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RESEARCH

Considerations for the Use of Captive-Reared Delta Smelt for Species Recovery and Research

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ABSTRACT

An extreme decline in Delta Smelt (*Hypomesus transpacificus*) abundance has led to a number of management actions to support this endangered species, including the development and refinement of culture techniques and the creation of a refuge population. The wild Delta Smelt population has diminished to the point that many in the scientific community believe population supplementation using cultured fish needs to be experimentally evaluated as a possible management tool. Concerns about supplementation include the effectiveness of this action, and its potential to divert attention and funding from other needed management actions such as habitat restoration. Here, we describe the outcomes of a 2-day workshop that described the current refuge population, and identified key issues for potential future use of cultured Delta Smelt for research and management. Expanded use of cultured Delta Smelt is controversial and requires consideration for complexities that include legal constraints and permitting requirements. Developing policies that allow for in situ experiments using cultured Delta Smelt appears to be a precursor for advancing policies that might allow supplementation actions. Releases of cultured fish, either experimentally or as a management action, clearly need to be conducted within an adaptive management program that is integrated with other strategies, including habitat restoration. We describe a general framework for evaluating the potential risks of supplementation and include suggestions for how to reduce risks and uncertainty. Overall, we conclude there is sufficient baseline information about Delta Smelt and the existing culture program to proceed with targeted field research that utilizes cultured fish. Finally, given the dire status of this species, we conclude that rapid progress toward the development of a viable and

testable supplementation program must be a priority for Delta Smelt conservation.

KEY WORDS

Delta Smelt, *Hypomesus transpacificus*, refuge population, supplementation, conservation aquaculture

INTRODUCTION

Delta Smelt (*Hypomesus transpacificus*) is a small (maximum length ~120 mm FL) estuarine fish endemic to the upper reaches of the San Francisco Estuary (estuary) (Moyle 2002; Bennett 2005; IEP–MAST 2015). Once very abundant, Delta Smelt are now rare, and are protected under the federal (ESA; threatened) and California Endangered Species Acts (CESA; endangered). The species currently consists of a single remnant population (Moyle and Herbold 1992; Fisch et al. 2011) that completes its entire life cycle in the upper estuary. Delta Smelt live 1 to 2 years, and historically demonstrated high variability in spatial distribution and annual abundance, generally responding better to wetter conditions, high turbidity, moderate temperatures, and improved food availability (Moyle et al. 2016). The decline of this species began during the early 1980s, which ultimately led to its federal listing in 1993 (USFWS 1993). Population abundance decreased further around 2002, which included declines of several other pelagic fishes of the upper estuary—a phenomenon known as the "Pelagic Organism Decline" (POD) (Sommer et al. 2007; Thomson et al. 2010; IEP–MAST 2015).

Research indicates the POD was caused by multiple biotic and abiotic factors; however, the specific mechanisms causing decline in Delta Smelt have not been adequately resolved (MacNally et al. 2010; Thompson et al. 2010; Maunder and Deriso 2011; Miller et al. 2012; Rose et al. 2013a, 2013b; IEP–MAST 2015; Kimmerer and Rose 2018). The Delta Smelt decline is thought to be a result of multiple factors, including water diversions, increased contaminant inputs, habitat changes, and a series of invasive species introductions (IEP–MAST 2015; Merz et al. 2016; Moyle et al. 2016). The uplisting of Delta Smelt to endangered under CESA, and permitting requirements for continued operation of the Central Valley Project (CVP) and State Water Project (SWP), resulted in the 2008 Biological Opinion that included several actions aimed at recovering the species, including: limiting exports, managing local tidal flows (Old and Middle River) to minimize entrainment of adults and larvae, and experimentally increasing Delta outflow in the fall of wet years to increase suitable habitat during its transition from juveniles to sub-adults (USFWS 2008a). An increase in Delta Smelt abundance was observed in association with wet conditions of the 2011 water year; however, the subsequent historic drought (2012–2016) and extreme wet year of 2017 have been accompanied by continued record low abundance, increasing concerns that the resilience of this species has been undermined, or that habitat in the Delta remains poor, even in years where flow-related habitat metrics may have improved.

