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A Conceptual Framework For Conservation Hatchery Strategies for Pacific Salmonids

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Summary

One of the goals of fisheries conservation is to rebuild stocks. The role of the conservation hatchery is to assist the rebuilding by lessening the genetic and ecological impacts of hatchery releases on wild fish.

This technical memorandum presents a conceptual framework of production strategies which can be applied in conservation hatcheries to produce fish with the wild-like attributes necessary for rebuilding depleted stocks. The background of this document is the goal of rebuilding the endangered salmon stocks of the Columbia River Basin, but the framework can be applied equally for rebuilding or improving any endangered stock.

The strategies are reinforced with a specific rationale and scientifically referenced justification. Each is briefly summarized as follows:

Inbreeding, outbreeding, domestic selection, and other genetic considerations. Conservation hatcheries should provide fish with minimal genetic divergence from their counterparts to maintain long-term adaptive traits.

Broodstock sourcing. Conservation hatcheries should use locally adapted broodstock to maintain long-term fitness traits.

Broodstock maturation and reproduction. Conservation hatcheries should manage and rear broodstock to maintain appropriate seasonal timing of maturation, ensure high quality gametes, and minimize precocious maturation of male fish.

Enriched environments. Conservation hatcheries should have incubation and rearing vessels with options for habitat complexity to produce fish more wild-like in appearance, and with natural behaviors and higher survival.

Growth rate modulation. Conservation hatcheries should base their goals for growth patterns of hatchery fish and size at emigration on natural population parameters.

Rearing density. Conservation hatcheries should use low rearing densities to improve juvenile survival during rearing and increase adult return percentage.

Anti-predator conditioning. Conservation hatcheries should have options to apply anti-predator conditioning methods in hatchery rearing vessels.

Release size. Conservation hatcheries should release smolts at a size which equals the size distribution of smolts in the wild population.

Release time and volitional release. Fish from conservation hatcheries should be released on their own volition, and out-migrate during windows for natural downstream migration of the stock.

Imprinting and homing. Conservation hatcheries should adopt practices to reduce straying, such as on-site rearing and release, and other promising imprinting or homing techniques.

Habitat carrying capacity. Conservation hatcheries should program their production to accommodate the natural spatial and temporal patterns of abundance in wild fish populations.

Hatchery monitoring and evaluation. A monitoring and evaluation team should be established. The team should be empowered to assess the performance of all anadromous fish hatcheries in the Columbia River Basin with respect to the objectives of the Endangered Species Act.

The exact application of any guideline will depend on the physical limitations of individual hatcheries, and on the management.

I. INTRODUCTION

Conservationists recognize that rearing any living creature in captivity and then releasing it into its natural habitat is a difficult process. It requires application and integration of a number of rearing strategies, all of which are known individually to affect the inherent fitness of the creature to survive and breed in its natural ecosystem. For an aquatic creature, like fish, the process is even more complex, as some strategies must be executed within an invisible ecosystem and not in the controllable confines of captivity.

A conservation hatchery may be defined as a rearing facility to breed and propagate a stock of fish with equivalent genetic resources of the native stock, and with the full ability to return to reproduce naturally in its native habitat. A conservation hatchery is therefore a facility equipped with a full complement of culture strategies to produce very specific stocks of fish in meaningful numbers. It can also permute individual strategies to match the particular requirements and biodiversity of any individual stock to its ecosystem. One combination of strategies may be used to produce fish to restore a depressed stock, and another to reduce the risks of a certain supplementation program. The operation and management of every conservation hatchery is therefore unique in time, specific to an identifiable stock and its native habitat.

There are no true conservation hatcheries in existence at the present time. Various production hatcheries are applying some individual conservation strategies in an attempt to improve fitness and increase stock survival, but there is currently no single hatchery capable of applying a full package of strategies to produce a fish with the equivalent genetic resources of a local native stock.

One reason for the absence of conservation hatcheries is that the elements of their make-up have never been conceptualized in a single document. This Technical Memorandum presents a conceptual framework to meet the definition of a conservation hatchery. It presents the full complement of culture strategies available to hatchery managers. It recommends practical expedients to save depleted stocks, reform traditional hatcheries, and produce more adaptable juveniles to maximize the benefits and reduce the risks of supplementation programs. Collectively, the framework is a serious test of recent research results which encourage alternative practices for fish supplementation.

The framework has been written by scientists of the National Marine Fisheries Services (NMFS), Northwest Fisheries Science Center, Resource Enhancement and Utilization Technologies Division. Principally, it offers guidelines for the management and operation of conservation hatcheries for species of Pacific salmon listed under the Endangered Species Act (ESA). Although the background here is the ESA-listed species of the Columbia River Basin, the framework is equally applicable to any endangered stock of fish in any ecosystem.

II. HISTORY OF THE CONSERVATION HATCHERY CONCEPT

Modern production hatcheries are so instrumental in supplying salmonids to the common property resource that it is almost impossible to separate management of the fisheries from management of the hatcheries. Over five billion hatchery-reared juveniles are released annually into the Pacific Ocean from North American hatcheries. On the Columbia River alone, nearly 100 hatcheries produce about 200 million fish, which provide up to 80% of the fish in several key fisheries. However, despite the great success of production hatcheries, the final decades of the Twentieth Century have seen the emergence of a different philosophy behind salmon resource management.

Exactly one hundred years ago, the Nineteenth Century was ending on an optimistic note for the recovery of depleted commercial fisheries stocks on both sides of the Atlantic Ocean. The new field of fisheries science had just been born out of scientific and public concern, and the new technology of artificial hatching was developing into the tool to make recovery possible.

Today, after five generations of scientific endeavor and developing hatchery technology into an efficient farming process, this century is ending in controversy and pessimism for the future of fisheries. Except for the years when wars prevented most commercial fishing, both inland and coastal fisheries have continued their decline unabated. Moreover, the decline is now on a global scale, with some stocks thought to be near the point of extinction; and hatchery technology has gone from panacea to patsy - the convenient inhuman scapegoat to shoulder the blame for human failure.

But hatchery technology is not the only culprit. One hundred years ago, most of the early fisheries scientists recognized there was no single panacea for stock recovery (Wood 1953). In 1901, for example, the Royal Commission on Salmon Fisheries in England reviewed the issue of artificial hatching in Great Britain and North America, and its report in 1902 did not recommend artificial hatching (Calderwood 1931). As one contributor at the hearings observed, "There is no example of the establishment or maintenance of a commercial salmon fishery upon any river in North America which has depended for its yield upon artificial culture, unsupported by restrictions upon netting or by accessible spawning grounds."

Clearly, these pioneers recognized that fisheries management and fish habitat were equally important pieces in the game of stock recovery. Artificial culture, however, proved to be a powerful piece on the board and one easy to overplay. Moreover, the intricacies, boundaries, and length of the game were never fully understood; and some of the rules have only started to emerge in the final decades of the Twentieth Century.

With population and economic pressures tightening around the environment after World War II, the existence of many species became increasingly put at risk on a number of fronts all at the same time. Firstly, for every aquatic species the principal threat was the increasing and irreversible loss of habitat. This was due to either industrial and social progress, resulting in physical degradation and pollution, or from well-intentioned biological interventions creating an imbalance in the endemic populations in the ecosystem. Secondly, for aquatic species with any commercial value, an added threat was annual over-harvesting. With more well-intentioned attempts to control over-harvesting, and in compliance with regional fishing agreements promulgated by international organizations and fisheries commissions, increasing emphasis for stock recovery was being put on fisheries management. However, yet another risk for all species in this milieu became unwise fisheries management practices.

The response to the growing risks to all ecosystems from these threats and other types of human interventions was the ESA. The 1973 Act recognized that, "various species of fish, wildlife, and plants in the United States have been rendered extinct as a consequence of economic growth untempered by adequate concern and conservation." For Pacific salmon the emphasis of the ESA was on habitat conservation and the protection and recovery of the natural populations. But if habitat restoration was a critical part of any plan for conservation and recovery, it was no easy task. Firstly, the aquatic ecosystem for any diadromous fish was multi-dimensional and linked inseparably to a surrounding terrestrial ecosystem. Secondly, the biodiversity of each natural population was an absolute indispensable necessity for its survival. Therefore, if species biodiversity was to be maintained then genetic integrity of the species must be conserved and, in some cases, quickly. Consequently, the ESA acknowledged that conservation and recovery might still depend on artificial culture practices. Several of the roles and actions of artificial propagation in recovery plans were later summarized by Hard et al. (1992). The actions included the choice of donor stock, broodstock collection and mating, husbandry techniques, release strategies, monitoring and evaluation, and captive broodstock programs.

