimal degrees) and a southern boundary of 47.938553°N, 113.869431°W. The study area, typical Lake Trout spawning habitat (Marsden et al. 1995), was characterized by substrate of coarse sand to large boulders (Bain 1999), clean substrate interstices, and a conspicuous break in slope. From the shoreline to about 0.5 m deep, the slope was gradual (i.e., <10°); from 0.5 m to 3 m deep, the slope was steeper (i.e., 20–45°); and at depths greater than 3 m, the slope was again gradual. The specific conductance of Swan Lake varied from 185 $\mu S/cm^2$ to 210 $\mu S/cm^2$ during the study.

Gametes were collected from sexually mature Lake Trout from Swan Lake. Gametes were combined, water hardened, and fertilized embryos were transferred to an incubator and maintained at 8°C for 24 h. Only live embryos were placed into 5-cm by 5-cm by 1-cm mesh baskets, and unused embryos were monitored for mortality not associated with treatment or control exposure (i.e., background mortality). The baskets were made by folding 3-mm (bar measure) polyethylene mesh and sealing the edges. Baskets opened when squeezed, allowing embryos to be placed inside. The plastic mesh was nonconductive, and voltage gradient measurements measured within the mesh basket indicated that the baskets did not shield the embryos from the ambient electric field.

A string attached to the baskets allowed them to be lowered into substrate interstices. One of four different length strings were assigned to each basket, allowing them to be lowered to four different interstitial depths: 0, 5, 10, and 20 cm. After the basket was lowered into the interstices, the end of the string was clipped to 2.5-cm-long nylon webbing that was anchored at the edges of the study sites and laid across the surface of the substrate.

The towed electrode array used three cathodes and two anodes. The array was similar in concept to an electric seine (e.g., Angermeier et al. 1991), in that it used alternately polarized electrodes hanging from a cross member (Figure 1). The electrodes were attached to the cross member oriented in the same direction, allowing the array or electrodes

