Techniques for Suppressing Invasive Fishes in Lacustrine Systems: A Literature Review

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Draft Final Report to the National Park Service, Yellowstone National Park, Wyoming

Introduction

Sport fishing for both native and nonnative fishes, managed naturally or through aquaculture practices, contributes over $69 billion to the economy of the United States (Bjergo et al. 1995). Although the economic benefits are substantial, a conservative economic estimate of losses caused by nonnative fish introductions yields a negative effect on native fishes and other aquatic biota of more than $5 billion annually (Pimentel et al. 2005). In fact, it has been estimated that the environmental damages and losses due to all invasive and nuisance species in the United States exceed $120 billion annually (Pimentel et al. 2005). Additionally, nonnative fish are implicated in the classification of 44 native species of fish as either threatened or endangered in the United States (Wilcove et al. 1998; Courtenay 1993), and 27 other native fish species are negatively affected by nonnative fishes (Wilcove et al. 1998).

Nonnative predators, such as lake trout (*Salvelinus namaycush*) and northern pike (*Esox lucius*), are associated with substantial declines in native fish populations throughout the western USA, and both aquatic and terrestrial ecosystems (Tronstad 2007) have bee altered. Millions of dollars have been spent on nonnative-fish suppression (e.g., Yellowstone National Park, Wyoming; Lake Pend Oreille, Idaho; Lake Coeur d'Alene, Idaho; and Davis Lake, California) and native-fish supplementation and restoration programs using cultured fish. To date, there is no evidence that these strategies have been successful at eliminating nonnative predators from large lakes (e.g., Gresswell 2009).

Primary suppression methods used for nonnative-fish suppression in lakes include netting, chemicals, migration barriers, and electricity. Methodologies such as gill netting, piscicide application, or movement barriers are costly and have significant negative environmental effects (Martinez et al. 2009). Unintended consequences include bycatch of non-target organisms with gillnetting, mortality of non-target organisms from the use of piscicides, food-web alterations, and the obstruction of native fish spawning migrations and nutrient distribution in a watershed. Although using electricity to remove adult fish is practical for management in shallow water, this technique is not suitable for fish in deep water and in waters with low conductivity. Furthermore, electroshocking has been used successfully for removing lake trout from spawning areas in the littoral zone, but despite high catch rates, some lake trout successfully spawn each year. At present, however, eradication strategies that target developing embryos and larvae have not been investigated extensively.

A technique for destroying lake trout embryos on spawning grounds would provide an important tool for suppressing lake trout numbers. Such a tool could be used synergistically with methods that target free-swimming individuals (e.g., gill nets or electrofishing), or potentially, it could be effective alone. Furthermore, a successful outcome would have broad applicability to areas across the northern Rocky Mountains where introduced lake trout threaten the persistence of native trout (e.g., Yellowstone Lake, Lake McDonald, Priest Lake, and Lake Pend Oreille). For example, lake trout embryo and larvae destruction would enhance efforts to protect bull trout (*Salvelinus confluentus)* by suppressing the nonnative predator in lacustrine habitats, and it may be critical in attempts to preclude listing of Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) and westslope cutthroat trout *Oncorhynchus clarkii lewisi)* under the Endangered Species Act.

The purpose of this report is to review possible strategies for suppression and eradication of fish during early life-history stages in natural settings and briefly discuss some promising alternatives. The report is divided into three sections evaluating physical, chemical, and biological techniques currently in use, and those with substantial potential to eradicate invasive salmonids. To date, we have reviewed over 330 published articles on life-history traits, aquaculture, and mortality of salmonid fishes in order to determine candidate strategies for integrated suppression management. The majority of candidate strategies recommended are considered cost effective by the authors. Some alternatives, such as research on pheromones, could cost millions of dollars and require over a decade of focused study. We have attempted to focus on strategies that have limited negative effects on the environment, and therefore, chemicals that have not been tested in natural settings will not be addressed in this document but may be referenced in the literature cited. Although some techniques may be applicable for lotic systems, the intent of this document is to review applicable methods for species suppression from lacustrine systems.