Since the ESA was enacted, maintaining the biodiversity and genetic integrity of species of fish when the commercial fishery is enhanced by artificial hatching has proved to be a very complex and controversial issue, and one that has stretched the minds of many multi-disciplinary groups of scientists. In the mid-1980s, the National Research Council (NRC) of the United States National Academy of Science formed a Committee on Managing Global Genetic Resources and established an Aquatic Animal Working Group. Perhaps symptomatic of the complexity of the issues the Group could not produce a report for the Committee and the information was not published until 1995 (Thorpe et al. 1995). Although the Group included Atlantic salmon as one of four species reviewed at length, the six principal recommendations were general for effective management and conservation of all commercial aquatic species. No specific recommendations were addressed to the role of artificial culture, but the Group noted there was great scope for improvement in hatchery management, "especially in conservation hatcheries, to ensure that the initial genetic diversity was comparable to that in the wild stock to be augmented, and that the hatchery products were ecologically competent." The Group also recognized that hatcheries might be the only tractable solution to the conservation and recovery of many stocks.

In 1992 the NRC tried again. This time, through the Committee on Protection and Management of Pacific Northwest Anadromous Salmonids, the mandate was more specific and there was a full and scientific evaluation of hatcheries and their roles. At about the time the study ended, and the report of the Committee was being prepared in book form entitled, *Upstream* (NRC 1996), two other scientific perspectives of artificial hatching were being undertaken. One was the National Fish Hatchery Review Panel, which published its findings in 1994 (NFHRP 1994), and the other was an

Independent Scientific Group commissioned by the Northwest Power Planning Council. The report of this Group (ISG 1996) was published as a book called, *Return to the River*.

The conclusions and recommendations by these different scientific groups were almost identical, and in a review of salmonid artificial production in the Columbia River Basin, commissioned by the Northwest Power Planning Council (NWPPC), their findings were evaluated and compared by a Scientific Review Team. In its report (SRT 1998) the team identified the following 10 points as the common denominators of these documents:

1. Hatcheries have generally failed to meet their objectives

2. Hatcheries have imparted adverse effects on natural populations

3. Managers have failed to evaluate hatchery programs

4. Hatchery production was based on untested assumptions

5. Supplementation should be linked with habitat improvements

6. Genetic considerations have to be included in hatchery programs

7. More research and experimental approaches are required

8. Stock transfers and introductions of non-native species should be discontinued

9. Artificial production should have a new role in fisheries management

10. Hatcheries should be used as temporary refuges, rather than for long-term production

The team recommended that the first 7 of these elements should always be considered in the development of hatchery policies, and it went on to make 21 individual recommendations for production technology practices, hatchery management, and research and monitoring.

The issues regarding artificial hatching were not the sole prerogative of the large scientific groups commissioned to study the problems. For the last twenty years individual or groups of issues have been the subject of independent peer-reviewed papers written mostly by fisheries biologists and geneticists.

Dentler and Buchanan (1986) proposed a comprehensive review of the role of salmonid hatcheries and their relationship to wild salmon stocks. They concluded that hatchery production was necessary in many areas and hatcheries would continue to be a useful tool of fishery managers in the future, but they believed a more cautious and critical examination might reveal better ways to integrate wild and hatchery production with associated fisheries. Brannon (1993) subsequently stated in a critical analysis of what he called the perpetual oversight of hatchery programs that by neglecting the requirements of natural populations, and consequently their adaptive environmental traits, hatchery programs produced fish which had little chance of integrating into the ecosystem. Reisenbichler and Rubin (In press) concluded that the only similarities in hatchery and wild environments for salmon were water and photoperiod. Everything else, such as food, substrate, density, temperature, flow regime, competitors, and predators, was dissimilar.

In an analysis of salmon and steelhead supplementation, Miller (1990) studied over 300 projects designed to supplement these fisheries in North America. Among the many observations he commented that success at rebuilding runs was scarce. Projects were more successful at just returning fish. Moreover, adverse impacts to wild stocks had been shown or postulated from about every type of hatchery introduction, even though the goal of the project was to rebuild a run. Overstocking with hatchery fish might be one of the most significant problems in supplementation projects. He concluded that there were no guarantees that hatchery supplementation could replace or consistently augment natural production. Always the top priority was the protection and nurturing of the natural runs.

The issue of supplementation of wild salmon stocks was taken up by Sterne (1995). He examined the scientific, legal, and policy positions of those groups for and against the practices of supplementation in the Columbia River Basin. He identified a number of common areas for agreement, which included both supplementation and non-hatchery alternatives, such as a moratorium on ocean and in-stream fishing. But he concluded that habitat restoration and protection were the real cornerstones of supplementation. The primary goal of any program in the Basin was the biological health of the stocks, and therefore supplementation should take place only under carefully controlled conditions at non-permanent facilities in an adaptive, experimental framework.

In a paper on conservation aquaculture and endangered species, Anders (1998) discussed some basic tenets of endangered species management from the perspective of population biology, the role of conservation aquaculture in endangered species management, and the potential dangers of fisheries management policies which consider aquaculture as a last resort for conserving endangered fish populations. He defined conservation aquaculture as the use of aquaculture for conservation and recovery of endangered fish populations. It did not embrace standard hatchery practices and tried to eliminate as much artificial conditioning as possible. It contrasted directly with the ideology underlying more-traditional hatchery supplementation programs, which measure success by the numbers of fish released from a hatchery. He believed that the use of aquaculture for conservation and recovery should be based on objective science, not risk anxiety.

More recently, Waples (1999) identified and analyzed several myths and misconceptions about hatcheries and their effects on natural populations, which were impeding progress and contributing to the controversy about hatcheries. He concluded that hatcheries were intrinsically neither good nor bad, and their value could be determined only in the context of clearly defined goals. He believed that genetic changes in cultured populations could be reduced but not eliminated entirely. Some risks from hatcheries were over-stated, but there was some empirical evidence that hatcheries had many adverse effects. The priority was for risk-averse hatchery programs, supported by effective monitoring and evaluation. In conclusion, he recommended four areas where actions could resolve some of the controversies regarding fish hatcheries. These were identifying goals, conducting overall cost-benefit analyses to guide policy decisions, improving the information base, and dealing with uncertainty.

Backed by the increasing scientific concerns over traditional hatchery practices, the shift towards a conservation ethic has increased. The theme has become evident in all the new plans being formulated by involved agencies and management groups. The proposed recovery plan for Snake River salmon (Schmitten et al. 1995) opened with the statement that the focus of the plan differed from previous management strategies. New emphasis was being placed on natural fish escapement, improved migration conditions for juveniles and adults, increased riparian area protection, and equitable consideration of natural fish in resource allocation processes. The goal of the plan was now to restore the health of the Columbia and Snake River ecosystem and to recover listed Snake River salmon stocks. Implementation of the plan would conserve biodiversity, a factor which was essential to ecosystem integrity and stability. With specific regard to artificial propagation, the plan called for ecological interactions between hatchery fish and wild fish to be minimized but to use culture technologies to conserve remaining gene pools through captive broodstock, supplementation, and gene bank programs.

Similarly, to meet the objectives of the artificial production and evaluation plan for summer chum populations in the Hood Canal and Strait of Juan de Fuca regions, the tri-agency Supplementation Work Group (SWG 1998) produced a set of general principles calling for maintenance of natural population characteristics for fish taken into the hatchery environment. In general, these principles were previously identified by Kapuscinski and Miller (1993), and included procedures for broodstock collection and spawning, incubation, juvenile rearing, smolt release, and monitoring and evaluation. The plan also contained a set of specific criteria guiding supplementation and reintroduction program operations, which included donor-stock selection and collection methods, spawning and mating protocols, incubation and rearing protocols, and release strategies.

At the same time, the conservation theme was also becoming more evident in policy documents. The NWPPC, in preparation for developing its policy recommend-ations for the US Congress, drafted a policy statement for artificial production by the Columbia River Basin Hatcheries, (NWPPC 1999) which recognized that artificial production was undergoing a major transition. This conclusion was based on the findings of the Artificial Production Review, an initiative the Council had taken earlier to facilitate further discussion and assist in developing a coordinated policy for the hatcheries in the Basin. Program managers, the Review team said, were under pressure to transform hatcheries to widen the harvest opportunities, reduce the adverse impact of hatchery production on wild fish, and attempt to use artificial production techniques to try to rebuild naturally sustaining populations.

