

Bibliography in Support of Supplementation Science

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Purpose: The primary purpose of this bibliography is to present publications or studies that support the theory that supplementation (as defined by RASP 1992) techniques can be used to maintain or increase natural production, while maintaining the long-term fitness of the wild and native salmonid populations and keeping adverse genetic and ecological impacts within acceptable limits.

Note: The term “abstract” is used here to denote an abstract as published by the authors. The term “synopsis” is used when compilers of this bibliography summarized publications, generally using sentences taken directly from the publications.

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Can supplementation maintain or increase natural production?

Araki, H., W. R. Ardren, E. Olsen, B. Cooper, and M. S. Blouin. 2007. Reproductive success of captive-bred steelhead trout in the wild: evaluation of three hatchery programs in the Hood River. *Conservation Biology* 21 (1), 181-190.

Abstract: Population supplementation programs that release captive-bred offspring into the wild to boost the size of endangered populations are now in place for many species. The use of hatcheries for supplementing salmonid populations has become particularly popular. Nevertheless, whether such programs actually increase the size of wild populations remains unclear, and predictions that supplementation fish drag down the fitness of wild fish remain untested. To address these issues, we performed DNA-based parentage analyses on almost complete samples of anadromous steelhead (*Oncorhynchus mykiss*) in the Hood River in Oregon (U.S.A.). Steelhead from a supplementation hatchery (reared in a supplementation hatchery and then allowed to spawn naturally in the wild) had reproductive success indistinguishable from that of wild fish. In contrast, fish from a traditional hatchery (nonlocal origin, multiple generations in hatcheries) breeding in the same river showed significantly lower fitness than wild fish. In addition, crosses between wild fish and supplementation fish were as reproductively successful as those between wild parents. Thus, there was no sign that supplementation fish drag down the fitness of wild fish by breeding with them for a single generation. On the other hand, crosses between hatchery fish of either type (traditional or supplementation) were less fit than expected, suggesting a possible interaction effect. These are the first data to show that a supplementation program with native brood stock can provide a single-generation boost to the size of a natural steelhead population without obvious short-term fitness costs. The long-term effects of population supplementation remain untested.

Bailey, M.M., and J.D. Zydlewski. 2013. To stock or not to stock? Assessing the restoration potential of a remnant American Shad spawning run with hatchery supplementation. *North American Journal of Fisheries Management*, 33:459-467.

Abstract: Hatchery supplementation has been widely used as a restoration technique for American Shad *Alosa sapidissima* on the East Coast of the USA, but results have been equivocal. In the Penobscot River, Maine, dam removals and other improvements to fish passage will likely reestablish access to the majority of this species' historic spawning habitat. Additional efforts being considered include the stocking of larval American Shad. The decision about whether to stock a river system undergoing restoration should be made after evaluating the probability of natural recolonization and examining the costs and benefits of potentially accelerating recovery using a stocking program. However, appropriate evaluation can be confounded by a dearth of information about the starting population size and age structure of the remnant American Shad spawning run in the river. We used the Penobscot River as a case study to assess the theoretical sensitivity of recovery time to either scenario (stocking or not) by building a deterministic model of an American Shad population. This model is based on the best available estimates of size at age, fecundity, rate of iteroparity, and recruitment. Density dependence was imposed, such that the population reached a plateau at an arbitrary recovery goal of 633,000 spawning adults. Stocking had a strong accelerating effect on the time to modeled recovery (as measured by the time to reach 50% of the recovery goal) in the base model, but stocking had diminishing effects with larger population sizes. There is a diminishing return to stocking when the starting population is modestly increased. With a low starting population (a spawning run of 1,000), supplementation with 12 million larvae annually accelerated modeled recovery by 12 years. Only a 2-year acceleration was observed if the starting population was 15,000. Such a heuristic model may aid managers in assessing the costs and benefits of stocking by incorporating a structured decision framework.

Baumsteiger, J., D. M. Hand, D. E. Olson, R. Spateholts, G. FitzGerald, and W. R. Ardren. 2008.

Use of Parentage analysis to Determine Reproductive Success of Hatchery-Origin Spring Chinook Salmon Outplanted into Shitike Creek, Oregon. *North American Journal of Fisheries Management*, 28:1472-1485.

Abstract: Removal of fish passage barriers provides Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* the opportunity to recolonize previously accessible habitat, though the time scale of natural recolonization may not be sufficient for management or conservation goals. One strategy for accelerating recolonization is to outplant hatchery-origin adults into newly restored habitats. In this paper, we describe how genetic parentage analysis was used to determine the reproductive success of adult stream-type spring Chinook salmon *O. tshawytscha* taken from two localized hatchery stocks and outplanted into a stream. We defined reproductive success as the production of migratory juveniles. In 2002 and 2003, 83 and 265 adult hatchery salmon, respectively, were outplanted into Shitike Creek, Oregon, a tributary to the Deschutes River. Using 11 microsatellite markers, 799 and 827 migratory juveniles from the two brood years were genotyped and matched back to potential outplanted parents using genetic parentage analyses. Successful spawning of outplant-outplant, outplant-wild, and wild-wild fish occurred in Shitike Creek in both years. Adults outplanted in 2002 showed far fewer matches (18%) to sampled juveniles than those from 2003 (88%). Additionally, only 1% of juveniles had both parents identified as outplants in 2002, compared with almost 61% in 2003. Differences in the number of females outplanted each year appeared to account for the differential productivity. The number of offspring attributed to an individual outplant was variable, ranging from 1 to more than 10. Multiple outplant \times outplant matings were identified for each sex as males mated with up to seven females and females mated with up to four males. This study shows that, under the right conditions, outplanted adult hatchery fish taken from localized hatchery stocks can contribute to the overall juvenile production in a natural stream.