Given the dire state of Delta Smelt, fisheries researchers and other stake-holders have demanded urgent action from fisheries agencies. As such, there is increasing interest in the implementation of management actions to reduce the risk of species extinction, including the possibility of using cultured fish to bolster the wild Delta Smelt population (Hobbs et al. 2017). Specifically, Hobbs et al. (2017) suggested that the species may have declined to the point where recovery might depend, at least in part, on the use of cultured fish. As will be discussed below, Delta Smelt have been cultured since the mid-1990s (Lindberg et al. 2013), and are now held in a refuge population at the University of California at Davis Fish Culture and Conservation Laboratory (FCCL), with a portion of these fish also held at the Livingston Stone National Fish Hatchery. While cultured fish have been valuable for researching the basic life history and biology of Delta Smelt (e.g., Hasenbein et al. 2016; Komoroske et al. 2014), to date, these fish have not been released into the wild or used for in situ experiments in the Delta. As a result of the recent extreme declines, Hobbs et al. (2017) recommended the development of a management plan for artificial propagation of Delta Smelt, and implementation of carefully planned field experiments using cultured Delta Smelt. Toward that goal, the USFWS is considering the construction of a regional Fish Technology Center (in collaboration with the California Department of Water Resources [CDWR]) to be co-located at the Rio Vista Army Base, Redevelopment Area, to support an expanded refuge population and to support research and possibly supplementation (USFWS 2016a). Here, supplementation is defined as the intentional movement and release of an organism inside its indigenous range (if the species has disappeared, this same action would be considered reintroduction) (IUCN/SSC 2013).

However, even with strong consensus on the dire status of wild Delta Smelt, experts still have significant concerns about supplementation. These concerns are primarily based on two, somewhat related issues: (1) supplementation will not be a useful action if the stressors that cause decline are not resolved, and so could lead to increased stress on the wild population, and (2) supplementation will be expensive and time-intensive, potentially reducing resources available for large-scale habitat restoration.

To help guide future decision-making about the potential use of cultured Delta Smelt, the CDWR, UC Davis, the California Department of Fish and Wildlife (CDFW), USFWS, the U.S. Bureau of Reclamation (Reclamation), the American Fisheries Society CAL-NEVA Chapter, and Cramer Fish Sciences organized a 2017 workshop: "The Delta Smelt Culture Program: From Experiments to Supplementation." This workshop involved managers and technical experts from these agencies, local universities, other research organizations, outside experts in fish reintroductions, additional stake-holders, and relevant interested parties. The workshop's goal was to examine if and how cultured Delta Smelt could be used more broadly to avoid species extinction and support species recovery. The workshop did not address whether supplementation should proceed; this type of decision for Delta Smelt is under the jurisdiction of the USFWS under the federal ESA. However, the process of how such a decision should be made was a key topic of discussion. Here, we summarize some of the major findings of the workshop, including: (1) the state of science on Delta Smelt propagation; (2) regulatory and permitting considerations; (3) management considerations; and (4) monitoring considerations. We conclude with a discussion of some of the major information gaps that workshop participants identified, including immediate and long-term actions needed for successful use of captive-reared Delta Smelt for recovery and ongoing research.

PROPAGATION FOR SPECIES CONSERVATION AND RESEARCH

Culturing Delta Smelt

The goal of the Delta Smelt captive breeding program at the FCCL is to "create a genetically and demographically robust captive population that will act as a genetic bank in the event this species becomes extinct in the wild, as well as potentially serve as a source for supporting wild populations if such a need arises" (Fisch et al. 2012). The captive breeding program operates under a rigorous genetic management plan jointly managed by the FCCL and the Genomic Variation Laboratory (GVL) at UC Davis to maintain genetic diversity and minimize kinship among captive fish (Fisch et al. 2012). To achieve these goals, the FCCL is permitted to collect up to 100 wild Delta Smelt annually to supplement genetic diversity and mitigate increasing levels of hatchery ancestry within the refuge population. In addition, approximately 1,500 cultured sub-adult Delta Smelt are transported annually to the Livingston Stone National Fish Hatchery, which acts as a 'failsafe' population in case a catastrophic event occurs at the FCCL.

Culture methods used by the FCCL have been reviewed in detail by Lindberg et al. (2013) and have been recently modified (T. Hung, 2018a unpublished data, see "Notes"). To summarize briefly, the FCCL facility consists of several buildings located at the Skinner Fish Facility adjacent to Clifton Court Forebay (CCF). The facility relies on surface water drawn from the forebay, which is treated by settling, filtration, ozonation, and foam-fractionation before it is distributed to fish-rearing systems. Fish are transferred five or more times between fish-rearing systems to accommodate different life stages: (1) larval; (2) late-larval (3) juvenile; (4) sub-adult; and (5) adult (Mager et al. 2004).