The draft statement reinforced the Council's objective to develop policies consistent with eight previously identified scientific principles, one of which stated that the abundance and productivity of fish and wildlife should reflect the conditions they experience in their ecosystems over the course of their life-cycle. Furthermore, two basic premises for its initiatives regarding artificial production included mimicking wild population rearing conditions to improve survival, and mimicking natural rearing conditions to reduce impacts on wild populations. The draft went on to outline a series of policies for artificial production performance standards, ecological interactions, genetics, and fish health, and concluded with a section on the use of the tools in planning.

From these and other converging events and observations, it is clear that the pressing need to preserve indigenous wild salmon stocks has brought in a new era of conservation. Many stocks are now protected (ESA-listed) within their native habitats, and restrictions imposed by ESA mandates have a major impact on the management and operation of production hatcheries, and traditional users of hatchery fish. A conservation hatchery can play a vital part in the recovery of threatened and endangered species by maintaining their genetic diversity and natural behavior, and reducing the short-term risk of extinction.

The use of conservation measures in the management of salmonid fisheries is not a new idea. Several have already been proposed by fisheries managers in the Pacific Northwest. These include, for example:

- Prohibit non-indigenous fish stock transfers (intentional transplantation)
- Audit hatchery fish rigorously for health, genetic, and smolt quality problems
- Mass mark hatchery fish for identification
- Apply effective reintroduction measures
- Impose, if necessary, production caps to match release numbers with the finite carrying capacity of fresh and saltwater habitats
- Implement parallel captive broodstock techniques to avoid the risk of extinction, and conserve endangered gene pools
- Reduce selection for domestication by introducing more natural rearing protocols
- Produce better quality smolts indistinguishable from their wild counterparts
- Introduce hatchery techniques which reduce harmful post-release interactions between wild and hatchery fish

The last four of these measures have been the subject of research by the Northwest Fisheries Science Center (NWSFC) for over a decade. Guiding much of the Center's research is the fundamental hypothesis that successful stock recovery depends on the quality of juveniles reared in the hatchery. Consequently, the underlying objectives of its many research projects in all aspects of artificial propagation are to identify and maintain the attributes of wild fish.

Artificial rearing conditions within a hatchery, it is now recognized, can produce fish distinctly different from wild cohorts in behavior, morphology, and physiology. Hatchery methodologies can impose different selective pressures on fish and these can change overall fitness in many ways. Conventional hatchery rearing practices can alter genetic fitness through spawning and fertilization protocols. Hatcheries can inadvertently select for fish adaptable to high densities and feeding levels, and fish which cannot adapt may be selected against and not survive to release. Similarly, conventional practices purposely reduce individual size variability. Within a hatchery population this may be desirable, but in the long term this can be detrimental if fish are expected subsequently to rear and spawn in the wild. The wide natural variability in development and timing characteristic of wild fish may be inherent factors which enable them to adapt to changing freshwater and marine conditions.

With the emphasis on wild fish required under the ESA, there is opportunity to transfer the role of certain hatcheries from production to conservation. A conservation hatchery will operate on the concept that high quality fish, behaviorally and physiologically similar to wild cohorts, can be produced in conditions which simulate the natural life histories of each particular species under culture. Scientific information now available makes it feasible and practical for a hatchery to propagate juveniles similar in growth, development, and behavior to their wild cohorts. The probability of success is high. Animal behaviorists have shown that behavioral repertoires can often be recovered even after many generations simply by providing appropriate environmental stimuli.

The following sections identify the major culture strategies for the management and operation of conservation hatcheries in the Pacific Northwest, and outline potential protocols. The strategies are based on a combination of modern conservation principles and basic salmonid biology. They are common sense, logical approaches to the needs for culturing wild-like animals. Some are backed by scientific research; others are currently being researched. However, any of these particular strategies can be implemented by hatchery managers using the latest and best scientific information.

A generalized "decision tree" for timing the implementation of conservation hatchery strategies is illustrated in Figure 1. The concerns include the status of the population, its genetic composition, rate of decline, and the impact of any actions on native fish. The needs and concerns of each conservation program will therefore be site specific. They will also depend on the physical and management limitations of each individual hatchery. Consequently, the exact application of conservation hatchery strategies will depend on the particular stock of fish, its level of depletion, and the biodiversity of the ecosystem.

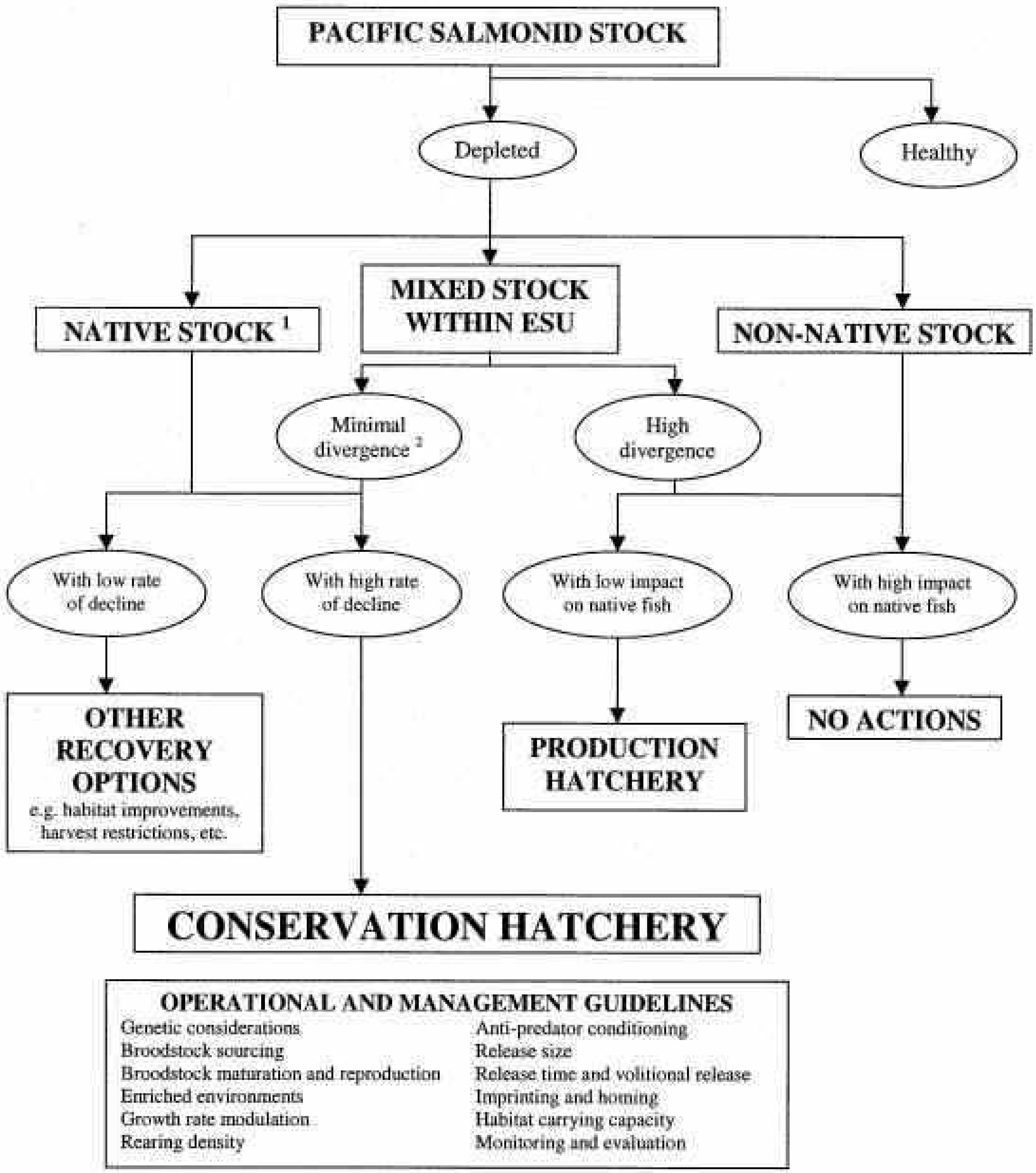

Figure 1. Conservation hatchery decision tree. Decision pathways depend on population status, genetic composition, and rate of decline of the stock, and impact of the operation on native fish.

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[1] In all cases this would be the preferred source. For an extirpated stock another from within the same Evolutionarily Significant Unit (ESU) can be substituted.

[2] Stock with traits identified as useful for recovery.