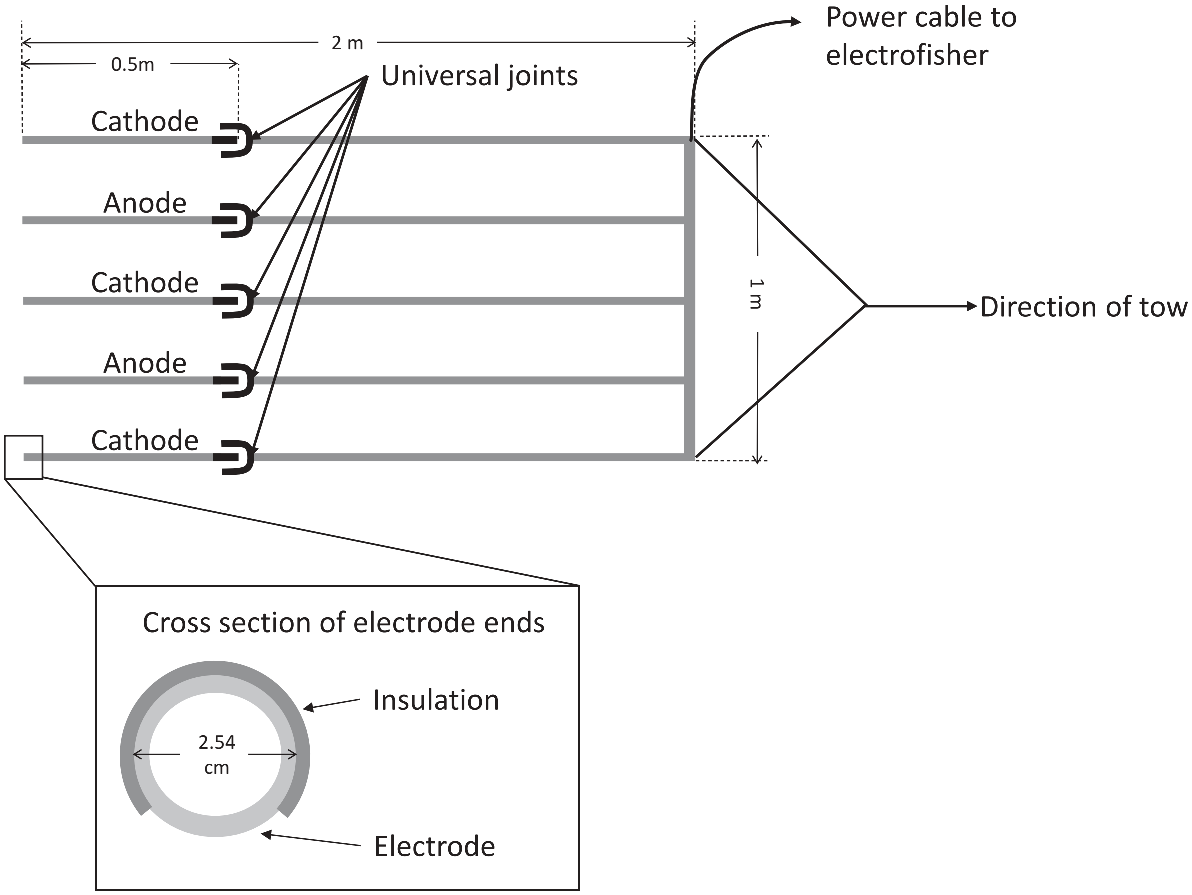

FIGURE 1. Diagram of the towed electrode array. The array was towed from left to right and powered by an electrofisher on the tow vessel.

to maintain uniform orientation when dragged. The cross member was 1 m wide, and the electrodes were dragged behind the cross member at a distance of 2 m (Figure 1). These dimensions were selected to maximize the available amperage while maintaining a lethal voltage gradient. Electrodes were made of aluminum tubes 50 cm long by 2.54 cm diameter. The electrodes were mostly insulated by plastic tubes, allowing 30% of each electrode to be exposed to water along one side (Figure 1). Electrodes lowered onto the substrate would lie horizontally in this uniform orientation, but they were allowed to contour along coarse substrates by using a universal joint. The universal joint allowed the electrodes to flex in all directions but did not allow them to rotate. The universal joint allowed the electrodes to cross when contouring along coarse substrate, but the plastic cover prevented the opposite polarity electrodes from short-circuiting when crossed (Figure 2).

The towed array was lowered onto the area and energized using between 5 and 10 A and 1,000 V of direct current from a Midwest Lake Electrofishing Systems Infinity electrofisher. The Infinity electrofisher was set to produce 1000 V of continuous direct current. When lying uniformly, the electrodes

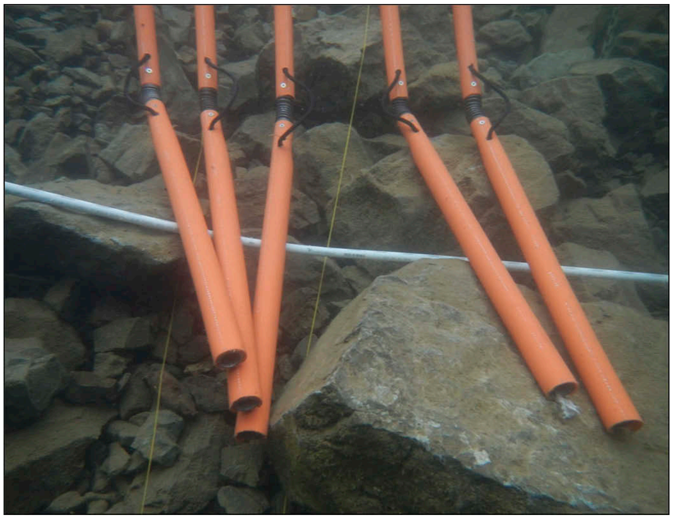

FIGURE 2. Underwater photo of the electrodes of the towed array. Electrodes extend from the spring to the end of each orange pipe. Electrodes can flex in all directions but cannot rotate; therefore, when they cross over one another, they cannot short-circuit. Electrodes are covered by orange pipe on the top but exposed to the lake bottom on the bottom.

produced a voltage gradient of 10 V/cm between the anode and cathode and 3 V/cm at 20 cm.