Berejikian, B. A., T. Johnson, R.S. Endicott, and J. Lee-Waltermire. 2008. Increases in Steelhead Redd Abundance Resulting from Two Conservation Hatchery Strategies in the Hamma Hamma River, WA. *Canadian Journal of Fisheries and Aquatic Sciences*, 65:754-764.

Abstract: Conservation hatcheries for anadromous salmonids that aim to increase production and minimizing genetic, ecological, and demographic risks have not been experimentally tested for their ability to increase number of adults spawning in the natural environment. The conservation hatchery program for steelhead (i.e., sea-run rainbow trout, *Oncorhynchus mykiss*) evaluated in this study caused an increase in the number of redds in the supplemented Hamma Hamma River compared with the presupplementation period. Three control populations (nonsupplemented) either remained stable or declined over the same period. The increase in redds from hatchery-produced spawners did not reduce the redd production from natural-origin spawners. The strategy of rearing and releasing adult steelhead accounted for the greatest proportion of redd abundance increases. Environmentally induced differences in spawn timing between the adult release group and anadromous adults of hatchery and natural origin may explain why the adult release group and anadromous adults assortatively formed pairing combinations on the spawning grounds. Although captively reared adults produced the majority of redds in years they were released in substantial numbers, uncertainty regarding the relative reproductive success of this strategy suggests caution in recommending one strategy over the other. A demographic boost to the naturally spawning population was effected while managing to minimize negative ecological consequences.

Berejikian, B. A. and D.M. VanDoornik. 2018. Increased natural reproduction and genetic diversity one generation after cessation of a steelhead trout (*Oncorhynchus mykiss*) conservation hatchery program. PLoS ONE 13(1):e0190799.

Abstract: Spatial and temporal fluctuations in productivity and abundance confound assessments of captive propagation programs aimed at recovery of Threatened and Endangered populations. We conducted a 17 year before-after-control-impact experiment to determine the effects of a captive rearing program for anadromous steelhead trout (*Oncorhynchus mykiss*) on a key indicator of natural spawner abundance (naturally produced nests or 'redds'). The supplemented population exhibited a significant (2.6-fold) increase in redd abundance in the generation following supplementation. Four non-supplemented (control) populations monitored over the same 17 year period exhibited stable or decreasing trends in redd abundance. Expected heterozygosity in the supplemented population increased significantly. Allelic richness increased, but to a lesser (non-significant) degree. Estimates of the effective number of breeders increased from a harmonic mean of 24.4 in the generation before supplementation to 38.9 after supplementation. Several non-conventional aspects of the captive rearing program may have contributed to the positive response in the natural population.

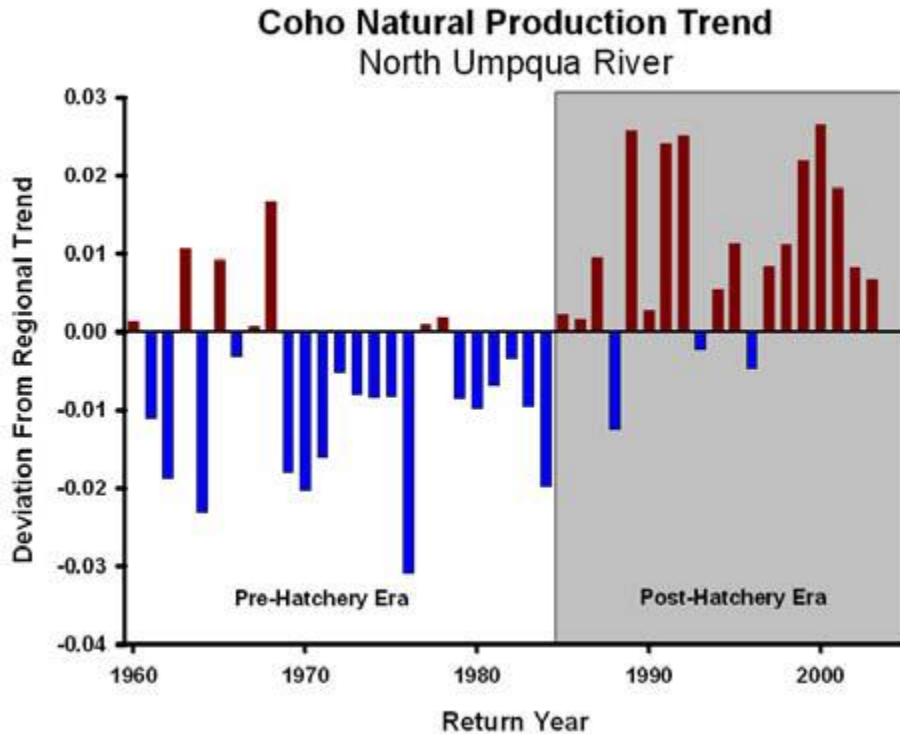
Caroffino, D. C, L. M. Miller, A. R. Kapucinski, and J. J. Ostazeski. 2008. Stocking success of local-origin fry and impact of hatchery ancestry: monitoring a new steelhead (*Oncorhynchus mykiss*) stocking program in a Minnesota tributary to Lake Superior. Canadian Journal of Fisheries and Aquatic Sciences 65:309-318.