III. STRATEGIES FOR THE MANAGEMENT AND OPERATION OF CONSERVATION HATCHERIES

A. Inbreeding, Outbreeding, Domestication Selection, and Other Genetic Considerations

Conservation hatcheries should provide fish with minimal genetic divergence from their natural counterparts to maintain long-term adaptive traits. It is recommended that they:

- Identify and follow hatchery protocols which avoid or minimize the processes of domestication selection, inbreeding, and outbreeding
- Release only smolts which have the fitness and diversity characteristics of their wild cohorts

Rationale

As the adaptability and diversity of wild fish have been shaped by interactions between a complex natural environment and natural selective forces, so are the characteristics of hatchery fish modified by their rearing environment and genetic changes imposed during the culture phase. The genetic consequences of inbreeding, outbreeding, and domestication selection are well documented for domestic livestock and other terrestrial organisms. Significantly less is known about Pacific salmonids. However, a risk-averse strategy encourages a course of action which avoids or limits genetic changes to hatchery populations maintained for conservation reasons. By avoiding or limiting those factors known to increase the incidence of domestication selection, inbreeding, or outbreeding depression, conservation hatcheries can produce populations of fish more consistent with the genetic structure and behavior of indigenous populations.

Justification

Any human intervention in the rearing of wild animals and birds has the potential to initiate some type of genetic change. Genetic change may result from 1) limited population sizes and the mating of close relatives (inbreeding); 2) mating of very divergent groups of individuals such that co-adapted gene complexes are disrupted (outbreeding depression), or by 3) close adaptation of a population to the hatchery environment such that adaptations to the natural environment are diminished (domestication selection).

Much has been written about genetic protocols for fish culture and enhancement (for example, see Ryman and Utter 1986, Waples 1991, Tave 1993, Hard and Hershberger 1995, Waples 1999). Although genetic changes are inevitable in cultured populations, the degree of change, or risk, could be reduced by adopting some specific management strategies. However, rearing cultured populations is a dynamic and complex process, and any strategy may have ramifications not only for the cultured population but also the wild population when the two intermix.

Genetic risks (such as hybridization, inbreeding depression, outbreeding depression, etc.) can be readily identified, but the trade-off between the effects of particular strategies (such as continuous introductions, stock transfer, germ-plasm storage, etc.), can only be calculated on a case-by-case basis. Much will depend on the purpose for which the fish are being raised. This is always important, even when juveniles are being released specifically to enhance a wild population which is below strength. The direct benefits in terms of increased population strength may be offset by the introduction of characteristic genetic traits of hatchery fish, such as straying, together with any damaging ecological effects, such as habitat and food competition or even direct predation. The trade-off becomes a more critical decision if the wild population is small and inbred. Here, a specific trait vital for its survival could be totally depressed or lost.

Therefore, to reduce the genetic and ecological impact of hatchery-releases on wild stocks, conservation hatcheries must maintain the genetic diversity of each population as much as possible. The genetic protocols of conservation hatcheries should include any practice which increases fitness which in turn reinforces population stability.

B. Broodstock Sourcing

Conservation hatcheries should use locally adapted broodstock to maintain long-term fitness traits. It is recommended that they:

- Select broodstock after careful analysis of environmental relationships and life history parameters, following the best genetic principles
- Provide options, such as captive broodstocks for critical populations
- Integrate wild and hatchery populations to avoid divergence and selection of maladaptive traits
- Maintain the necessary management and security of the stocks

Rationale

A basic operational premise for conservation hatcheries is the need to maintain fitness and diversity characteristics of targeted populations (see Section III.A, above). This obligates the use of local broodstock fully representative of the genetics of wild populations whenever possible. For extirpated populations, donor stock should be chosen following careful analysis of environmental relationships and life history parameters of the original stocks.

Justification

One of the potential negative effects of artificial production is that only relatively small breeding populations are used in hatchery programs (SRT 1998). When a broodstock is not representative of the entire population there may be detrimental genetic consequences. For example, a potential amplification of only a portion of a population may occur subsequently reducing the effective population size by dramatically increasing only a fraction of the available genotypes in the parent population (Hard et al. 1992, Hard and Hershberger 1995).

Ideally, conservation hatchery broodstocks should be founded on a relatively large number of spawners, representative of all segments of the natural population. However, optimal spawning matrix strategies may be compromised because of 1) demographics of the stocks, and 2) the need to limit production from conservation hatcheries to the carrying capacity of post-release environments.

SRT (1998) suggests that when a run (or production requirement) is relatively small, this may require live-spawning with removal of only a portion of eggs from each female, and subsequently releasing the fish to continue spawning naturally. Other options are redd mining or fry trapping. Whatever the practice, breeding or sourcing protocols should follow best genetic principles. In most cases, broodstock populations will be aided through infusion of wild genetic material by taking some portion of wild fish in every broodstock collection.

In cases where critical populations are dangerously close to extinction, a captive broodstock approach should be considered to provide population amplification (Flagg and Mahnken 1995, Flagg et al. 1995). Fish for captive broodstocks can be sourced from all available life stages; for example, eyed eggs, fry, smolts captured from the wild, and pre-spawning adults captured and artificially spawned. Each year-class of captive broodstock should be maintained for only a limited number of generations to ensure that genetic integrity and adaptability to native habitats are preserved.

Of paramount importance for a threatened or endangered species is protection of the broodstock from catastrophic loss or high mortality. This is especially true if all natural gametes have been removed from the wild to establish a broodstock program. Broodstock should be isolated from all other fish and kept under security. Rearing water supplies should be treated (sterilized) to remove pathogens. Natural water temperature profiles should be maintained to provide optimum maturation and gamete development. In severe cases of endangerment, the broodstock and gametes may need to be divided between at least two independent facilities to safeguard against environmental disasters (including equipment failure).

C. Broodstock Maturation and Reproduction

Conservation hatcheries should manage and rear broodstock to maintain appropriate seasonal timing of maturation, ensure high quality gametes, and minimize precocious maturation of male fish. It is recommended that they:

- Maintain broodstock on natural photoperiod and water temperature below 12^{o}C
- Select a diet and growth regime which reduces excessive early maturation of male fish

Rationale

In captive broodstock programs for conservation of endangered or threatened stocks there is a need to minimize genetic selection in the captive environment, and to avoid changes in the natural life history of the population, such as seasonal timing of maturation. In addition, rearing regimes should be used which maximize survival of captively-reared fish, minimize unnatural asynchronous maturation of fish, and ensure the production of high quality gametes and offspring.

Justification

In addition to genetic factors, the seasonal timing of spawning in salmonids is controlled by photoperiod, temperature, and an endogenous annual rhythm. Although photoperiod is regarded as the most important environmental factor controlling gonad development and spawning time in salmonids, it does not act alone in controlling reproductive function. The extent to which temperature acts in concert with photoperiod to regulate the timing and rate of gametogenesis is poorly understood. Studies have shown that temperatures ranging from 8 - 16°C have little effect on the seasonal timing of the reproductive cycle, but higher temperatures adversely affect the quality and quantity of gametes (Billard 1985). The approximate upper limit for successful reproduction of salmonids in the wild is considered to be 13°C (MacCrimmon 1971, Scott 1990). However, this upper limit may be lower for salmonids which spawn in the northernmost latitudes and high altitudes, and may vary considerably among stocks. High water temperatures (13-14°C) during the spawning season inhibit ovulation of Atlantic salmon, and have a detrimental effect on gamete quality (Taranger and Hansen 1993). In an ongoing unpublished study with Lake Wenatchee sockeye salmon, the gametes produced by broodstock reared in either constant 8°C or 12°C freshwater did not differ in quality, and fertilization rates and hatching survival were 80-90%.

Manipulation of spawning time by photoperiod control, which synchronizes or compresses the spawning period, is used by commercial salmon producers to prolong the availability of smolts for grow-out. This enables the farmers to supply markets all year round. In captive broodstock programs for depleted stocks, off-season spawning of fish may not be an appropriate goal, as production of progeny for release into the natural habitat should be timed appropriately for the requirements of the stock. However, the photoperiod is still controlled as the combination of uncontrolled lighting and water temperature can impair the quality of the gametes and subsequent survival of the offspring. Furthermore, exposure to continuous light can induce asynchronous maturation and atresia of oocytes (Bourlier and Billard 1984). The upper limit for rearing temperatures to produce high quality gametes in Pacific salmon may vary between species and stocks, but several broodstocks have been reared successfully in water temperatures of 8-12°C and produced high quality gametes.

A serious problem for captive rearing of chinook salmon is the loss of fish due to early sexual maturation of males. In many salmonid species males (jacks) may mature earlier than females, with the incidence varying between species, stocks, and rearing conditions for cultured fish. Thorpe (1994) suggested that the high degree of phenotypic plasticity in age of maturity in salmonids was probably an adaptation to the variable productivity of the freshwater environment, which the fish occupy during early life-history stages. The chinook salmon has a high degree of plasticity in its life cycle compared with other Pacific salmon species. Precocious male maturation can occur at several stages of the life cycle. Jacking rates as high as 90% have been observed by Hard et al. (1985), although most chinook stocks exhibit rates around 5-15% (Heath 1992).