The towed array was tested at a single site in the study area, where it was connected to rails on the shoreline to make repeated exposures over a representative area of Lake Trout spawning habitat. In practice, the array would be towed freely across spawning areas. The study area was 7 m long and 1.5 m wide and extended perpendicularly to the shoreline at water depths from 0.3 to 3.1 m. The towed array was moved over this area using a rectangular frame that moved along two rails. The tracks were 9.8 m long, 2 m apart, and anchored 1 m above the substrate using concrete footings. The electrode array was pulled along the rails using an electric winch mounted to the shoreline. The winch moved the electrode array at a rate of 3.2 km/h, the speed at which a boat could be reliably maneuvered along the shoreline. The exposure duration of the towed array was calculated at 0.5 s, given the electrode length and towing speed.

The towed array was evaluated during 10 trials; in 8 of these trials the energized electrode array was moved over the study site, and in 2 trials the unenergized electrode array was moved over the study site. Twelve baskets containing 10 embryos each were placed at each substrate burial depth for a total of 48 baskets per trial.

The sedentary array consisted of stainless steel electrodes attached to coated stainless steel cable. The electrodes were 2.54 cm long and 0.95 cm in diameter and were soldered to 10-cm lengths of 1.60-mm-diameter vinyl-coated stainless steel cable (Figure 3). The electrodes were soldered perpendicularly to 3.18-mm-diameter vinyl-coated stainless steel cable at 10-cm intervals to form a string of electrodes (Figure 4). Each string of electrodes was stretched within a frame at 30-cm intervals. The 3.66 m by 3.08 m frame was made of 5.08-cm-long fiberglass tubes with 6.35-mm-thick walls. Two of these rectangular frames were attached and allowed to hinge along their longest dimension to accommodate the break in slope common at Lake Trout spawning sites (Figure 4). A switching mechanism directed power to strings of electrodes; pairs of electrode strings were powered as anode and cathode for 60 s.

The sedentary array was tested at 11 sites within the study area; 9 were randomly assigned as treatment exposures, and 2 were randomly assigned as control exposures. The electrode array was lowered onto the site and energized for treatment exposures; for control exposures, it was lowered but not energized. Energized treatment exposures were powered using between 9 and 12 A and 1,000 V of pulsed direct current from a Smith-Root GPP 5.0 electrofisher. The GPP electrofisher produces a half-rectified sine wave; set to pulse at 120-Hz, it produced a 50% duty cycle (Miranda and Spencer 2005). When the strings were lying uniformly on the bottom, the voltage gradient was 10 V/cm between the anode and cathode strings and 5 V/cm at a distance of 20 cm.

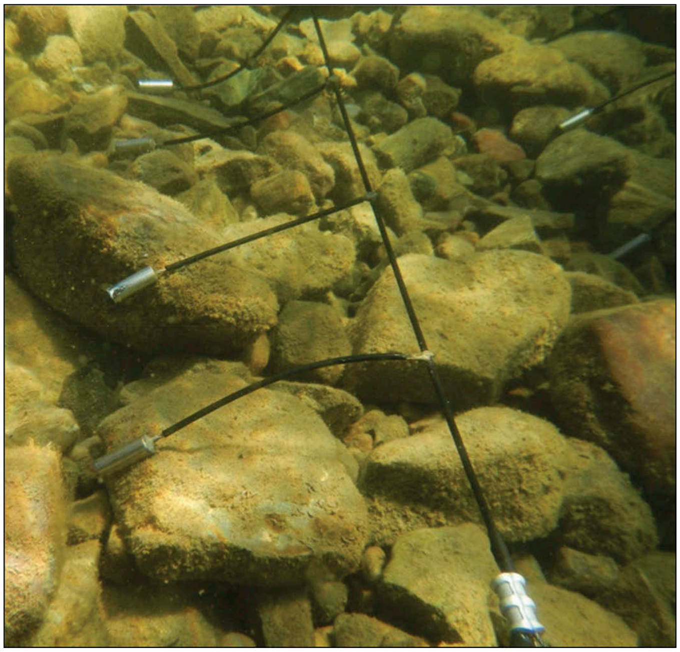

FIGURE 3. Underwater photo of stainless steel electrodes of the sedentary array. The electrodes are connected to 20 cm of vinyl-coated stainless steel cable to form a dropper. Each dropper is weighted to encourage the electrode to penetrate substrate interstices. Note clean gravel and cobble substrates in the Swan Lake study area.

Embryos exposed to the towed array were collected immediately after exposure to electricity and allowed to incubate for 24 h; gametes exposed to the sedentary array were allowed to incubate in situ for 24 h. Allowing embryos to incubate in situ was not feasible for testing of the towed array because the same site needed to be used repetitively. Embryos were considered dead if any portion of the yolk was opaque.