Physical Techniques

Perhaps the most common techniques used for suppressing free-swimming fish are associated with physical processes. Netting, migration barriers, and electricity have been used for this purpose, but few of these physical techniques have been applied to larvae or developing embryos. Of these, electricity may provide the greatest opportunity to eliminate large numbers of larval fish. Previous studies have demonstrated that developing embryos (<1-week post fertilization at 12º C) are susceptible to electroshock (Dwyer et al. 1993), but techniques for using electricity necessary to suppress populations have not been explored.

Other physical strategies may be effective larval control strategies (Table 1), but only techniques that exhibit minimal negative consequences to the physical environment and non-target biota were explored further. A promising technique could be implemented for long-term, chronic application, or for repeated short-term, acute applications. It is probable that the use of electricity, sound waves, ultraviolet radiation (UVB), smothering (covering with inert substance), and containment tarps (using a “tarp” to cover the target area concurrently with chemical application) are techniques that could be effective for eradication of fish larva and embryos.

Electricity

The application of electrical fields in water to influence movement, facilitate capture, and kill fish has been implemented for decades (e.g., Barton and Grosh 1996). Electrical fields have also been used to limit the spread of nonnative fishes in some locations (Dawson et al. 2006); however, the use of electrical fields to specifically target and kill nonnative species on a large scale has not been documented. There are a number of challenges associated with use of electrical fields for this purpose, including determining effective electrical current types, minimizing harm to non-target native fish populations, and achieving population-level reductions in nonnative fish populations.

Electrical fields have lethal and sublethal effects on fish, and substantial research has focused on immobilizing fish without causing injury (Miranda 2005). Evidence suggests that water conductivity, current type, fish species, and fish life-history

Table 1.- Potential physical strategies for eradication of salmonid embryos and larvae.

Method	Environmental uses	Life history stage	Spatial/Temporal effects
Electricity	Eradicate embryos with direct current.	All stages, but early embryos less susceptible.	Acute/non-persistent: electrical field between ground and top of substrate.
Light (visual and ultraviolet spectrum)	Embryos subjected to high end spectrum radiation.	Early embryo.	Acute/non-persistent: light will be emitted between bulb and top of spawning bed.
Sound (seismic technology)	Rupture embryos by physical pressure.	Variable effects on adults, inconclusive effectiveness against larval stages.	Generalized/non-persistent, but little is known about the lethal range of seismic field.
Containment tarps	Eliminate ability of hatched embryos to inflate air bladders.	Early larval stages.	Acute/non-persistent.
Silting	Reduce ability of embryos to access oxygen.	Early larval stages.	Acute/persistent: can disturb the environment by covering substrate with fine particulate matter.
Nets and traps	Capture species for removal purposes.	All stages.	Acute/Non-persistent: effects are localized to trap and non-target species are released.

stage are the primary variables affecting the likelihood of injury from electrical exposure (Dolan and Miranda 2004). Although water conductivity is difficult to manipulate, electrical current types can be adjusted, and specific electrodes can be designed to generate electrical fields that are lethal (Henry and Grizzle 2006). Furthermore, variation in sensitivity to electric shock suggests that specific life-history stages can be targeted by manipulating characteristics of the electrical field (Snyder 2003).

Targeting early life stages of nonnative fishes is advantageous because large numbers of young fish that congregate together enabling potential population-level effects to be achieved. Research on the lethal effects of electrical fields in embryos of numerous fishes indicate that (1) embryos are most vulnerable to DC electrical fields, (2) vulnerability varies with stage of embryonic development; and (3) even brief exposure is sufficient to induce high mortality in embryos during critical developmental stages (Henry and Grizzle 2003). The ability of DC electrical fields to kill fish embryos is related to the intensity (V/cm) of the electrical field, and the intensities generated by normal electrofishing equipment (1-20 V/cm) are sufficient to induce high mortality in fish embryos during sensitive stages (Dolan et al. 2002). Vulnerability is also positively related to embryo diameter, and the similarity of response among species suggests that the phenomenon is related to the interaction of physical properties of the embryos with the electrical field rather than species differences (T. Henry, University of Plymouth United Kingdom, personal communication).