In a captive broodstock program it is undesirable to produce mature males when females of the same stock are not mature. Although cryopreservation of milt from early maturing males is possible the technique is not yet sufficiently reliable to obtain consistently high-quality sperm. Selective removal of precocious males is not an option, as it reduces the effective breeding population size of a captive broodstock, therefore it is necessary to use rearing conditions which reduce early maturation of males in broodstock populations.

The age of sexual maturation is controlled by a large number of genetic, biotic, and abiotic factors, and their interaction is clearly complex. The research of Rowe and Thorpe (1990a, 1990b), Rowe et al. (1991), Simpson (1992), Kadri et al. (1996), and Shearer and Swanson (1997), among many others working primarily with Atlantic and chinook salmon, has indicated that growth rate, size and levels of stored energy at specific times of year, or critical periods of the life cycle, are important factors affecting the incidence of early male maturation. Other studies by Thorpe et al. (1990) and Duston and Saunders (1999) indicated that reduced growth through reduced food availability during the winter or spring reduced the number of maturing male fish. Silverstein et al. (1997 and 1998) and Shearer and Swanson (1997) found that high growth rates (or large body size) and high body fat levels of spring chinook salmon one year prior to maturation increased the proportion of male fish maturing in the subsequent autumn.

A critical period for initiation of maturation is therefore the autumn one year prior to maturation, but the period may extend into late winter and early spring. As the threshold of growth or body fat levels for initiating and maintaining sexual maturation are not yet known, the optimum strategy at present is to mimic the patterns of growth and body fat levels of wild fish. This can be achieved by feeding high-protein, low-fat diets and reducing the feeding ration over the winter period.

D. Enriched Environments

Conservation hatcheries should have incubation and rearing vessels with options for habitat complexity to produce fish more wild-like in appearance, and with natural behaviors and higher survival. It is recommended that they:

- Provide matrix substrates and darkened environments for egg incubation and alevin development

- Promote development of body camouflage coloration in juvenile fish by creating more natural environments in hatchery rearing vessels, for example, overhead cover, and in-stream structures and substrates

- Condition young fish to orient to the bottom rather than the surface of the rearing vessel by using appropriately positioned feed delivery systems

- Exercise young fish by altering water-flow velocities in rearing vessels to enhance their ability to escape predators

- Improve foraging ability of young fish by supplementing diets with natural live foods

- Reduce rearing densities to more natural spatial distributions

Rationale

Providing animals with more complex rearing habitats which approximate natural conditions is an increasingly popular method for improving the well-being of animals in captivity. In many cases, behavioral repertoires are recovered even after several generations simply by providing appropriate environmental stimuli. Techniques which have been used to enrich captive habitats for animals and birds may also have application to hatchery populations of salmonids. They may remedy many environmentally influenced differences between cultured and wild fish, and increase post-release survival by decreasing stress, reducing domestication, and acclimating fish more appropriately for their future environments.

Justification

Surveys of programs for the reintroduction of captive-bred terrestrial and aquatic animals show that few establish wild populations successfully (DeBlieu 1991, Gipps 1991, Minckley and Deacon 1991, Clark et al. 1994, Olney et al. 1994). Causes of failure are thought to be due largely to behavioral deficiencies in released animals. Research on higher vertebrates has shown that simple and practical changes to the way animals are kept and grown in captivity can have beneficial effects on behavior.

Many studies indicate that hatchery rearing environment can profoundly influence the social behavior of Pacific salmon. Social divergence of cultured fish may begin at the incubation stage. In nature, salmonid eggs incubate and alevins develop in the darkened matrix-rich environment of the gravel substrate in the redd. Lack of substrate and excess extraneous light which may occur in the hatchery environment appear to induce excess alevin movement, lowered energetic efficiency and, in some wild stocks, death. Hatchery incubation environments which used artificial matrix substrates, such as plastic bio-rings, saddles, or mesh, produced substantially larger fry (Poon 1977, Leon and Bonney 1979, Murray and Beacham 1986, Fuss and Johnson 1988). Those with darkened incubation environments produced both larger and more alert fry (Poon 1977, Mighell 1981).

In nature, stream dwelling salmonids prefer solitary habitats that include substrates of small particle-size stones or gravel, and the physical cover of fallen trees, undercut banks, and overhead vegetation (Groot and Margolis 1991). However, production hatcheries rear fish in uniform concrete raceways under environmentally sterile conditions and, not surprisingly, the fish are distinctly different from their wild cohorts in behavior, morphology, and physiology. Due in some part to these deficiencies, hatchery fish often do not survive as well after release as their wild cohorts. Olla et al. (1995, 1998) suggested that fish reared in a psycho-sensory-deprived hatchery environment are less able to carry out the most basic of all survival skills: to eat and not be eaten.

Recent habitat enrichment studies with chinook suggested that increased rearing habitat complexity increases development of appropriate body camouflage coloration, and may increase behavioral fitness (Maynard et al. 1995, 1996a, 1996b). In these studies, fish reared in raceways equipped with cover, structure, and substrate experienced up to a 50% increase in-stream survival compared with conventionally-reared fish. Currently, a hatchery-scale study is underway to determine whether rearing fish in enriched habitats will result in higher adult returns to their spawning grounds.

In general, the complexities of experimental artificial rearing habitats have attempted to simulate the release habitats. Substrates have been configured in several ways, using sand, gravel, artificial corrugated inserts, or painted patterns. Every effort has been made to match the color of the substrate (which produces cryptic coloration patterns in fish) to that of the receiving-stream environment to produce body camouflage patterns most likely to reduce vulnerability to predators.

In-stream structures have been created by suspending small defoliated fir trees in rearing vessels occupying 30-60% of the surface area. Natural stream-side cover has been created over about 75% of each vessel by suspending camouflage nets about 1 m above the water surface along the margins of the raceways. Other potential components of an enriched rearing environment for salmonids include foraging training, natural-like feed delivery systems, and changing flow velocities to exercise the fish. These may all offer advantages for increased survival and behavioral fitness.

Enriched rearing environments appear to be required for the transition of salmonid hatcheries from production to conservation for the rebuilding of ESA-listed species. Habitat enrichment strategies can provide wild-like hatchery fish more suited for release in natural habitats than conventionally reared fish, and will help minimize potential genetic divergence between wild and hatchery-reared stocks.

E. Growth Rate Modulation

Conservation hatcheries should base their goals for growth patterns of hatchery fish and size at emigration on natural population parameters. It is recommended that they:

- Determine spawning, hatching and emergence times of local populations, and duplicate these in the hatchery by controlling water temperature to natural profiles

- Measure growth rates, body size, and proximate composition of fish in the local population at critical periods: viz., first summer and fall prior to over-wintering, and spring growth/smolt size at migration

- Simulate growth rate, body size, and proximate composition by controlling water temperature, diet composition, and feeding rates

Rationale

The first rationale for this conservation hatchery protocol is that the likelihood of hatchery fish dominating wild individuals in competitive encounters will be reduced if they are similar in size. Second, in wild fish, high rates of growth during parr-to-smolt transformation are correlated with rapid downstream migration and low rates of residualization. Simulating growth patterns of wild fish in hatchery populations will increase smolt-to-adult yield by fostering rapid smolt emigration. Interactions between hatchery and wild cohorts will also be minimized by preventing residualization. Third, body composition and morphology, which usually differ between wild and hatchery reared smolts, can affect critical life-cycle transitions, including smolting and precocious sexual development. Dietary composition, feeding levels, and growth regimens which permit appropriate smolt development will minimize impacts on wild stocks by reducing differences in survival rates and reproductive success.

Justification

The goal of hatchery programs designed to reinforce natural production is to provide salmon smolts morphologically and physiologically identical to their wild counterparts. However, production hatchery rearing programs usually produce large smolts in an attempt to overcome the relatively poorer survival of hatchery-released fish compared with wild fish (Bilton et al. 1982, Martin and Wertheimer 1989). Large smolts can dominate smaller wild fish in competitive encounters and negatively impact wild stocks. Thus, the challenge is to develop hatchery-rearing protocols yielding relatively small juveniles surviving at rates equivalent to wild salmon juveniles.

Modulating growth and development cycles is the most logical approach to producing wild-like salmon juveniles. Growth rates which are high in spring and low in winter months match growth patterns of wild fish, and should result in high quality smolts (Beckman et al. In press). A high growth rate during parr-to-smolt transformation of spring chinook salmon during their second spring is correlated with high smolt-to-adult survival in production hatcheries (Dickhoff et al. 1995).