Percent mortality was compared among the treatment groups at the four burial depths and the control exposures. We used a Kruskal–Wallis one-way analysis of variance (ANOVA) to compare percent mortality among treatment and control groups because the data did not meet the assumptions of normality.

RESULTS

Embryo mortality differed significantly among depth-treatment groups when exposed to the towed array (Kruskal–Wallis statistic, $H = 63.6$, df = 4, $P < 0.001$), and mortality decreased as burial depth increased (Figure 5). Mortality of embryos at the surface varied from 40% to 100% and differed significantly from treatments at 10 cm and 20 cm. Mortality of embryos at 5 cm varied from 10% to 90%, and mortality at 10 cm varied from 0% to 60%. In the deepest interstices, mortality at 20 cm varied from 0% to 40% and was not significantly different from the 10-cm treatment or the control.

Embryo mortality was higher than 98% at all depths when exposed to the sedentary array (Figure 6). The

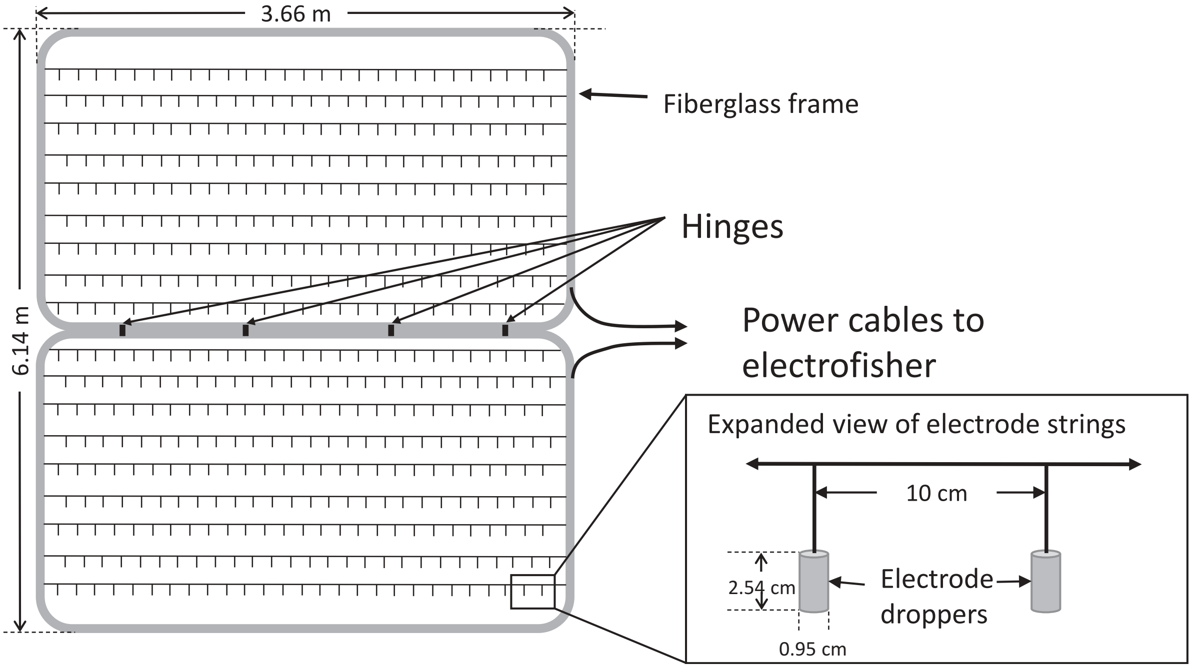

FIGURE 4. Diagram of the sedentary array. The array was moved and powered by an electrofisher on a boat.

electrode array caused 100% mortality of the embryos at the surface of the substrate. Mortality of embryos (±SD) was 99% (±2%) at 5 cm, 100% (±1%) at 10 cm, 98% (±3%) at 20 cm, and was 8% (±5%) for the control. Embryo mortality was significantly greater in the treatment exposures than the control exposures (Kruskal–Wallis, H = 56.0, df = 4, $P <$ 0.001) and was statistically similar among treatment groups (Figure 6).