The key strategy adopted by managers of the Delta Smelt captive breeding program is to develop and implement an intentional breeding matrix using empirical genetic data (Fisch et al. 2012). A 2012

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evaluation of the Delta Smelt captive breeding program found that the initial 2008 captive population contained high levels of allelic diversity and heterozygosity, and it has continued to retain these important genetic characteristics (Fisch et al. 2012). Annual analyses reveal that, to date, neither allelic diversity nor heterozygosity between the propagated captive population and the newly captured wild fish are significantly different (Finger et al. 2018). Monitoring of phenotypic patterns in the cultured population has, so far, not found any differences in observed metrics (e.g., size at maturity, fecundity) of the cultured population as compared to wild fish; however, Finger et al. (2018) found that increasing levels of hatchery ancestry in a cross led to a greater probability of producing offspring that survive to maturity the next year, signaling domestication selection. These results suggest that the genetic management plan has effectively maintained the initial genetic diversity in the refuge population thus far, but the population may be adapting to captive conditions. Continued reliance on annually-collected wild broodstock to maintain genetic diversity within the cultured population represents a key demographic and genetic risk to the refuge population. Should the wild population decline to the point where adequate numbers are no longer available for broodstock, the refuge population will begin to suffer from a loss of genetic diversity and increased genetic adaptation to captivity (i.e., domestication), which is well documented to reduce fitness in cultured fish and their offspring in the wild (Wang et al. 2002; Araki et al. 2007). If this situation arises, the species as a whole will be at risk, and the refuge population will be compromised.

Use of Cultured Delta Smelt in Research

The maximum adult capacity of the FCCL facility is currently only 53,500 adult fish; thus, large numbers of cultured animals are culled from the population because of space limitations. This excess production could be used by a wide range of researchers for experiments relevant to Delta Smelt recovery; however, to date, use of these fish has been fairly limited. Some of the fish produced by the FCCL have been used in research studies that examine the organismal and ecological biology of Delta Smelt. The FCCL continues to be involved in several collaborative studies with researchers from academia, government agencies, and corporations (e.g., Castillo et al. 2014; Hasenbein et al. 2016; Kammerer et al. 2016). Fish propagated at the FCCL have primarily been used for controlled laboratory experiments focused on improving our understanding of various aspects of Delta Smelt biology, including reproduction and development (Mager et al. 2004); feeding ecology (Baskerville–Bridges et al. 2004); physiology (Swanson et al. 1998, 2000; Komoroske et al. 2014; Hasenbein et al. 2016; Jeffries et al. 2016; Kammerer et al. 2016); contaminant sensitivity (Connon et al. 2009, 2011); and tagging methods (Hobbs et al. 2012; Castillo et al. 2014; Wilder et al. 2016). In addition to laboratory studies, a mesocosm experiment was conducted on cultured sub-adults in a trough near the CCF, which confirmed that hatchery origin fish can successfully feed and achieve high survival rates (in the absence of predation) solely on natural food sources (T. Hung, 2018b, unpublished data, see "Notes"). Cultured Delta Smelt from FCCL have also been used for mark–recapture studies in the CCF (Castillo et al. 2012) and the Tracy Fish Collection Facility (Sutphin and Svoboda 2016).

REGULATORY AND PERMITTING CONSIDERATIONS

The U.S. Endangered Species Act (ESA; U.S. Congress 1973) protects species formally listed under the law, as well as the designated critical habitat on which they depend. Therefore, any studies that include "actions" considered take for wild Delta Smelt (actions that harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect) must be permitted by the USFWS (USFWS 2013). This is true of studies conducted in natural habitats using cultured fish (even if those fish are in cages intended to keep them from interacting with wild fish) and any population-supplementation actions. There are several permitting routes for these activities for ESA-listed species under the ESA, including the 4(d) rule and regulations, consultation among federal agencies (Section 7), direct and indirect take (Section 10) permitting, and listing or development of experimental populations that could either be designated as essential or non-essential to recovery (Section 10(j). Each of these permitting strategies is described briefly below, along with comments from workshop participants on options for Delta Smelt.