Abstract: The inception of a hatchery program to rebuild a naturalized steelhead (*Oncorhynchus mykiss*) population in Minnesota waters of Lake Superior gave us the rare opportunity to monitor the success of fry stocking and determine if hatchery ancestry can reduce fitness of stocked fish in the early generations of a stocking program. Through genetic monitoring of two year classes, we determined that hatchery adults produced 1.3-6.2 times as many age-2 juveniles per female than naturally spawning fish. Survival of stocked fry of parents born in a hatchery relative to those of parents born in the wild was 70% in paired-stocking comparisons. These results suggest that stocking local-origin fry can increase the short-term abundance of depleted populations and that fish with no hatchery history are a better source for supplemental stocking. Additionally, sampling small numbers of adults for broodstock created genetically distinct groups, which could potentially cause long-term genetic change in the population. Genetic monitoring of adults will be essential to determining whether differences observed persist through the life cycle of the stocked fish.

Cramer, S. P., N. K. Ackerman, and J. B. Lando. 2005. Viability of Oregon Coastal Coho: Comments on Oregon's 2005 Assessment. Report to Oregon Forest Industries Council and Douglas County. S.P. Cramer & Associates, Inc. Gresham, OR.

Synopsis: Review of data set dating back to 1958. Hatchery fish were virtually non-existent in the North Umpqua for the first 24 years of data, 1958-1981, and composed an average 76% of natural spawners after 1982. The North Umpqua showed a highly significant increase in natural production after 1982. Since 1985, when substantial returns from naturally spawning hatchery coho began, the trend in natural production of coho from the North Umpqua consistently out-performed the regional

trend in natural production (see figure). This difference clearly indicates that hatchery fish were successfully reproducing and having a detectable positive influence on natural production.



Fast, D.E., W.J. Bosch, M.V. Johnston, C.R. Strom, C.M. Knudsen, A.L. Fritts, G.M. Temple, T.N. Pearsons, D.A. Larsen, A.H. Dittman, and D. May. 2015. A Synthesis of Findings from an Integrated Hatchery Program after Three Generations of Spawning in the Natural Environment. *North American Journal of Aquaculture* 77:377-395.

Abstract: The Cle Elum Supplementation and Research Facility in the Yakima River basin, Washington, is an integrated spring Chinook Salmon *Oncorhynchus tshawytscha* hatchery program designed to test whether artificial propagation can increase natural production and harvest opportunities while keeping ecological and genetic impacts within acceptable limits. Only natural-origin (naturally spawned) fish are used for hatchery broodstock. Spawning, incubation, and early rearing occur at a central facility; presmolts are transferred for final rearing, acclimation, and volitional release at sites adjacent to natural spawning areas, where returning adults can spawn with natural-origin fish. The first wild broodstock were collected in 1997, and age-4 adults have returned to the Yakima River since 2001. An unsupplemented population in the adjacent Naches River watershed provides a reference for evaluating environmental influences. The program has been comprehensively monitored from its inception. A synthesis of findings, many already published, is as follows: supplementation increased the harvest, redd counts, and spatial distribution of spawners; natural-origin returns were maintained; straying to nontarget systems was negligible; natural-origin females had slightly

higher breeding success (production of surviving fry) in an artificial spawning channel, while the behavior and breeding success of natural- and hatchery-origin males were similar; hatchery-origin fish showed differences in morphometric and life history traits; high rates of hatchery age-2 (minijack) production were reported, but the observed proportions of out-migrating juvenile and adult (ages 4 and 5) returning males were comparable for hatchery- and natural-origin fish; hatchery smolts did not affect the levels of pathogens in natural smolts; and the ecological interactions attributed to the program were within adopted guidelines. Continued study is required to assess the long-term impacts on natural production and productivity.

Fitzsimons, J.D., A. Dalton, B. MacVeigh, M. Heaton, C. Wilson, and D.C. Honeyfield. 2013. Use of Stable Isotopes to Identify Redds of Putative Hatchery and Wild Atlantic Salmon and Evaluate Their Spawning Habitat and Egg Thiamine Status in a Lake Ontario Tributary. *North American Journal of Fisheries Management* 33:741-753.

Abstract: Both wild and hatchery Atlantic Salmon *Salmo salar* can contribute to restoration but can exhibit differences in spawning habitat selection (e.g., water depth, current speed) and egg nutritional quality (e.g., thiamine), which affect reproductive success. Hence, there is a need to be able to differentiate the spawning contribution of the two groups in the wild. As diets of wild and hatchery-reared spawners are markedly dissimilar and diet is known to influence stable isotope signature, egg stable isotope signatures offer the potential to discriminate redds of each. Using stable isotope analysis of carbon and nitrogen ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of naturally spawned Atlantic Salmon eggs, we were able to discriminate the redds of putative wild (i.e., previously stocked life stage feeding in Lake Ontario; EWSR) from putative hatchery-reared Atlantic Salmon (EHSR). Eggs of EWSR were significantly more enriched in nitrogen ($\delta^{15}\text{N}$: $15.0 \pm 0.5\text{‰}$ [mean \pm SE]) but more depleted in carbon ($\delta^{13}\text{C}$: $-26.6 \pm 0.3\text{‰}$) than eggs of EHSR ($\delta^{15}\text{N}$ = $9.8 \pm 0.6\text{‰}$; $\delta^{13}\text{C}$ = $-17.5 \pm 0.0\text{‰}$). Eggs of EHSR were indistinguishable from eggs of known hatchery Atlantic Salmon for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. Using stable isotopes to discriminate redd type, few differences were found between the spawning habitat of putative wild and hatchery spawners. Similarly using the same criteria, thiamine levels in eggs of EWSR ($8,474 \pm 840$ pmol/g) were not significantly different from eggs of known wild Atlantic Salmon ($3,691 \pm 782$ pmol/g) or of eggs of EHSR ($14,865 \pm 1,050$ pmol/g), whose thiamine levels were indistinguishable from eggs of known hatchery Atlantic Salmon ($14,200 \pm 1,167$ pmol/g). Egg thiamine levels for all groups were above established mortality thresholds. Our results indicate that both hatchery and wild Atlantic Salmon can make reproductive contributions, which can be differentiated and quantified using stable isotope signatures.