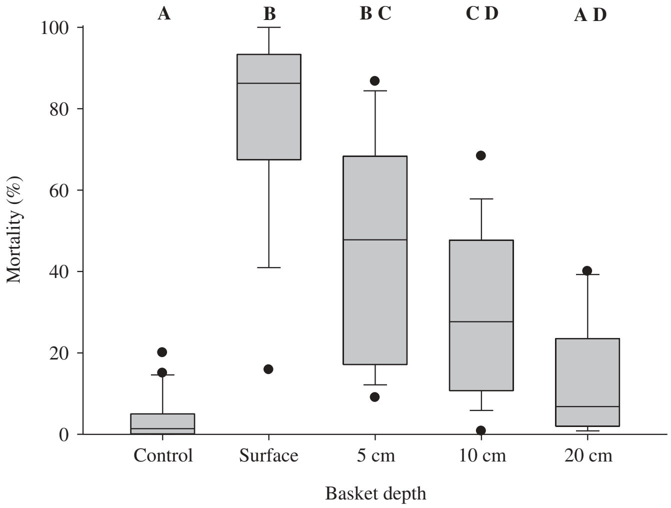

FIGURE 5. Percent mortality of embryo baskets in control and at four interstitial depths treatments when exposed to a towed electrode array. Control exposures exposed the embryo baskets to a moving but unenergized electrode array. The horizontal line indicates the median value, the box represents the 25 and 75th percentiles, whiskers represent the 10th and 90th percentiles, and dots represent outliers. Letters represent results of Kruskal–Wallis one-way ANOVA on ranks; the same letter above boxes indicates there is no significant difference between those boxes.

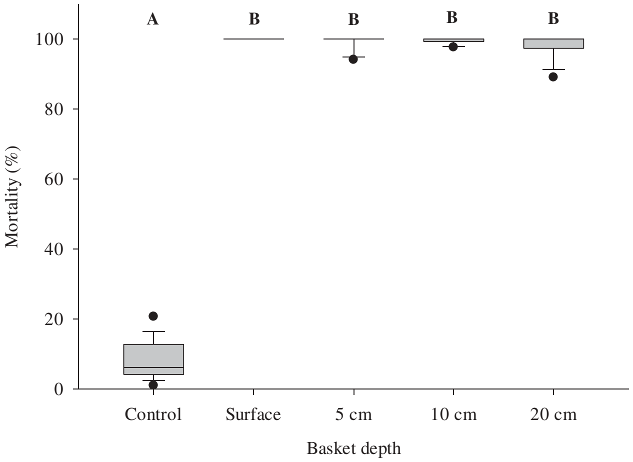

FIGURE 6. Percent mortality of embryo baskets in control and at four interstitial depths treatments when exposed to a sedentary electrode array. Control exposures exposed the embryo baskets to an unenergized electrode array. The horizontal line indicates the median value, the box represents the 25 and 75th percentiles, whiskers represent the 10th and 90th percentiles, and dots represent outliers. Letters represent results of Kruskal–Wallis one-way ANOVA on ranks; the same letter above multiple boxes indicates there is no significant difference among those boxes.

DISCUSSION

The sedentary array was more effective than the towed array for increasing mortality of Lake Trout embryos. The towed array was able to induce mortality at shallow burial depths, but the sedentary array induced mortality when embryos were placed deeper into the interstices. Embryos at deeper depths were further from the towed electrodes and were exposed to a lower voltage gradient. Voltage gradients measured at 20 cm from the towed array electrodes were sufficient to kill embryos (>3 V/cm); however, long exposures may be necessary to be effective at these voltage gradients (e.g., 20 s; Bohl et al. 2010). A towed electrode array can cause mortality in Lake Trout embryos using standard electrofishing equipment; however, the efficacy of a towed array is likely limited by the interactive influences of a short exposure duration and interstitial depth and therefore can cause high mortality only at shallow burial depths.

High mortality of embryos among treatment depths indicates that the sedentary electrode array we tested can be used to increase mortality of Lake Trout embryos. The sedentary array is highly effective to 20 cm and allows for greater penetration of the substrate through three design elements: being sedentary, having a two grid-hinged design, and placing electrodes at the end of droppers. The sedentary nature of the array allows for a longer exposure time, making a lower voltage gradient effective. A two-grid hinged design allowed the array to flex where the substrate slope changed, preventing the array from being suspended over an area of the lake bottom. Electrodes hanging from a horizontal cable (i.e., droppers) can penetrate substrate interstices because gravity carries the electrode into open voids.