The first strategy involves Section 4(d) of the ESA, which allows the USFWS to issue species-specific regulations it deems necessary or advisable to provide for conservation of a listed species. The Delta Smelt is currently listed as threatened under the federal ESA; thus, the 4(d) rule would apply. As part of species-recovery planning, the USFWS can use special 4(d) regulations to allow for the reintroduction or supplementation of hatchery-produced individuals into the wild, as well as special take rules for those populations (under ESA Sections 7 and 10). These types of programs work particularly well when the reintroduction has complete spatial separation from other wild populations, minimizing any risks to wild populations from hatchery-origin fish. For example, anglers have been permitted to take Lahontan Cutthroat Trout (*Oncorhynchus clarkii henshawi*) in accordance with California state law as part of an ongoing reintroduction and supplementation program (without annual Section 7 consultation). Hatchery-reared Lahontan Cutthroat Trout are now routinely released into specific, hydrologically-isolated mountain lakes where they historically occurred but from which they had been extirpated (Al–Chokhachy et al. 2009). For Delta Smelt, to determine if supplementation can contribute to increased population resilience, special 4(d) regulations could be used to allow experimental supplementation of cultured fish in areas of suitable habitat in the Delta (e.g., isolated wetlands or channels).

The second strategy could make use of permitting under Section 10 of the ESA, which gives the USFWS the authority to issue permits for direct take (i.e., Section 10(a)(1)(A) permit) and incidental take (i.e., Section 10(a)(1)(B) permit). Section 10(a)(1)(A) permits allow for scientific research on a listed species or activities to enhance recovery of a listed species. Examples of Section 10 permitted activities include: abundance surveys, genetic research, relocations, and telemetric monitoring. Section 10 permits can also be extended to include reintroduction and post-reintroduction monitoring; however, after the individuals are released they are fully protected by the ESA (except under certain Safe Harbor Agreements). Examples of ESA-listed species reintroductions achieved with Section 10 permits include the California condor (*Gymnogyps californianus*), Bull Trout (*Salvelinus confluentus*), whooping cranes (*Grus americana*), and myriad listed plants and small mammals (USFWS 2016b). Indeed, as mentioned previously, the FCCL already has a Section 10 permit to allow for the annual capture of up to 100 wild Delta Smelt each year for broodstock in the refuge population. A recommendation from the workshop was that the FCCL try to modify their existing permit to allow for the experimental use of propagated fish in more natural experiments to address critical uncertainties. However, to permit any new or expanded field-based research activities, the USFWS must evaluate the scale of the experiment and other details to ensure that minimal risk is posed to the wild population.

Section 10(j) of the ESA provides the USFWS with the authority to designate populations of listed species as "experimental." This designation allows the USFWS to permit the handling, transport, and release of the "experimental" populations of listed species to re-establish self-sustaining populations. Two important requirements for this designation are that: (1) the "experimental" population must be reintroduced to regions that are outside the species' current range, and (2) proposed actions support species conservation and recovery. An experimental population must be a geographically-described group that is isolated from other existing populations of the species so that they cannot compete or interbreed. This requirement is a key barrier to this permitting route for Delta Smelt experimental releases and reinforcement actions, because there is only one, continuous population; however, Section 10(j) may be useful for hydrologically-isolated, wetland-based research studies.

Based on these considerations, and comments from regulatory staff at the workshop and in later discussions, permitting is expected to potentially be a challenging issue. Depending on the strategies employed using cultured fish, the approach to permitting and required consultation may take a substantial amount of coordination and time. Hence, this issue is the one most in need of immediate attention when the use of cultured Delta Smelt

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in initial field studies and for potential future applications to species recovery is evaluated.

MANAGEMENT CONSIDERATIONS

There was broad consensus at the workshop that the potential use of cultured Delta Smelt for in situ experimentation should be part of a suite of additional management actions designed to understand and reduce stressors on the species (USFWS 2008a; CNRA 2016). For example, under the current Delta Smelt Biological Opinion (USFWS 2008a) several management actions—including fall outflow requirements and tidal marsh restoration—are designed to increase suitable habitat for the species. Similarly, the Delta Smelt Resiliency Strategy (CNRA 2016) includes 13 different management actions, including spawning substrate augmentation, sediment supplementation to increase turbidity, and the development of the FTC. These actions were largely derived from conceptual models and empirical studies investigating the factors that limit Delta Smelt, yet the importance of each factor that limits the species is not known.