Hess, M.A., C.D. Rabe, J.L. Vogel, J.L. Stephenson, D.D. Nelson, and S.R. Narum. 2012. Supportive breeding boosts natural population abundance with minimal negative impacts on fitness of a wild population of Chinook salmon. *Molecular Ecology* 21:5236-5250.

Abstract: While supportive breeding programmes strive to minimize negative genetic impacts to populations, case studies have found evidence for reduced fitness of artificially produced individuals when they reproduce in the wild. Pedigrees of two complete generations were tracked with molecular markers to investigate differences in reproductive success (RS) of wild and hatchery-reared Chinook salmon spawning in the natural environment to address questions regarding the demographic and genetic impacts of supplementation to a natural population. Results show a demographic boost to the population from supplementation. On average, fish

taken into the hatchery produced 4.7 times more adult offspring, and 1.3 times more adult grand-offspring than naturally reproducing fish. Of the wild and hatchery fish that successfully reproduced, we found no significant differences in RS between any comparisons, but hatchery-reared males typically had lower RS values than wild males. Mean relative reproductive success (RRS) for hatchery F₁ females and males was 1.11 ($P = 0.84$) and 0.89 ($P = 0.56$), respectively. RRS of hatchery-reared fish (H) that mated in the wild with either hatchery or wild-origin (W) fish was generally equivalent to $W \times W$ matings. Mean RRS of $H \times W$ and $H \times H$ matings was 1.07 ($P = 0.92$) and 0.94 ($P = 0.95$), respectively. We conclude that fish chosen for hatchery rearing did not have a detectable negative impact on the fitness of wild fish by mating with them for a single generation. Results suggest that supplementation following similar management practices (e.g. 100% local, wild-origin brood stock) can successfully boost population size with minimal impacts on the fitness of salmon in the wild.

Hessenauer, J-M., J. Vokoun, A. Welsh, J. Davis, R. Jacobs, and E. O'Donnell. 2017. Can Largemouth Bass Transplanted from an Unexploited Population Genetically Contribute to an Active Fishery? A Test Case for Genetic Management of Exploited Fish Populations. *North American Journal of Fisheries Management* 37:271-283.

Abstract: Recreational fishing is one of the most popular outdoor activities in the world, resulting in substantial effects on recreational fish stocks. Recent studies have found that recreational angling may drive fisheries-induced evolution, resulting in changes in the size, behavior, and physiology of exploited recreational stocks. Traditional harvest-based management of recreational fisheries may be unable to mitigate these changes, especially with the rise of catch-and-release practices for many fisheries. We explored the potential to genetically manage exploited fisheries by introducing individuals from unexploited populations as a means to mitigate selection from recreational angling. We stocked 77 individuals from an unexploited population of Largemouth Bass *Micropterus salmoides* and 79 individuals from an exploited population into a third water body (with an active fishery) and evaluated the extent to which each group of stocked fish contributed to fall age-0 recruits. Fifty-four percent of the sampled age-0 Largemouth Bass with reliable parentage were hybrids of stocked and resident parents. Individuals from the exploited and unexploited populations contributed to the age-0 sample in proportion to their initial abundances. No sex-biased contribution was detected between the exploited and unexploited individuals stocked into the pond, although the largest females had the highest contribution to the age-0 sample. Age-0 fish originating from hybridization between unexploited and resident parents had significantly higher condition than age-0 recruits originating from two resident parents. We conclude that individuals from unexploited populations can successfully reproduce in an exploited system and that genetic management may be a feasible option for mitigating the effects of recreational fisheries-induced evolution.

Janowitz-Koch, I., C. Rabe, R. Kinzer, D. Nelson, M.A. Hess, and S.R. Narum. 2019. Long-term evaluation of fitness and demographic effects of a Chinook Salmon supplementation program. *Evolutionary Applications* 12:456–469.