Disadvantages of a sedentary array include mortality of nontarget species, the inability to deploy over large obstacles (e.g., boulders, trees), and the inability to reliably cover deep spawning areas. We observed fewer than 20 dead sculpins *Cottus* spp., Pea Mouth *Mylocheilus caurinus*, Redside Shiner *Richardsonius balteatus*, and Rainbow Trout among the trials. We did not observe any dead invertebrates. We consider mortality of nontarget species acceptable in this situation because these species are abundant throughout Swan Lake and only a limited section of shoreline would be treated during lake trout suppression efforts in this lake. However, the potential for killing nontarget species will need to be evaluated on a case-by-case basis if our array design is used in other waterbodies. Boulders perched on the surface of the substrate were common in the study area and will pose a problem for deployment and efficacy of the array. When the array is deployed on these boulders, a portion of the array is suspended in the water column, preventing the electric field from making contact with the bottom. Effective deployment over 100% of a spawning area is limited because the array cannot be reliably placed sequentially along the shoreline. The array can be lowered to depths greater than 5 m, but control when placing the array on the substrate is limited, allowing for gaps in coverage of spawning areas. This limitation may be overcome two ways: attaching a waterproof camera to the array would allow operators to deploy the array along preplaced markers; detaching the strings of electrodes and prepositioning them in the substrate would eliminate the need to raise and lower an array. To ensure that 100% of the spawning area is treated with electricity, prepositioned strings of electrodes would be connected to plugs on a buoy at the water surface or along the shoreline. The prepositioned electrodes would be spaced and powered in the same manner as described in this study, except that a Smith-Root GPP 7.5 would be able to provide more power, allowing for a larger array. Preplaced strings would also be advantageous because they could be placed close to large boulders, allowing for treatment of these areas, and the length of the dropper could be increased. Currently, the dropper length is set at half the distance between strings; the distance between strings is set by the maximum voltage output of the electrofishing unit we used (i.e., 1,000 VDC) and the target voltage gradient for salmonid eggs (3 V/cm; Bohl et al. 2010).

The electrode array may also be used to affect other life stages of Lake Trout. The presence of dead fish where the array was deployed suggests that the array is effective for larger and more mobile life stages. After Lake Trout embryos hatch, they become mobile, but movements are limited by the presence of the yolk sac (Baird and Kruger 2000). Embryos that survived the initial electrode deployment would move to a different interstitial position during this period and potentially become vulnerable to a second deployment. Further, Lake Trout are known to stay near spawning substrates for up to 700 degree-days (Baird and Kruger 2000), making multiple deployments feasible.

The success of the sedentary array shows potential for its application to complement Lake Trout suppression programs. Full-scale efficacy of alternative suppression methods relative to traditional methods (i.e., gill netting) is currently unknown. Furthermore, the level of bycatch that is acceptable varies by natural resource agency and often depends on the abundance of the species being conserved. Thus, the trigger point for when alternative methods will be implemented will be highly variable among natural resource agencies and ecosystems. One of the most probable factors influencing the use of alternative methods is cost of the traditional suppression program. Alternative approaches will likely become more attractive as the cost per Lake Trout harvested by traditional methods increases; this would occur when Lake Trout density decreases while similar suspression efforts are maintained. Gill-netting programs are costly; for example, Lake Trout suppression in Yellowstone Lake, Wyoming, costs approximately US$2 million per year. For comparison, the sedentary array tested in this study would cost about US$20,000, require two operators, and cover about 250 m^2 in one night. However, the efficacy of these two methods has not been compared at the population level.

In the near future, alternative methods are unlikely to replace traditional suppression methods for Lake Trout. Nonetheless, we argue that alternative methods should continue to be evaluated as complementary methods to traditional approaches. Using multiple methods of suppression is an approach that has been implemented for decades in Integrated Pest Management. Another advantage to studying alternative methods is that proven methods may be transferable to other species and ecosystems. For example, the sedentary array in this study may be useful in controlling Walleye *Sander vitreus* and Smallmouth Bass *Micropterus dolomieu* in waterbodies with specific conductance values similar to that of Swan Lake, Montana.

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