In general, current evidence suggests that using electrical fields that are targeted on embryonic stages of development could substantially enhance nonnative fish suppression programs. At the same time, further information is needed concerning the effects of water conductivity on vulnerability of embryos to electroshock. Furthermore, it will be necessary to identify the specific electrode configurations necessary to apply electrical current directly to substrates or sediments where developing embryos of targeted species are located.

Light

Numerous studies have evaluated the effects of the light spectrum on the physiology of aquatic organisms. For example, experiments have demonstrated that reproduction, survival, and fitness of fishes are tied to light duration and intensity (Meseguer et al.2008; Rodriguez et al. 2009). Other studies suggest that the light itself, and not the indirect temperature change, elicits additional oxygen consumption and increased metabolism in turbot *Psetta maxima* 9-12 d following fertilization (Finn and Ronnestad 2003). Furthermore, with increasing duration of visible light, mortality rates in developing embryos increase in hatchery settings (MacCrimmon and Kwain 1969).

The deleterious and sublethal effects of ultraviolet (UV) radiation to the gametes and larvae of aquatic organism are well documented. In fact, a reduction in sperm motility, due to sperm inactivation, has been observed (Arias-Rodriguez et al. 2004). A meta-analysis of UVB effects on freshwater and marine ecosystems suggested that UVB radiation has greater negative effects on embryos than on other life history stages. Although there was much variation among species, overall it appears that UVB radiation has negative effects on the aquatic ecosystem (Bancroft et al. 2007). For example, water transparency influences the susceptibility of *Galaxias maculatus* to UV radiation, and in turn, habitat suitability of the species is directly related to the UV radiation levels (Battini et al. 2000). It appears, however, that the sum of UV radiation is more important than the exposure rate, but shorter wavelengths of UV radiation have more pronounced effects on fish survival regardless of dosage (Browman et al. 2003). Although fish embryos are more susceptible to UV radiation at early stages of embryogenesis, it appears that fishes reared in an open environment, as opposed to a hatchery, exhibit a higher tolerance to UVB radiation (Dong et al. 2007).

Adult fishes may also be affected by UV radiation. In controlled experiments, UVB radiation caused sunburn and sloughing of the mucous membrane in trout (Blazer et al. 1997). Adult trout have also exhibited greater vulnerability to disease after multiple days of exposure to UV radiation (Jokinen et al.2008). Exposure to UVA radiation elicits restless behavior and increased metabolism in adult trout (Alemanni et al. 2003).

Sound

Public awareness and scrutiny of underwater explosives have become more common with increased exploration of energy resources and concern about the effects on adult fishes, turtles, and marine mammals. In fact, aquatic organisms are highly sensitivity of to rapid pressure changes generated by underwater explosions (Wright 1982). It has been suggested that vertebrates with gas-filled internal organs (i.e., lungs or swim bladders) may be vulnerable at greater distances from explosions (Hubbs and Rechnitzer 1952), but there is substantial uncertainty in predicting the ecological risk of injury and mortality.

Information about the effects of underwater explosions on fish embryos and small juveniles is scarce, and although more research has been conducted on adult and large juvenile fishes, data on the effects of underwater detonations is limited and highly variable (Popper and Hastings 2009). Environmental factors, such as turbidity, wave action, currents, and water depth, may have substantial influence on the effects of sound waves. Concomitantly, experimental factors (e.g., handling stress, sudden pressure changes while lowering fish to study depth, and failure to acclimatize experimental fish to water chemistry and temperature) have confounded results of some studies (Popper and Hastings 2009).