Abstract: While the goal of supplementation programs is to provide positive, population-level effects for species of conservation concern, these programs can also present an inherent fitness risk when captive-born individuals are fully integrated into the natural population. In order to evaluate the long-term effects of a supplementation program and estimate the demographic and

phenotypic factors influencing the fitness of a threatened population of Chinook Salmon (*Oncorhynchus tshawytscha*), we genotyped tissue samples spanning a 19-year period (1998–2016) to generate pedigrees from adult fish returning to Johnson Creek, Idaho, USA. We expanded upon previous estimates of relative reproductive success (RRS) to include grandparentage analyses and used generalized linear models to determine whether origin (hatchery or natural) or phenotypic traits (timing of arrival to spawning grounds, body length, and age) significantly predicted reproductive success (RS) across multiple years. Our results provide evidence that this supplementation program with 100% natural-origin broodstock provided a long-term demographic boost to the population (mean of 4.56 times in the first generation and mean of 2.52 times in the second generation). Overall, when spawning in nature, hatchery-origin fish demonstrated a trend toward lower RS compared to natural-origin fish ($p < 0.05$). However, when hatchery-origin fish successfully spawned with natural-origin fish, they had similar RS compared to natural by natural crosses (first-generation mean hatchery by natural cross RRS = 1.11 females, 1.13 males; second-generation mean hatchery by natural cross RRS = 1.03 females, 1.08 males). While origin, return year, and body length were significant predictors of fitness for both males and females ($p < 0.05$), return day was significant for males but not females ($p > 0.05$). These results indicate that supplementation programs that reduce the potential for genetic adaptation to captivity can be effective at increasing population abundance while limiting long-term fitness effects on wild populations.

Kassler, T. W., D. K. Hawkins, and J. M. Tipping. 2008. Summer-Run Hatchery Steelhead Have Naturalized in the South Fork Skykomish River, Washington. *Transactions of the American Fisheries Society* 137:763-771.

Abstract: Evaluation of natural-origin, hatchery-origin, and unmarked steelhead *Oncorhynchus mykiss* from the Skykomish River drainage basin, Washington, was conducted to determine the source of unmarked steelhead that return to Sunset Falls (South Fork Skykomish River). One possible source is the large number of steelhead stocked into the Skykomish River basin from Reiter Ponds Hatchery; this hatchery stock was founded with fish from Skamania Hatchery in the Washougal River system, Washington. A microsatellite DNA analysis of 10 loci was used to evaluate unmarked samples in comparison with natural-origin samples from the North Fork Skykomish River and hatchery-origin samples from Reiter Ponds Hatchery. Results of the analyses provide evidence that the unmarked steelhead collected at Sunset Falls are more closely related to Reiter Ponds Hatchery fish than to natural-origin fish from the North Fork Skykomish River. There is evidence that unmarked steelhead at Sunset Falls are also mixing with natural-origin North Fork Skykomish River fish but to a lesser degree than with Reiter Ponds Hatchery fish. This study documents that Skamania Hatchery-origin steelhead have naturally produced offspring that are returning to spawn in a northern Puget Sound river basin.

Liermann, M., G. Pess, M. McHenry, J. McMillan, M. Elofson, T. Bennett, and R. Moses. 2017. Relocation and Recolonization of Coho Salmon in Two Tributaries to the Elwha River: Implications for Management and Monitoring. *Transactions of the American Fisheries Society* 146:955-966.

Abstract: In 2012 the lower of two Elwha River dams was breached, restoring access of anadromous salmonids to the middle Elwha River (between the two dams), including two distinct tributaries, Indian Creek and Little River. While comparable in size, Indian Creek is considerably less steep than

Little River (mean slope of 1.0% versus 3.5%, respectively) and has a warmer stream temperature regime due to its source, Lake Sutherland. During and after breaching, Coho Salmon *Oncorhynchus kisutch* were relocated to these tributaries from lower Elwha River hatcheries (below the dams) to determine if individuals from a hatchery-dominated population would successfully spawn and seed the systems with juveniles and to assess differences in recolonization between the streams. Transplantation led to immediate spawning, which resulted in levels of smolt out-migrants per stream kilometer comparable with other established Coho Salmon populations in the Pacific Northwest. During the first 2 years of the relocation, redd densities in the two systems were similar but Indian Creek produced four to five times as many smolts per kilometer as Little River. In addition, fry out-migration occurred 2 to 4 weeks earlier in Indian Creek, as predicted by the warmer incubation temperatures. In the first years of the study, there was little evidence of natural colonization of the two tributaries by adults. However, in 2016 over half of the observed adults returning to the two tributaries were not transplanted, suggesting that the progeny from the transplanted fish were returning to their natal waters. This work demonstrates that transplanting hatchery-dominated Coho Salmon adults into newly available habitat can result in immediate freshwater production that is comparable to other systems and that density and timing of juvenile out-migrants can differ dramatically based on the seeded habitat.

McLean, M.L., P.T. Lofy, and J.D.M. Schwartz. 2006. Successful natural production of hatchery spring chinook salmon: A lesson from Lookingglass Creek in Eastern Oregon. Oregon Chapter AFS Meeting Presentation, March 3, 2006.

Synopsis: Reintroduction of a non-endemic hatchery spring Chinook stock from Rapid River (RR) was evaluated and various survival parameters were compared with an endemic stock from Lookingglass Creek (LCE) and other naturally produced fish from the Grand Ronde River (GRR) or other Columbia Basin tributaries (CSR). “There was no significant difference in mean adults-per-redd among the RR, LCE, or CSR. There was no significant difference in mean juveniles-per-redd between RR, LCE, and GRR. Progeny-per-parent ratios for RR were not significantly different than those estimated for GRR.”

Perrier, C., F. Daverat, G. Evanno, C. Pecheyran, J-L Bagliniere, and J-M Roussel. 2011. Coupling genetic and otolith trace element analyses to identify river-born fish with hatchery pedigrees in stocked Atlantic salmon (*Salmo salar*) populations. Canadian Journal of Fisheries and Aquatic Sciences, 68(6): 977-987.