A key issue when considering recovery actions for any imperiled fish species is identifying the primary causes of decline, and implementing actions that effectively minimize extinction risk. Managing Delta outflow is one management strategy under active investigation (USFWS 2008a). Habitat restoration in Suisun Marsh and the north Delta are being implemented, as are other elements of the Delta Smelt Resiliency Strategy. However, abundance of wild Delta Smelt has reached such low levels that observing relative abundance changes may not reliably indicate the effectiveness of management actions (La Luz 2017). Management actions that target Delta Smelt will be expensive to implement, and difficult to justify, without a clear methodology for quantifying benefits to the species. Furthermore, the low abundance of wild Delta Smelt has led to substantial limitations in the number of fish that can be sampled, because of concerns about effects on the population. This sampling constraint further reduces our ability to use wild-caught fish to assess the effectiveness of management actions. We consider the use of cultured fish to help evaluate management actions to be an essential and valuable application for the Delta Smelt culture program.

An important consideration in the timing of these actions is that—although it would be preferable to first restore the habitat conditions necessary to ultimately improve the status of wild populations—hatchery production and supplementation using cultured Delta Smelt may be the only viable, short-term means to prevent extinction. This is often the case when natural production of imperiled or ESA-listed species is likely both habitat- and stock-limited, such as with endangered Kootenai River White Sturgeon (Anders 1998; Anders et al. 2002; Ireland et al. 2002). This is particularly true for an ecosystem as altered as the estuary and for a species with as very short a lifespan as Delta Smelt. In such cases, a supplementation program should be developed as soon as possible to: (1) incorporate as much standing genetic diversity as possible in founding broodstock, (2) develop and refine techniques for successful supplementation, and (3) engage scientific experts and stake-holders to ensure that the program benefits from scientific information that can maximize benefits and minimize risks.

Coordination

Development and implementation of a potential future supplementation program for Delta Smelt will require concerted coordination. Strong support from agency personnel, the public, and stake-holders was identified at the workshop as a key factor for success across other national reintroduction efforts (e.g., George et al. 2009; George and Sandhaus 2016; Riley and Sandstrom 2016). Many of the workshop presentations involved fish species with strong links to professional societies or multiple stake-holder groups (e.g., Lake Sturgeon, White Sturgeon, Bull Trout, Winter-run Chinook). Such alliances are useful to garner support for recovery or conservation plans (George et al. 2009; George and Sandhaus 2016; Riley and Sandstrom 2016). Recovery of Delta Smelt will likely require broad-scale habitat-restoration actions combined with extensive coordination among researchers, hatchery managers, agency staff, and water managers—along with an effective public relations campaign.

Demands on California's water resources are projected to increase with population growth (CDOF 2017), and, with the most recent drought that began in 2012 (Mann and Gleick 2015), awareness of California's water vulnerability has been heightened. These growing consumption-based demands are not well aligned with the requirements for Delta Smelt recovery actions (USFWS 2008a). This disparity highlights the difficulty for California to achieve the mandated coequal goals of "providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem" (CA Water Code §85054). Despite substantial regional and national attention on the status of the Delta Smelt, opportunities for recovery of the species (e.g. habitat restoration, supplementation) will need to be elevated within the broader public consciousness, beyond the people who regularly concern themselves with species listings. Public engagement with this issue may be a key factor to motivate the time, political pressure, and financial support required to fully implement recovery actions. Example tools for increased public engagement could include hiring additional outreach staff who focus on Bay–Delta fisheries issues, generation of accessible outreach materials, increased contact with stake-holder groups, and working more with educators.

Uncertainty and Risk Management

The design and implementation of conservation aquaculture facilities and associated supplementation strategies necessarily generates a broad set of potential risks and benefits (Anders 1998; IUCN/SSC 2013; Jachowski et al. 2016). Concerns have been raised about the potential risks to the wild Delta Smelt population from releasing hatchery-adapted fish that could introgress (interbreed) with the wild population. Such risks include reduced genetic diversity of the species, reduced fitness of the wild population, and/or unintentionally spreading pathogens from hatcheries (Anders 1998; Bohling 2016). However, the potential benefits of supplementation include: (1) maintaining genetic diversity (with hatchery-managed crosses of wild broodstock) of Delta Smelt in the absence of natural reproduction; (2) encouraging demographic and genetic vigor; and (3) supporting population resilience in a wild recipient population that has infrequent and vulnerable natural production (Anders 1998; Anders et al. 2002; IUCN/SSC 2013). It is important to strategically weigh these pros and cons before an action as potentially significant as population supplementation (IUCN/SSC 2013).