Recent studies indicate that growth manipulation by fasting juvenile coho salmon during winter, prior to enhancing spring growth, has no detrimental effect on physiological indices of smolting (Larsen et al. In prep.). Hatchery-reared salmon usually have higher levels of stored lipid and therefore differ in body morphology from their wild counterparts. This is primarily due to the feeding of high levels of nutrient-dense diets and maintenance of high growth rates throughout the year. Current standard protocols which produce high rates of growth during their first year can produce under-yearling spring chinook salmon smolts during autumn (Beckman and Dickhoff 1998). This is undesirable, because immune suppression during smolting can magnify disease epizootics if such fish are retained in the hatchery.

Research shows that plasma insulin and body fat levels increase with increasing dietary fat level, while the growth factor IGF-1 responds to body fat (Shearer et al. 1997). Additionally, high levels of stored lipid have been correlated with precocious maturation (Silverstein et al. 1998). Feeding protocols, which include both dietary modification and feeding level control based on the nutritional needs of the fish at critical life-cycle stages, are required for application in conservation hatcheries.

Additional support for growth rate manipulation is evident in studies of life history variation. Matching body size and physiological state of wild salmon juveniles at key developmental stages may require simulating natural environmental conditions at other times. For example, embryonic development, hatching, and emergence should emulate natural timing.

F. Rearing Density

Conservation hatcheries should use low rearing densities to improve juvenile survival during rearing and to increase adult return percentage. It is recommended that:

- Density criteria for rearing juveniles in conservation hatcheries should be hatchery-specific, as the potential impact of density may depend strongly on the incidence of existing clinical and sub-clinical infections

- Rearing densities are reduced to produce quality smolts

Rationale

The propagation of smolts of low quality does not contribute to hatchery performance, which is measured by the number of adult returns. The effect of rearing density on adult returns appears to be quite species specific, and may be related to disease interactions which occur long after release from the hatchery.

The optimum density for the rearing juvenile salmonids in hatcheries depends on a number of physiological, behavioral, and disease factors. For some species, such as spring chinook, high densities trigger outbreaks of disease, such as bacterial kidney disease (BKD). In such cases rearing densities should be below those normally used.

Justification

The purpose of a salmon conservation hatchery is to produce returning adults to the fishery, and the only valid measures of its performance are 1) total adult contribution, and 2) the percentage smolt-to-adult return. The historic strategy for most salmon hatcheries was to produce as many juvenile fish as possible, often at the cost of quality, based on the belief that maximizing juvenile production would equate to maximizing adult production. Mass production is easily achieved by controlling certain environmental parameters, such as oxygen and ammonia concentrations in the water, thus enabling young fish to be reared at high-density levels.

The number of valid studies on the effects of rearing density on the quality of juveniles of Pacific salmon is small. Ewing and Ewing (1995) conducted a yearly analysis of published studies by Banks (1992, 1994), and others. The results were discussed in terms of smolt-to-adult ratio (SAR) and adult yield (adults per cubic foot of rearing volume). Some interesting relationships were found when data were combined by species. For example, the SAR for chinook tended to decrease with increasing rearing density, but for coho little relationship could be found. The adult yield for coho salmon increased with increasing density, while the adult yield for chinook remained constant. Until further data are available, the maximum density index proposed by Banks (1994), and Ewing and Ewing (1995) is 0.15 $lb/ft^3/in$ for spring and fall chinook salmon, and between 0.30-0.40 $lb/ft^3/in$ for coho. Banks (1994) speculated that the adult return of spring chinook might be further improved in the range of 0.08-0.11 $lb/ft^3/in$.

Differences in survival between species may be due to the greater susceptibility of some species to BKD. Working with chinook salmon in salt water, Mazur et al. (1993) found the presence of bacteria in the kidneys was directly proportional to rearing density. In addition to known physiological results of crowding, which can decrease the ability of fish to resist infection, direct ingestion of fecal matter was observed during feeding. Because of the high loads of bacteria in fecal matter from infected fish, it was hypothesized that horizontal transmission of BKD may be more prevalent at higher density.

G. Anti-Predator Conditioning

Conservation hatcheries should have options to apply anti-predator conditioning methods in hatchery rearing vessels. It is recommended that they:

- Foster higher in-stream survival by exposing fish to a variety of anti-predation and training exercises

- Evaluate and improve various training methods

Rationale

Innate reactions of juvenile fish to avoid predators are triggered by exposure to specific stimuli, and training juveniles in a natural environment complete with predators may increase post-release survival.

Justification

Juvenile salmonids from wild and hatchery populations differ in predator avoidance behavior (Johnsson and Abrahams 1991) and ability (Berejikian 1995), suggesting a genetic basis for these traits. However, the ability of juvenile salmonids to avoid predation improves with experience. Laboratory studies have demonstrated that anti-predator behavior and predator avoidance ability of juveniles of several salmon species improved following brief exposure to actual predation events (Patten 1977, Olla and Davis 1989, Berejikian 1995, Healey and Reinhardt 1995). These anti-predator conditioning efforts have involved various combinations of visual, olfactory, and auditory stimuli, all of which can trigger innate anti-predator responses (Suboski 1988, Olla and Davis 1989). Conditioning, using a combination of injured con-specific predator odors in the absence of visual and auditory stimuli, also improves subsequent predator recognition and avoidance behavior in rainbow trout and chinook salmon (Brown and Smith 1997, Brown and Smith 1998, Berejikian et al. 1999).

Several studies have demonstrated an increase in post-release survival of juvenile salmonids following anti-predator conditioning in hatchery vessels. In a natural stream, post-release survival of chinook salmon smolts exposed to electrified predator models was greater than for unconditioned smolts (Thompson 1966). Similar conditioning of chum salmon improved their post-release survival in an experimental stream (Kanayama 1968). Chemical anti-predator conditioning of chinook salmon smolts in hatchery tanks containing complex structures improved their post-release survival in a natural stream, but conditioning did not improve the survival of smolts reared in barren vessels (Berejikian et al. 1999). There is no evidence that anti-predator conditioning has a detrimental effect on post-release survival.

Anti-predator conditioning techniques will require refinement with increasing knowledge of their benefits to specific hatchery populations. Therefore a monitoring system will be required to evaluate their effectiveness. At this point, anti-predator conditioning should be applied to hatcheries that release cohorts from replicate vessels, so that differential tag codes (e.g., coded wire tags) and release-to-adult survival differences can be used to estimate between conditioned and non-conditioned groups. This enables continued evaluation and monitoring of the success or failure of anti-predator conditioning to improve adult returns, and evaluate the efficacy of the program overall. These and other anti-predator conditioning operations should be developed with cooperation between hatchery operators and behavioral research scientists.

H. Release Size

Conservation hatcheries should release smolts at a size which equals the size distribution of smolts in the wild population. It is recommended that they:

- Release smolts within the size range of wild smolts from which the population is derived, except a case when imminent extinction requires maximal survival.

Rationale

The size a juvenile salmonid is released affects its ability to compete with its peers, escape predators, adapt to seawater, migrate rapidly, mature early, and most importantly survive and recruit into the fishery or spawning population. Releasing young high-quality smolts (see Section III. E, above) within a size range similar to the natural population from which they are derived will reduce competition with wild smolts, and minimize selection pressures which occur when there is clear disparity in size.

Justification

The greatest risk of releasing large fish from production hatcheries is that they will out-compete endangered and threatened stocks not yet taken into conservation programs. This is because in intra-specific contests over food and space, all else being equal, the largest fish usually win (Hoar 1951, Chapman 1962, Mason and Chapman 1965, Jenkins 1969, Noakes 1980, Abbot et al. 1985, Maynard 1987).

A second risk is that large fish from production hatcheries will residualize and therefore compete with wild fish in the ecosystem for a prolonged period of time. This is because some male juveniles grow rapidly in the year before they smolt and exhibit a precocious male reproductive strategy. Therefore, instead of out-migrating they remain in freshwater to spawn in the coming fall. As residents of the same streams and rivers as wild stocks, they are serious competitors.

I. Release Time and Volitional Release

Fish from conservation hatcheries should be released on their own volition and out-migrate during windows for natural downstream migration of the stock. It is recommended that conservation hatcheries:

- Practice volitional release strategies which maintain within-population variability in out-migration timing by programming liberation windows which mimic the natural time and age patterns found in wild populations of the fish under culture

- Allow non-smolts (parr) to remain, and either smolt, residualize, or perish through natural selection

Rationale

Within any population of young salmon, individuals out-migrate at a variety of different times and ages. This variation in behavior enables the population to persist in an unpredictable environment. A goal of a conservation hatchery is to maintain this genetic variation within the population. This can be achieved through techniques which offer the fish multiple release windows to out-migrate on their own volition.