Abstract: This study combines otolith trace element and genetic analyses to explore the origin of individuals when hatchery-reared fish are released into wild populations. We sampled 90 juvenile Atlantic salmon (*Salmo salar*) in four rivers in Normandy (France) and in the hatchery stock. Individuals were analyzed at six microsatellite markers and their otolith elemental concentrations (14 elements) were measured using femto-second laser ablation inductively-coupled plasma mass spectrometry. Wild populations were genetically differentiated from the hatchery strain ($F_{ST} \approx 0.06$). Significant differences in elemental concentrations were found among otoliths of juveniles from the four rivers and the hatchery, allowing the identification of their geographic origin (83%–100% correct assignment). Coupling genetic and trace element analyses on the same individuals provided formal evidence that hatchery-born juveniles released into the wild can migrate to the sea and return as adults to breed on natural spawning grounds. Their progeny have pure hatchery pedigrees but have

otoliths typical of river-born juveniles, meaning that they can be mistaken for hatchery-raised juveniles if only genetic data are considered. The presence of hybrids also confirmed that individuals with hatchery pedigrees can breed with wild conspecifics.

Phillips, J.L., J. Ory and A. Talbot. 2000. Anadromous salmonid recovery in the Umatilla River Basin, Oregon: A case study. *Journal of the American Water Resources Association*, Vol. 36, no. 6, pp. 1287-1308. Dec 2000.

Synopsis: The mean adult-to-adult return rate of hatchery-reared steelhead exceeded replacement and that of the naturally-spawning population. Although the smolt-to-adult survival rates of hatchery-reared fish fluctuate, salmonid escapement has increased in recent years, permitting steelhead and spring chinook harvest. Enumeration of potential spawners and observed redds reveals an increase in natural production of all supplemented species.

Plumb, J.M., C.M. Moffitt, and W.P. Connor. 2009. Hatchery Supplementation Success and the Juvenile Life-History of Wild-Reared Fall Chinook Salmon in the Lower Snake River, Idaho. AFS poster presentation, national meeting, Nashville, TN, Sept. 2009.

Synopsis: Since 1998, a fall Chinook supplementation program has been conducted in the Snake River Basin with brood captured from fish passage facilities and Lyons Ferry State Fish Hatchery. In association with hatchery releases, abundance of the wild spawning population has increased substantially. The increased release of hatchery juveniles into the river was strongly ($P < 0.0001$) related to the increase in redds 3 years later. This increase in redds was, in turn, strongly related ($P < 0.0001$) to an increase in CPUE of wild juveniles in the rearing areas. This study documents the success of hatchery supplementation with a known-origin stock to restore a wild population.

Scheuerell, M.D., E.R. Buhle, B.X. Semmens, M.J. Ford, T. Cooney, and R.W. Carmichael. 2015. Analyzing large-scale conservation interventions with Bayesian hierarchical models: a case study of supplementing threatened Pacific salmon. *Ecology and Evolution*, 5(10):2115-2125.

Synopsis: This study evaluated the effects of a large-scale supplementation program on the density of adult Chinook salmon *Oncorhynchus tshawytscha* from the Snake River basin in the northwestern United States currently listed under the U.S. Endangered Species Act. The study analyzed 43 years of data from 22 populations, accounting for random effects across time and space using a form of Bayesian hierarchical time-series model common in analyses of financial markets. As the researchers modeled the 22 populations over the course of 25 years, they found “very limited support for a supplementation effect at both the individual population and ESU levels,” the report says. In fact, there was a 16 percent to 50 percent chance that supplementation had actually “caused some decrease in densities of wild adults across the ESU.” However, when the researchers excluded two of the twelve populations – the Minam and the Wenaha rivers had some hatchery-origin adults spawning but had not been “intentionally supplemented” – supplemented populations of wild fish increased from 1 percent to 13 percent relative to non-supplemented populations. “If habitat capacity has been reduced due to long-term structural alterations, then supplementation without concomitant habitat restoration will be unlikely to provide strong conservation benefits and may simply result in displacement of natural-origin fish by hatchery fish,” the study concludes. On the other hand, if carrying capacity is reduced because of a loss of nutrients in the stream, then supplementation could

provide carcasses and increase carrying capacity. “Also, it is important to note that even if supplementation does result in a modest abundance increase, there are concerns that long-term use of artificial propagation could reduce genetic fitness, contribute to ecological risks such as competition for resources, and serve as vectors for diseases or parasites,” the study says.

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. *Nature*, 465:609:612.

Abstract: One of the most pervasive themes in ecology is that biological diversity stabilizes ecosystem processes and the services they provide to society, a concept that has become a common argument for biodiversity conservation. Species-rich communities are thought to produce more temporally stable ecosystem services because of the complementary or independent dynamics among species that perform similar ecosystem functions. Such variance dampening within communities is referred to as a portfolio effect and is analogous to the effects of asset diversity on the stability of financial portfolios. In ecology, these arguments have focused on the effects of species diversity on ecosystem stability but have not considered the importance of biologically relevant diversity within individual species. Current rates of population extirpation are probably at least three orders of magnitude higher than species extinction rates, so there is a pressing need to clarify how population and life history diversity affect the performance of individual species in providing important ecosystem services. Here we use five decades of data from *Oncorhynchus nerka* (sockeye salmon) in Bristol Bay, Alaska, to provide the first quantification of portfolio effects that derive from population and life history diversity in an important and heavily exploited species. Variability in annual Bristol Bay salmon returns is 2.2 times lower than it would be if the system consisted of a single homogenous population rather than the several hundred discrete populations it currently consists of. Furthermore, if it were a single homogeneous population, such increased variability would lead to ten times more frequent fisheries closures. Portfolio effects are also evident in watershed food webs, where they stabilize and extend predator access to salmon resources. Our results demonstrate the critical importance of maintaining population diversity for stabilizing ecosystem services and securing the economies and livelihoods that depend on them. The reliability of ecosystem services will erode faster than indicated by species loss alone.