To create a tool for future research and management for Delta Smelt, workshop participants developed a framework that outlined some of the known risks of supplementation with cultured Delta Smelt (Table 1). The approach used was based on the framework for a White Sturgeon hatchery program in the Columbia River basin that specifically identifies and manages risk (CRITFC 2015). The framework addresses four primary types of risk associated with conservation aquaculture: ecological, demographic, genetic, and uncertainty. Workshop participants developed potential strategies to reduce or remove each of these risks (Table 2).

Although there is a complex suite of potential risk factors (Table 1 and 2), progress can be made while areas of uncertainty are addressed. A key recommendation from the workshop was to consider the use of a structured decision-making (SDM) approach to guide research and management decisions (Martin et al. 2009; Gregory et al. 2012). SDM is a general term for a formal decision-analysis framework that the USFWS and other agencies use and promote (USFWS 2008b). SDM, in this context, organizes an analysis of problems for the purpose of reaching consensus on decisions and management actions that are focused clearly on achieving fundamental objectives such as species recovery or invasive species extirpation (Gregory et al. 2012; Brignon et al. 2017). Based in decision theory and risk analysis, SDM includes a straightforward set of concepts and steps (Martin et al. 2009; Gregory et al. 2012).

SDM steps include identifying the problem, objectives, management action options (alternatives), anticipated consequences, trade-offs of objectives, uncertainty, risk tolerance, and linked decisions to apply a transparent method to evaluating the problem statement in the light of objectives (Martin et al. 2009; Gregory et al. 2012; Benjamin et al. 2017; Brignon et al. 2017). Adaptive management is a special case of SDM for decisions that are iterative or linked over time (Martin et al 2009; Brignon et al.

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Table 1 Components of a precautionary risk-based evaluation framework for a Delta Smelt hatchery program (modified from CRITFC 2015)

Risk type	Risk factor	Summary and description for Delta Smelt
Ecological	Interspecific interactions	Effects of competition or predation on other components of the aquatic community and food web
	Intraspecific interactions	Depression of wild population survival, growth, maturation, etc. from competition or predation (i.e., density-dependent effects)
	Pathogen transfer	Increased incidence of pathogen transfer or disease resulting from transmission in and from the hatchery and/or pathogen transfer to supplemented population leading to failure of recovery program
	Lack of suitable habitat for reintroduction	Habitat restoration efforts may not be successful or may require more time than estimated persistence of wild Delta Smelt population
	Lack of suitable spawning or early life habitat conditions	Spawning and early life stage habitat conditions may be unsuitable (e.g., in low water years) for successful natural production or survival of stocked early life stages.
	Behavioral changes	Behavioral selection from hatchery rearing could result in fish adopting in-hatchery behaviors that could reduce post-release growth or survival
Demographic	Broodstock mining	Annual removal of a significant fraction of the wild reproductive population could result in reduced natural recruitment in areas, particularly relevant during years of favorable conditions for natural production
	Broodstock selection	Selective collection of the broodstock from narrow time windows or small areas could artificially select for unintended traits in the hatchery population that we do not want re-introduced or removed from the wild population. Additionally, narrow collection methods likely do not capture the full range of genetic diversity in the species, thus potentially limiting resilience in the hatchery-produced fish
	Spawner disruption	Disruption of natural spawning by capture activities for wild adults for the hatchery
Genetic	Loss of diversity	Low effective spawning population size resulting from use of a limited number of broodstock, or broodstock with low genetic diversity
	Inbreeding Depression	Unbalanced contribution of hatchery-produced progeny groups to the next generation could lead to swamping of locally-adapted wild alleles and future inbreeding from increased relatedness among broodstock
	Selection	Directional change in genetic composition from domestication or inadvertent selection over time in the hatchery
Uncertainty	Measurement error	Uncertainty in estimates of population parameters upon which the hatchery program is scaled (survival, growth, carrying capacity, limiting factors, etc.), uncertainty about effectiveness of monitoring plans
	Process error	Incomplete understanding of limiting factors, habitat requirements, and population dynamics, which can produce unintended consequences
	Implementation error	Failure to operate the Delta Smelt hatchery program activities in an effective and timely manner based on best available plans, information, and practices

Table 2 Risk reduction strategies for a Delta Smelt hatchery program. Risk factors are described in Table 1.