Justification

Out-migration behavior is under both genetic and environmental control (Clarke et al. 1994) and has been shaped within each population by evolutionary processes which adapt salmon to their environment. Healey (1994) pointed out that the variation within individual populations of salmon is a strategy to utilize a range of habitat types and, perhaps, reduce the risk of catastrophic mortality in an uncertain environment. Thus, many Pacific salmon populations have evolved an out-migration strategy which produces fish migrating to sea over a wide range of times and ages. This strategy ensures that some members of each year class will reach the ocean when the mix of food and prey conditions are best, even though the mix will shift from year to year. In addition, it ensures that some members of the population are at sea when major disasters occur on land, such as catastrophic floods, droughts, and volcanic eruptions, etc., which could wipe out all year class members remaining behind in the freshwater environment.

The key assumption of volitional release is that fish will not leave the hatchery until certain physiological processes, such as smoltification, trigger their downstream migratory behavior (Brannon et al. 1982, NRC 1996, Kapuscinski 1997, SRT 1998). The technique is simply to provide windows of opportunity for out-migration which mimic time and age patterns found in the wild populations. Within these windows, fish may leave if they wish or remain behind to fend for themselves and smolt, residualize, or perish as natural selection takes it course. The fish are not crowded out of the hatchery in a traditional forced release until the last out-migration window is closing. Furthermore, volitional release has the added advantage of permitting fish to migrate at night rather than during the day, a behavioral preference which probably evolved in response to those predators, such as mergansers, kingfishers, and squawfish, which hunt during the day.

By adopting strategies for volitional release, a conservation hatchery will maintain the within-population variability in out-migration behavior called for by Kapuscinski (1997). It ensures that each individual fish will be at its own peak of readiness and adaptability to seawater, and that some members of the population will have the opportunity to find the best mix of food resources and prey pressure in the marine environment.

J. Imprinting and Homing

Conservation hatcheries should adopt practices to reduce straying, such as on-site rearing and release, and other promising imprinting or homing techniques. It is recommended that they:

- Rear fish for their entire juvenile freshwater lives in water from the intended return location to imprint natural odors and reduce straying of returning adults

- Acclimate juveniles at selected release sites where this approach is not possible

Rationale

Before out-migration, juvenile salmon learn odors associated with their natal streams which guide their homing migrations as adults. Homing behavior of salmon produced in hatcheries is extremely variable, and many returning adults stray – some species more than others. Straying of endangered salmon stocks reared in conservation hatcheries will dilute efforts to enhance endangered stocks. Rearing and releasing juvenile salmon in water from their intended return location has the greatest potential to minimize straying.

Justification

Imprinting in salmon may occur at multiple life history stages. It is well known that olfactory imprinting occurs during sensitive periods associated with surges in plasma thyroxine levels during parr-smolt transformation (Dittman et al 1995). However, in a number of stocks of Pacific salmon species (e.g., sockeye and stream-type chinook) parr-smolt transformation may occur downstream from incubation and early-rearing habitats (Groot and Margolis 1991), but returning adults migrate past areas where they underwent transformation and return within close proximity of their natal habitat. This may indicate the occurrence of multiple presmolt imprinting periods.

Improper or incomplete imprinting opportunities may increase the straying rate of populations released from hatcheries. For example, empirical evidence indicates that fish transported and released in a distant location are more susceptible to straying than those released where they were reared (Sholes and Hallock 1979, Labelle 1992, Pascual et al 1995). Also, fish released too long before or after the critical parr-smolt transformation may not experience the appropriate combinations of temporal, spatial, and physiological parameters necessary for successful homing (Unwin and Quinn 1993).

To maximize imprinting opportunity, juvenile salmon must experience the odors of their natal system at various times and physiological states so the odors can be learned. Conservation hatcheries should, therefore, rear fish for their entire juvenile freshwater lives in water from the intended return location. When this is not possible, a period of acclimation in the intended return water should improve imprinting and homing, and reduce straying.

K. Habitat Carrying Capacity

Conservation hatcheries should program their production to accommodate the natural spatial and temporal patterns of abundance in wild fish populations. It is recommended that they:

- Adopt strategies for releasing numbers of hatchery-reared juveniles to equal (or not exceed) carrying capacities of receiving waters
- Formulate an Ocean Productivity Index as the basis of modulating fish hatchery production in fisheries management plans

Rationale

The annual release of large numbers of fish from industrial-scale production hatcheries does not consider the reality that aquatic ecosystems can only absorb so many fish, and their annual carrying capacity is variable and unpredictable. Fortunately, total regime shifts, or major changes in ocean productivity, occur infrequently. This means that, for long periods, trends are established which can be observed in several ways, such as increasing fish landings or decreasing populations of certain seabirds. By interpreting physical, chemical, and biological signals of changing oceanic productivity, certain impacts can now be anticipated. Even though the output of conservation hatcheries may be relatively small, it is practical and feasible to adjust fish hatchery production more in balance with periods of high or low oceanic productivity.

Justification

The present production hatchery system for raising Pacific salmon was developed to produce increasingly higher numbers of fish in an oceanic ecosystem believed to be near limitless in its carrying capacity. Until recently, this ecosystem was believed to be stable, internally regulated, and deterministic. The current view is one characterized by ecological uncertainty – a system in near constant flux, without long term stability, and often under the influence of stochastic factors, many originating outside the ecosystem itself.

Based on the assumption that ocean carrying capacity was unlimited, or had not yet been reached, the goal of increasing the size of a fishery was simply achieved by building more hatcheries and releasing more fish. As a result, for more than 20 years there has been massive growth in salmon hatchery releases in the Pacific Northwest (Mahnken et al. 1998), with more smolts entering the ocean from the Columbia-Snake River system than at any time in the past. The Northwest Power Planning Council (NWPPC 1986) estimated that annual abundance before 1850 was 264 million smolts. Since the late 1980s, public hatcheries in the Columbia River Basin have reared between 200 - 300 million juveniles annually for release (Chapman 1986, Schiewe et al. 1989). In 1992, for example, based on releases of nearly 203 million hatchery fish and an estimated 145 million wild fish, almost 350 million smolts were in the Basin that year, or 32 % above the historic high of 1850. Such vast numbers of out-migrants clearly place a heavy demand on the food production capabilities of any ecosystem, whether in the natal streams and rivers, the coastal estuaries, or in the ocean itself. Furthermore, in the intense competition for food which must occur, the dramatic increase in numbers of hatchery fish has obviously affected the chances for survival of the smaller numbers of native stocks.

Studies on abundance of stocks in widely separate geographic areas over time have indicated oceanic conditions are primarily responsible for changes in annual returns of adult salmon (Cooper and

Johnson 1992, Beamish and Bouillon 1993, Lichatowich 1993, Olsen and Richards 1994). The way in which these ocean conditions, which are a web of physical, chemical, and biological processes above and below the surface, can impact fish populations and production trends are reasonably well known. Furthermore, the magnitude of these changing ocean conditions probably masks any changes on the migratory salmon during their lives in the freshwater habitat.

Based on an analysis of climatic trends and salmon fisheries in the North Pacific, Beamish and Bouillon (1993) said the strategy of releasing large numbers of artificially reared smolts during a period of decreasing marine survival was not appropriate. Concerns over the limits of ocean carrying capacity, and other factors, are conspiring to force a re-evaluation of industrial hatchery production of North Pacific salmonids (Mahnken et al. 1998). These include 1) high harvest rates of wild fish in fisheries targeting on the more abundant hatchery stocks, 2) over-production of hatchery chum salmon in Japan, and both pink and chum salmon in Alaska, 3) declining fish size, and 4) altered return timing and age at maturity. Concern for declining size and increasing age at maturity observed in North Pacific stocks of five salmon species suggests that large-scale hatchery production may be resulting in density-dependent growth reduction (Kaeriyama and Urawa 1992, Rogers and Ruggerone 1993, Bigler and Helle 1994).

Given that the carrying capacity of the ocean has a primary impact on salmon returns, it is eminently sensible that hatchery releases should be reduced during periods of poor ocean productivity to protect wild fish. This approach has been used successfully in Japan for chum salmon. Hatchery production, by stock or species, could be modulated through development of an Ocean Productivity Index, and integration of such an index into fisheries management plans could be critical to the long-term survival of Pacific salmon.