Steffensen, K.D., L.A. Powell, and J.D. Koch. 2010. Assessment of Hatchery-Reared Pallid Sturgeon Survival in the Lower Missouri River. *North American Journal of Fisheries Management* 30:671-678.

Abstract: The population of pallid sturgeon *Scaphirhynchus albus* in the lower Missouri River between Gavins Point Dam (river kilometer [rkm] 1,305.2) and the confluence with the Mississippi River (rkm 0.0) remains imperiled, little to no natural recruitment occurring. Artificial propagation and subsequent population augmentation (i.e., stocking) may be the only viable option for maintaining pallid sturgeon populations in the lower Missouri River in the near term. Because relatively little is known about the ability of hatchery-reared pallid sturgeon to survive, the objective of this study was to quantify survival estimates for hatchery-reared pallid sturgeon stocked into the lower Missouri River. We used stock–recapture data collected from 1994 to 2008 to derive survival estimates based on the Cormack–Jolly–Seber model within program MARK. Since 1994, a total of 78,244 hatchery-reared pallid sturgeon have been released and 1% of these have been recaptured.

Recapture numbers by size at stocking were as follows: 48 age 0, 730 age 1, and 38 older than age 1. Stocked age-0 hatchery-reared pallid sturgeon had an estimated apparent survival rate of 0.051 (SE = 0.008), compared with 0.686 (SE = 0.117) for age-1 fish and 0.922 (SE = 0.015) for fish older than age 1. Our analysis confirms that hatchery-reared pallid sturgeon can survive in the wild and contribute to the overall population of this species.

Van Doornik, D.M., B.A. Berejikian, L.A. Campbell, and E.C. Volk. 2010. The effect of a supplementation program on the genetic and life history characteristics of an *Oncorhynchus mykiss* population. *Canadian Journal of Fisheries and Aquatic Sciences*, 67(9): 1449-1458.

Abstract: Conservation hatcheries, which supplement natural populations by removing adults or embryos from the natural environment and rearing and releasing parr, smolts, or adults back into their natal or ancestral streams, are increasingly being used to avoid extinction of localized populations of Pacific salmonids. We collected data before and during a steelhead (*Oncorhynchus mykiss*) supplementation program to investigate the effect that the program has had on the population's genetic diversity and effective population size and any changes to an important life history trait (residency or anadromy). We found that supplementation did not cause substantial changes in the genetic diversity or effective size of the population, most likely because a large proportion of all of the steelhead redds in the river each year were sampled to create the supplementation broodstock. Our data also showed that the captively reared fish released as adults successfully produced parr. Furthermore, we found that during supplementation, there was an increase in the proportion of *O. mykiss* with anadromous ancestry vs. resident ancestry.

Venditti, D.A., R.N. Kinzer, K.A. Apperson, B. Barnett, M. Belnap, T. Copeland, M.P. Corsi, and K. Tardy. 2017. Effects of hatchery supplementation on abundance and productivity of natural-origin Chinook salmon: two decades of evaluation and implications for conservation programs. *Canadian Journal of Fisheries and Aquatic Sciences*, <https://doi.org/10.1139/cjfas-2016-0344>. See also: <https://nwcouncil.app.box.com/s/gsolcxk9nv1w3897am4th5nl7xe6108g>.

Abstract: Hatchery supplementation has been developed to conserve salmonid populations and provide fisheries. We evaluated supplemented and reference Chinook salmon (*Oncorhynchus tshawytscha*) populations prior to, during, and after supplementation ceased for 22 years in two major drainages in Idaho, USA. Basin-level analyses showed supplementation increased abundance at some life stages, but effects did not persist into the post-supplementation phase and had no apparent influence on productivity. Natural-origin juvenile abundance increased during supplementation but results for adults were ambiguous. After supplementation ceased, abundance and productivity in supplemented and reference populations returned to their pre-supplementation relationships. Intensive analyses of supplemented populations with weirs showed abundance increased at some life stages with the addition of female spawners. However, the rate of increase varied with female origin (natural > supplementation ≥ non-treatment hatchery) and effects diminished through the life cycle. Based on these findings, we provide guidance for conservation programs. Supplementation alone is not a panacea because it does not correct limiting factors, which must be addressed to achieve population levels capable of sustaining ecological function and harvest.

Can supplementation hatcheries be managed to maintain the long-term fitness of wild/natural populations?

Anderson, J.H., P.L. Faulds, W.I. Atlas, and T.P. Quinn. 2013. Reproductive success of captively bred and naturally spawned Chinook salmon colonizing newly accessible habitat. *Evolutionary Applications* 6:165-179. doi: 10.1111/j.1752-4571.2012.00271.x.