Risk type	Risk factor	Risk reduction strategies
Ecological	Interspecific interactions	Scale and adjust (via adaptive management program) release numbers to optimize production while avoiding significant, density-related, intraspecific effects or interspecific ecological risks. Requires monitoring program and adaptive management decision loop on an annual basis.
	Intraspecific interactions	
	Pathogen transfer	Use best management practices to minimize or eliminate pathogen transfer; implement rigorous fish health screening and maintenance program.
	Lack of suitable habitat for reintroduction	Don't release hatchery-reared Delta smelt in areas where habitat conditions or capacity are insufficient (this is still an unknown for Delta Smelt spawning habitat).
	Lack of suitable spawning or early life habitat conditions	Experimentally release a range of life stages and use a monitoring and adaptive management program to guide decision-making on life stage releases to increase post-release survival for demographic enhancement of recipient wild population.
	Behavioral changes	Develop, refine, and employ best management practices that integrate hatchery-produced Delta Smelt with the natural genetic and life history diversity of wild Delta Smelt to minimize possible behavioral changes in progeny.
Demographic	Broodstock mining	Because the effect of broodstock mining depends on the likelihood that fish would reproduce successfully if left in the wild, consider reducing broodstock take during high water years. There is no risk if there is no natural production.
	Broodstock selection	Collect 100 wild broodstock annually (based on current take limit) across greatest available temporal and spatial ranges to maximize diversity of broodstock and resulting phenotypes, genotypes and adaptive plasticity among progeny groups. Broodstock requirement could change with scale of the hatchery and genetic diversity in the wild.
	Spawner disruption	Refine and implement most efficient means of wild broodstock collection to minimize disturbance to wild spawners/spawning in the river.
Genetic	Loss of diversity	If feasible, continue to annually supplement captive refuge population with 100 new wild-origin broodstock annually (based on current take limit). Broodstock requirement could change with scale of propagation and genetic diversity in the wild. Continue to define and implement breeding matrices annually, using empirical genetic data to minimize kinship in broodstock crosses and resulting progeny groups, and to minimize risk of selection.
	Inbreeding depression	
	Selection	
Uncertainty	Measurement error	Conduct hatchery supplementation in an experimental framework that includes a robust monitoring and evaluation program, relevant measurable benchmarks to evaluate benefits and risks, and a clear decision structure for future adaptive management. Promote and evaluate tools and techniques that facilitate improved evaluation of the contribution and survival of cultured fish in the wild. Review practices with expert hatchery evaluation team to ensure use of best available information, operations, and protocols to minimize implementation error.
	Process error	
	Implementation error	

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2017). When used within a species recovery program, SDM allows for informed decisions to be made in the face of uncertainty (Martin et al 2009; Brignon et al. 2017). Importantly, SDM can be designed to link recovery goals with different management actions via predictive models of ecological relationships (Brignon et al. 2017). An example presented at the workshop focused on the SDM model developed by the USFWS and USGS to evaluate the trade-offs between six Bull Trout (*Salvelinus confluentus*) reintroduction decisions with the goal of maximizing the number of adults in the recipient population without reducing abundance of the donor population to an unacceptable level (Brignon et al. 2017). The consensus of the workshop was that SDM is a very useful tool, and that to facilitate decision-making its use should be prioritized to evaluate alternative management actions for Delta Smelt.

MONITORING AND EVALUATION

Risks are generally recognized to be associated with nearly any management decision for the imperiled Delta Smelt population. The fragility of the population, combined with the difficulty of restoring a population in an ecosystem as large and complex as the estuary, makes any decisive action both procedurally and physically difficult to implement, and its effectiveness at a population-relevant scale difficult to track. Therefore, all management actions involving cultured or wild Delta Smelt will also require rigorous monitoring and evaluation. These actions include the on-going care and development of the refuge population, as well as experimental uses of cultured fish, all the way to supplemental releases of cultured Delta Smelt to bolster the wild population.