The use of an Index is timely for the conservation of endangered stocks. By nature, ecosystems are complex and highly variable biological systems, subject to many natural disturbances and human interventions. Although ocean harvest rates are generally scaled back when the abundance or productivity of wild stocks is low, regime shifts do not become evident until some years after certain trends began. Scientific ignorance of all the ramifications of such shifts, and their impact on the variability of fish abundance and survival, has acted against wild fish populations through poorly informed or ill-considered hatchery production and harvest policies. The coast-wide record is replete with examples of harvest rates being based on the production of hatchery fish in an attempt to avoid the consequences of smaller harvests. Fishery managers now know they should decrease harvest rates during periods of lower productivity, that is, they should scale fisheries to the natural spatial and temporal patterns of abundance of wild fish populations. However, there are consequences for the commercial fisheries because the harvest rates of hatchery fish scaled to natural spatial and temporal patterns of abundance in wild fish populations will probably result in a smaller surplus for harvest.

IV. HATCHERY MONITORING AND EVALUATION

It is recommended that a Hatchery Monitoring and Evaluation Program (HMEP) for smolt production is established to centralize specific data for all anadromous fish hatcheries on a regional basis, beginning with the Columbia River Basin. This should be carried out by a small team created and empowered to assess the performance of all hatcheries in the region with respect to meeting the objectives of the ESA.

Rationale

Currently, no one entity is monitoring and evaluating the hatcheries of the Columbia River system on a Basin-wide basis. Hatchery production and release data are collated and coordinated through the Production Advisory Committee (PAC), while the Integrated Hatchery Operations Team (IHOT), which is no longer funded, developed performance standards for the operation of all Columbia and Snake River anadromous fish hatcheries. Moreover, each operating agency collects voluminous amounts of information in its own specific format, which makes inter-agency comparison of data and access difficult. As a result, little or no Basin-wide analysis of hatchery performance is being carried out. No one is asking the fundamental questions of which hatcheries are doing well and which are doing poorly.

Justification

Monitoring and evaluation (M&E) is an effective approach to determine if juvenile salmon from hatcheries match their respective rates of development and target size, and smolts achieve acceptable quality criteria. Although a number of hatchery programs have M&E programs of varying degrees of effectiveness, these tend to focus primarily on their own production activities.

Kapuscinski (1997) recommended that the entire Pacific Northwest region, not just the Columbia River Basin, needs periodic audits of Pacific salmon hatcheries based on application of explicit genetic and ecological monitoring guidelines. Audits should be carried out by an independent party with no stake in the outcome. A rigorous audit would involve a two-tiered evaluation based on information gathered from written agency documents, selected interviews with administrators and operators of hatcheries, reviews of hatchery records, and hatchery site visits.

The primary objective of the HMEP is to evaluate the effectiveness of hatchery operations in the Columbia River Basin. To be effective, the HMEP must be independent of the operating agencies. The HMEP Team would collect basic information on hatchery performance measures (see Appendix), conduct analysis of data, and publish an annual summary of hatchery effectiveness measures. Over a period of time the Team should be in a position to develop hatchery standards based on comparison of different rearing protocols.

Team members may also assist in the planning and operation of experimental rearing studies to test promising new techniques and, where necessary, train hatchery personnel to collect and store data, and provide monthly updates. The Team would review monthly updates and prepare an annual report for each hatchery in the Program. Much of the information could be completed and made available through the Internet.

Because of the scientific orientation of such a Program, and ensuing legal responsibilities under the terms of the ESA, scientists and experienced personnel from the agencies operating hatcheries in the Columbia River Basin would be active members on a rotating basis. Furthermore, an effective conservation hatchery program in the region may require some legislative and/or policy changes at the federal and state levels.

V. CONCLUSIONS

The principal strategy of any salmon conservation policy continues to be the protection and restoration of habitat. But this strategy is long-term and action is needed immediately. Hatcheries, partially or totally dedicated to conservation offer a practical short-term solution.

Conservation hatchery programs are consistent with the recommendations proposed in the NMFS Snake River Salmon Recovery Plan (Schmitten et al. 1995). Implementation of such programs would require significant capital expenditure, with increased hatchery operational costs and reduced fish production. Some increased costs will be offset by conservation hatcheries releasing smaller numbers of highly adaptable fish. These programs would also require considerable cooperation between scientists, fish producers, and fishermen, not only in planning, implementing, and monitoring programs, but also conducting the necessary research and development.

The reform of hatchery practices for the benefit of both ESA-listed stocks and even healthy stocks has been emerging for more than a decade. It has grown from a logical integration of encouraging results from independent scientific research on a variety of hatchery-related topics. However, as the title of this document implies, the idea of conservation hatcheries remains conceptual. Many individual activities remain to be initiated, completed, and analyzed for their benefits and cost-effectiveness before certain rearing protocols or conservation hatcheries become the norm.

There are four areas which require additional research to help make the transition to conservation hatcheries. These, and their research tasks, are as follows:

Basic scientific research

High priority must continue to be given to basic scientific research to meet four principal goals of conservation hatchery systems. Specifically these goals are:

- increasing juvenile quality
- increasing adult quality
- increasing in-culture survival
- maintaining the genetic integrity of the population

The coordination of research between the various agencies and scientific institutions must continue because of the high-cost of basic research, and to make the most use of the results.

Applied research and field testing

Top priority must now be given to applied research and field testing of postulated reforms of certain rearing protocols. These are identified in Section III (above), which are genetic protocols, broodstock sourcing, maturation and reproduction, enriched environments, growth rate modulation, rearing density, anti-predator training, release size, release time and volitional release, imprinting and homing, and habitat carrying capacity. Applied research on this scale is multidisciplinary in scope and long-term, as most of the results are measured by the number of returning adults. Therefore it requires close inter-agency cooperation and coordination.

Test facilities

From past experience, controlled research at any fish culture facility operating with production targets is seriously at risk. A number of hatchery managers are already trying to apply some reforms, but when emergencies occur production targets often take precedence over experimental information. Consequently, the urgent requirement for the next step in the evolution of the conservation hatchery is to identify one or two sites where reforms in production practices and conservation strategies can be tested on a pilot-scale level without any outside encumbrances. Several hatcheries have been identified as possible sites for applied research and field testing in the Columbia River Basin. While responsibility for the management and operation of these first conservation sites should rest with one authority, the broad scope of the program would provide many opportunities for inter-agency cooperation.

Monitoring and evaluation

The HMEP should be initiated to centralize data for all anadromous fish hatcheries in the Columbia River Basin, as described in Section IV and the Appendix. A Team should be created and empowered to assess the performance of these hatcheries with respect to the objectives of the ESA. This would be the first step in the long-term Basin-wide coordination and management of salmonid fisheries.

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APPENDIX

REQUIRED DATA BY THE HATCHERY MONITORING AND EVALUATION PROGRAM

Any hatchery monitoring and evaluation program (HMEP) for the Columbia River Basin is only as effective as the reliability and accuracy of the data collected for each hatchery and entered into the database. The cost and benefits of data collection is an additional consideration. While it may be desirable to collect as much data as possible, including measures of juvenile salmonid development, it is not possible or reasonable to expect such data to be collected on a Basin-wide basis. Therefore, three sets of data are proposed.

1. Stock data – Collected for each separate stock on a yearly basis:

- Hatchery name and stock name
- Egg take and fry ponded
- Density, loading, mean length, and mean weight on a monthly basis (for representative rearing units)
- Health status and proximate body composition of release groups
- Release number by location and date
- Tag information (percentage/number and dates) for the following types, Ad Clips, CWT, PIT, and others
- Hatchery rack returns
- In-river fishing (if available)
- Adult contribution (from the CWT database)

2. Hatchery-related data – Collected from specific reference hatcheries, to enable comparisons to be made between hatcheries and/or experimental rearing studies:

- Physiological data (growth and smoltification related hormone and enzyme assays)
- Morphological data (body truss measurements, fin quality, cryptic coloration)
- Behavioral data (social behavior, agonistic responses, foraging/anti-predator behavior, habitat use)
- Migration data (in-stream survival and migratory rate)
- Ecological interactions/habitat carrying capacity

- Homing/straying incidence
- Reproductive success
- Genetic information (inbreeding/domestication/outbreeding effects)

3. Natural production-related data – Collect from specific reference habitats for qualitative risk assessment:

- Annual population level abundance
- Proportion of hatchery fish in natural spawning areas
- Natural productivity data
- Hatchery productivity data
- Straying data
- Life history, morphology, and behavior data for natural and hatchery fish

Individual hatchery managers should have responsibility for collecting and entering the data into a protected web-based on-line system, which will then be processed by database managers and systems analysts. The amount of data verification and number of hatchery inspection visits will be determined after the HMEP is underway.

The collection of these data will probably be required by the Biological Opinion for Hatchery Operations in the Columbia River Basin.