Effects of mechanical stimulation on developing larvae may vary with stage of development (Pearson et al. 1994). Although some studies have suggested that larval fish are less sensitive to injury than are juvenile and adult fish (Wright 1982), other studies have reported increasing sensitivity to blasting with decreasing fish size (Goertner and Blatstein 1978; Munday et al.1986). Moreover, most studies have focused on the direct effects (i.e., mortality), but there are many sublethal indirect effects of blasting activities. These effects (e.g., impairment of predator avoidance behavior or substrate alteration in spawning areas) can result in additional mortality and diminished reproductive potential (Rosenthal and Alderdice 1976).

Recent reviews suggest that effects of sound waves may be a viable tool for suppression of nonnative fishes (Bennett et al.1994; Popper and Hastings 2009). Seismic technology offers many advantages over traditional methods of fish removal (e.g., gillnetting, poisons, or habitat alterations) because developing embryos and larval fish can be killed by emitting sounds directly over spawning beds, and therefore, recruitment is reduced without altering the spawning habitat. Several studies have examined the effects of sounds on fish embryos and larvae (Kostyuchenko 1973), and significant mortality of several marine species (Atlantic cod *Gadus morhua*, saithe *Pollachius* *virens*, and herring *Clupea harengus*) at a variety of ages occurred within 5 m of the source (Booman et al. 1996). The most substantial effects were to fish that were within 1.4 m of the source, and the authors noted that an exceedingly large particle velocity may be the cause of mortality as the embryos and larvae were very close to the airgun array (Booman et al.1996).

Silting/Containment Tarping

Salmonid juveniles appear to be very sensitive to suspended sediment and silt, and both sublethal and lethal effects have been evaluated in the laboratory and the field (Korstrom and Birtwell 2006). Salmonid redds must have sufficient interstitial water flow (Sowden and Power 1985), and the proportion of fine sediment in spawning substrate is the primary predictor of spawning habitat quality (Levasseur et al. 2006). In fact, even small increases in sand content can negatively affect survival to hatch. For example, LaPointe et al. (2004) found that when sand content of substrate exceeded 10%, survival to hatch was reduced three times for every 1% increase in sand content. Furthermore, studies focused on the effects of clay particulate on embryo oxygen consumption suggest that developing salmonids embryos oxygen consumption can be reduced by 98% following small additions of clay particulate (Greig et al. 2005). Because high interstitial water flow is important for the maintaining oxygen availability to developing embryos (Dillon et al. 2003), silting may be another viable technique for destroying lake trout during this vulnerable life stage.

Moreover, containment tarps may also be able to create a smothering effect on embryos and larvae. The use of tarps has primarily been implemented to control invasive plants, and when integrated with the application of chemical agents, results have been promising. For example, the deployment of containment tarps, along with chlorine injection, resulted in the complete eradication of the invasive marine alga *Caulerpa taxifolia* from an intertidal estuary along the Southern California coast (Anderson et al. 2005).

Nets and Traps

Nets and traps are commonly used to capture fish embryos, fry, juveniles, and adult fish, and in addition to capturing fish for commercial and subsistence consumption, and fisheries research and monitoring, nets may be used for nonnative fish suppression (Doyle et al. 2008). Information concerning netting strategies for adult and juvenile fish is abundant (Hubert 1996), but the utility of using nets and traps for suppressing developing embryos and larvae is not well documented (Chotkowski et al. 2002).

Chemical

Chemicals have been used to capture and kill fish for hundreds of years. It is of no surprise that chemicals still pose a viable strategy for the eradication of nonnative fishes (Lennon 1971; Dawson and Kolar 2003). The most common current use piscicide is Rotenone. Unfortunately, most piscicides are not selective and may affect native fish and invertebrate populations (Dawson and Kolar 2003). Furthermore, information focused specifically on the destruction of embryos or larva is inadequate.

Dawson and Kolar (2003) evaluated 45 chemical compounds for potential use as piscicides. Evaluation criteria included selectivity, ease of application, non-target organism toxicity, human safety, environmental persistence, bioaccumulation, and cost.

Based on those criteria, only Squoxin (an unregistered selective piscicide for northern pikeminnow *Ptychocheilus oregonensis*) scored as high as chemical toxins that were registered at the time of publication.