Workshop attendees discussed the need for adaptive monitoring and evaluation plan(s) with key metrics and objective-based, numerical decision points for all types of management actions. Different risks and decision-based issues are understood to be associated with each level of use of cultured fish from low-risk, highly-controlled, mesocosm experiments to targeted natural experiments and supplementation, that, for now, are considered high- or unknown-risk. The monitoring and evaluation plans for each type of action will need to provide information adequate to determine if the action should be continued, altered, or stopped. Based on this expectation, workshop participants developed a suite of metrics that included both population and habitat metrics of interest (Table 3). Along with determining what to measure, other key aspects of a monitoring plan include how each metric should be evaluated (e.g., time trends, location(s), life stage, fish origin). The specific methods to assess each have not yet been determined; however, most of the proposed metrics have been included as part of previous Delta Smelt

Table 3 Recommended population and habitat metrics needed for a holistic monitoring and evaluation plan within a theoretical supplementation program for Delta Smelt species recovery

Population metrics (hatchery and wild origin)	**Habitat metrics (spatial and temporal patterns in San Francisco Estuary)**
Growth rate	Water temperature
Survival	Water velocity
Breeding success	Turbidity
Relative reproductive success (including families)	Salinity
Condition and health	Prey density
Genetics (genetic diversity, effective population size, parentage)	Delta Smelt predator and competitor density
Sex ratio	Spawning habitat
% Hatchery fish (in a given location or CPUE)	Turbidity
Life history diversity	

studies on wild fish and their habitats (e.g., IEP–MAST 2015).

While many of the listed metrics represent explicit comparisons between wild and hatchery-origin fish, all metrics would need to be evaluated for the relevant component(s) of the population affected by the management action (hatchery/wild origin). This evaluation would assess response trends relative to stated goals, and adaptively adjust program practices, as needed, based on outcomes of empirical data analyses. To guide adaptive management of activities as part of a recovery plan, thresholds for selected population metrics would need to be developed, including thresholds that will stop these activities when the plan's objectives are observed.

SUMMARY AND NEXT STEPS

In agreement with a previous workshop (Hobbs et al. 2017), the 2017 workshop concluded that the status of Delta Smelt is serious enough that hatchery supplementation needs to be considered as part of future management strategies developed within a decision-analysis framework. Overall, workshop participants concluded that continuing the status quo is not a viable option, and akin to taking no action at all. Doing nothing increases the likelihood of extirpation of the single extant Delta Smelt population. Further declines in wild broodstock availability will reduce successful natural production as well as reduce levels of genetic diversity available for conservation aquaculture, making species recovery that much harder. Given the precarious demographic status of Delta Smelt and the severely degraded conditions of its habitat, the benefits of designing and performing adaptive, properly-monitored release experiments to assess the feasibility of using cultured Delta Smelt as a recovery tool now outweigh the risks of such experiments (Anders 1998; Bohling 2016; Hobbs et al. 2017).

Workshop presentations and discussions confirmed that much is known about Delta Smelt biology, although spawning behavior and spawning habitat requirements remain an ongoing knowledge gap. The estuary is an intensively monitored and studied ecosystem, and Delta Smelt may be one of the most intensively studied endangered fish species in the United States (IEP–MAST 2015). People invested in Delta Smelt conservation are, therefore, far ahead of groups working on other species recovery programs that have greater levels of uncertainty. Thus, lack of specific knowledge (e.g., questions of habitat need and restoration effectiveness) should not be considered barriers to using propagated fish to learn about potential future supplementation actions. In addition, conservation aquaculture programs for other species, and guidelines presented and discussed at the 2017 workshop, provide excellent examples to guide management of a supplementation program for Delta Smelt. These other programs, including local programs such as the Central California Coast Coho Salmon and the Sacramento Winter-run Chinook Recovery Programs (NMFS 2012, 2014), offer basic principles, management plans, guidelines, and lessons learned that provide valuable insight for further refining and expanding a Delta Smelt program.

Many of the steps and concepts needed to generate a decision-support process (e.g., SDM) for Delta Smelt are underway by various groups, although this information still needs to be compiled and summarized to develop a comprehensive management action plan. Using a structured process could help bring major risks to the forefront so they can be dealt with in a scientific and transparent framework, while scientific progress for critical uncertainty or experimental studies to support recovery is simultaneously enabled. For such an effort to succeed, there needs to be sufficient policy, technical and financial support, and substantial outreach to agencies, stake-holders, universities, NGOs, and the public. In addition, progress on supplementation methods must be considered in parallel with, not in lieu of, habitat restoration and other critical management strategies.

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NOTES

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