Some chemical compounds that were considered “relatively benign” and not particularly effective piscicides by Dawson and Kolar (2003) included lime, potassium permanganate, calcium hypochlorite, sodium sulfite, and sodium hydroxide. These chemicals are particularly interesting for use in destroying lake trout embryos because they are approved for environmental discharge and are commonly used in aquaculture and water treatment facilities. Potassium permanganate and sodium hydroxide are fungicidal and bactericidal agents used protect fish embryos during development. Peracetic acid and iodine are fungicidal chemicals that were not evaluated by Dawson and Kolar (2003) but meet the proposed criteria. Iodine has been used historically as a fungicide in hatcheries, but very little research, if any, has been conducted concerning the effects of peracetic acid on fish.

We have selected six chemical candidates for further consideration for eradication of lake trout embryos and larvae (Table 2). These chemicals exhibit limited potential to bioaccumulate and biomagnify in the food chain, are not persistent, and tend to degrade rapidly. All chemicals have either historically been used in aquaculture, in water treatment, approved for discharge into surface waters, or for potable water use. When applied in concert with physical strategies such as a containment tarp, these chemicals may provide an effective and low-risk strategy for use in localized spawning areas. Of the six chemicals selected, we have limited further discussion to CO_2 because the toxic

Table 2.- Potential chemical strategies for eradication of salmonid embryos and larvae

Method	Environmental uses	Life-history stage	Spatial/temporal effects
Potassium permanganate	Inactivator of rotenone (piscicide) and water disinfection	Embryo and larval stage	Acute/semi-persistent: It can bioaccumulate in lower organisms (e.g., phytoplankton, algae, mollusks, and some fish), but not in higher organisms, and in surface waters, manganese occurs in both dissolved and suspended forms, depending on such factors as pH, anions present, and oxidation-reduction potential.
Sodium and calcium hypochlorite	Water disinfection	Embryo and larval stage	Acute/non-persistent: Broken down into salts in water and hypochlorite ions react immediately with substances in the water and are broken down by sunlight.
Iodine	Antimicrobial	Embryo and larval stage	Acute/non-persistent: In surface water will vaporize and off gas.
Peracetic acid	Antimicrobial and bleaching agent	Embryo and larval stage	Acute/non-persistent: Oxidizes quickly with substances in water.
Ammonia	Fertilizer and cleaning agent	Embryo and larval stage	Acute/non-persistent: Rapidly broken down by microorganisms in water.
Carbon dioxide	Fish anesthetic	Embryo and larval stage	Acute/non-persistent: Rapidly off gases and diffuses readily.

effects of the other five chemicals on fish embryos have been reviewed extensively (except for peracetic acid).

Carbon dioxide

Carbon dioxide gas may be a viable eradication agent because it does not accumulate in the environment, and although it diffuses readily in water, it does not persist. The efficacy of CO_2 for eradicating nonnative fishes has not been evaluated extensively, and lethal concentrations have been determined for only a few fish species. Although it is apparent that tolerance to CO_2 is species-specific (Ishimatsu et al.2005), variation in susceptibility to CO_2 among life stages within fish species has not been explored comprehensively (Ishimatsu et al. 2004). Regardless, CO_2 is currently used as an approved method of euthanasia for laboratory fishes and in the aquaculture industry (Pirhonen and Schreck 2003). In the field, CO_2 could be deposited directly on the spawning beds as a solid (dry ice) because it is denser than water and will sink rapidly. Alternatively, it could be applied by inserting gas bubblers (in gas phase) throughout the spawning beds.

Biological

Of all integrated pest management practices, biological strategies (e.g., release of genetically manipulated fishes into a water body in order to alter sex ratios and population numbers) have been explored least. Biological methods may require many years to suppress invasive species populations under natural conditions (Vrijenhoek 1994), and in aquatic environments, they have primarily been tested using mathematical models (Vrijenhoek 1994). For example, introducing triploid fish or fish that produce only male offspring is controversial because manipulative treatments may not be completely effective (i.e., unanticipated consequence of actually increasing the target species; Pandian and Koteeswaran 1998). Furthermore, the altered fish may not function behaviorally as wild fish and may not compete successfully with established males for spawning areas and or mates (Benfey 1999).

A biological strategy that alters fish physiology, ultimately impacting behavior or reproduction may offer promise. For example, chemo-attractants (pheromones) utilized by fish for various behaviors such as predator avoidance, reproductive timing, and migration are capable of luring fish into a particular area to be captured by nets. Sexually mature adults express pheromones for spawning behavior, and larvae can also be attracted to adult pheromones (Burnard et al. 2008). In the Great Lakes region, pheromones specific to sea lamprey *Petromyzon marinus* have been successfully used to suppress this nonnative invader (Sorensen and Vrieze 2003).

Another strategy that has shown mixed results is the culture and release of fish predators that target embryos and juveniles as a major component in their diet (Fitzsimons et al. 2006). This strategy has been especially effective when nonnative predators reduce native species recruitment (Jones et al. 1995). A cultured native species that already exists in a natural equilibrium with resource availability, may suppress larvae and embryos of the invasive species if the cultivars can be increased quickly during the spawning season. Although biological strategies may require extended time to be effective and may require considerable effort in development and testing, they may have great promise for eradication and suppression efforts (Table 3). For this report we have

Table 3.- Potential biological strategies for eradication of salmonid embryos and larvae

Method	Environmental uses	Life-history stage	Spatial/temporal effects
Pheromones	Attracting only target species to traps spawning areas.	All Stages	Generalized/non-persistent: Release of pheromones maybe widespread, however, they will rapidly dissipate.
Genetic manipulations	Reduce ability to produce fertile offspring.	Adult	Acute/persistent: Genetic manipulation will not take place in the system and will affect only reproduction potential of target species.
Aquaculture of predator	Eliminate embryos through predation.	Embryo and larval stages	Generalized/persistent: Predator would be widespread and would have potential to survive and reproduce in the system once introduced.

focused on possible applications of pheromone use for trout embryo and larvae suppression and eradication.

Pheromones

Pheromones are externally secreted hormones that have strong communicative capacities among individuals of the same species. In general, fish pheromones can be organized into three main categories: reproductive cues, anti-predator cues, and social cues (Sorensen and Stacey 2004). Fish species are able to discern between chemical signals within (Olsen et al. 2002; Appelt and Sorensen 2007), and among species (Laberge and Hara 2003). Therefore, pheromones offer a unique opportunity to elicit specific responses from a target species.

The effects of fish pheromones on behavior have been evaluated for at least 30 years. Earliest studies suggest that the behavioral response to the same chemical cue differs by life-history stages (Yambe and Yamazaki 2000). For instance, pheromones are used by fish to signal spawning readiness and location of viable mates. In some case, however, similar pheromone compositions occur in different species of fish. For example, brook trout *Salvelinus fontinalis* and brown trout *Salmo trutta* are able to hybridize, and individuals from both species respond to the same pheromone derivatives. It appears that from a reproductive aspect, these fish rely more heavily on pheromone cues than visual cues (Essington and Sorensen 1996). Studies have showed that three different sex pheromones are excreted in different ratios by females depending on the reproductive status, and males displayed different behavior and varied the period of behavior as the ratio of pheromones changed (Poling et al. 2001).

Releasing spawning pheromones is one possible technique that could be used to attract or drive target fish species to trap nets. Using species-specific pheromone compounds to trap nonnative species would reduce bycatch of native species and potentially accelerate the suppression process. To date, however, only one pheromone for the control of sea lamprey in the Great Lakes has been successfully developed for suppression and trapping of adult fish.

Because pheromones are also used by fishes as an alarm signal that may allow individuals to escape predation (Chivers et al. 1996), this type of hormone might be applied to spawning grounds in order to reduce the probability of successful spawning. Although the use of pheromones has many potential applications, many millions of dollars were spent over a decade for research and development for this single application. On the other hand, this level of funding may be warranted given amount of money already spent on lake trout suppression programs throughout the western USA.

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