Abstract: Captively reared animals can provide an immediate demographic boost in reintroduction programs, but may also reduce the fitness of colonizing populations. Construction of a fish passage facility at Landsburg Diversion Dam on the Cedar River, WA, USA, provided a unique opportunity to explore this trade-off. We thoroughly sampled adult Chinook salmon (*Oncorhynchus tshawytscha*) at the onset of colonization (2003–2009), constructed a pedigree from genotypes at 10 microsatellite loci, and calculated reproductive success (RS) as the total number of returning adult offspring. Hatchery males were consistently but not significantly less productive than naturally spawned males (range in relative RS: 0.70–0.90), but the pattern for females varied between years. The sex ratio was heavily biased toward males; therefore, inclusion of the hatchery males increased the risk of a genetic fitness cost with little demographic benefit. Measurements of natural selection indicated that larger salmon had higher RS than smaller fish. Fish that arrived early to the spawning grounds tended to be more productive than later fish, although in some years, RS was maximized at intermediate dates. Our results underscore the importance of natural and sexual selection in promoting adaptation during reintroductions.

Araki, H. 2008. Hatchery Stocking for Restoring Wild Populations: A Genetic Evaluation of the Reproductive Success of Hatchery Fish vs. Wild Fish. Pp. 153-167 in K. Tsukamoto, T. Kawamura, T. Takeuchi, T. D. Beard, Jr. and M. J. Kaiser, eds. *Fisheries for Global Welfare and Environment, 5th World Fisheries Congress*.

Abstract: Potential impacts of hatchery programs on wild populations have long been discussed, and of particular interest is the reproductive success of hatchery born fish in natural environments. Here I summarize our recent studies, in which DNA fingerprinting and genetic parentage analyses were used to estimate adult-to-adult reproductive fitness of steelhead trout (*Oncorhynchus mykiss*) in the Hood River, Oregon (USA). We found: (1) Hatchery fish left fewer adult offspring per parent than wild fish, but supplementation hatchery fish (from local, wild broodstock; H_{supp}) left larger numbers of offspring than traditional hatchery fish (from nonlocal, multi-generation hatchery broodstock; H_{trad}); (2) The reproductive fitness of H_{supp} declined unexpectedly fast (~40% per generation) when H_{supp} were reused as broodstock in a hatchery, suggesting that the negative effects of hatchery rearing are cumulative and heritable; (3) Effective population size was mainly restricted by variance in reproductive success among individuals, rather than by biased sex ratio and temporal fluctuation of population sizes; (4) H_{trad} showed particularly large variance in reproductive success, indicating another negative effect of traditional programs. Our case studies suggest that using local, wild broodstock reduces negative effects of hatchery rearing, but the repeated use of H_{supp} as broodstock should be minimized for efficient supplementation.

Baillie, S.M., C. Blackie, L. Gerardi, and P. Bentzen. 2015. Deciphering Hatchery Stock Influences on Wild Populations of Vermont Lake Trout. *Transactions of the American Fisheries Society*

Abstract: To better understand the influence of hatchery practices on wild populations of Lake Trout *Salvelinus namaycush*, we used a landscape genetic approach to tease apart the population genetic patterns expected due to natural processes versus hatchery stocking, i.e., human-mediated gene flow. In several lakes across our study area in Vermont, the presence of exogenous mitochondrial DNA haplotypes supported our human-mediated gene flow hypothesis. Microsatellite DNA analyses showed introgression of hatchery genotypes into the wild populations. Nonetheless, clustering patterns within river drainages and signatures of isolation by distance were consistent with natural postglacial colonization. We conclude that though the genetic makeup of Vermont Lake Trout populations has been influenced by stocking, a lack of genetic bottlenecks and concordance with landscape processes suggests that much of the indigenous genetic diversity remains intact. We were able to attribute departures from expectations based on natural genetic patterns to hatchery introgression in specific lakes. To preserve the adaptive potential of local populations that have persisted since the last ice age, we suggest areas for which hatchery supplementation could be minimized.

Berejikian, B. A., E.P. Tezak, T.A. Flagg, A.L. LaRae, E. Kummerow, and C.V.W. Mahnken. 2000. Social dominance, growth, and habitat use of age-0 steelhead (*Oncorhynchus mykiss*) grown in enriched and conventional hatchery rearing environments. *Canadian Journal of Fisheries and Aquatic Sciences*, 57:628-636.

Abstract: This study investigated whether culturing age-0 steelhead (*Oncorhynchus mykiss*) in habitat-enriched rearing tanks, containing a combination of in-water structure, underwater feeders, and overhead cover, affected competitive ability and habitat use compared with juveniles cultured in more conventional vessels. In laboratory tests, steelhead juveniles grown in the enriched tanks socially dominated size-matched competitors grown in conventional tanks. When both treatments were introduced into separate sections of a quasi-natural stream, no differences in growth were found between them. However, when intermixed, fish reared in the enriched tanks grew at a higher rate than conventionally reared competitors, suggesting greater competitive ability of juveniles grown in the enriched tanks. Visual isolation and defensible food resources in combination in the enriched tanks were considered as the primary factors causing the observed competitive asymmetries. Steelhead juveniles from the two rearing environments exhibited very similar use of woody structure in the quasi-natural stream, both in the presence and in the absence of mutual competition. Rearing steelhead in more naturalistic environments could result in hatchery fish that behave and integrate into the postrelease (natural) environment in a manner more similar to wild fish.

Berejikian, B. A., D. M. Van Doornik, J. A. Scheurer, R. Bush. 2009. Reproductive behavior and relative reproductive success of natural - and - hatchery - origin Hood Canal summer chum salmon (*Oncorhynchus keta*). *Canadian Journal of Fisheries and Aquatic Sciences*, 66:781-789.

Abstract: Estimates of the relative fitness of hatchery- and natural-origin salmon can help determine the value of hatchery stocks in contributing to recovery efforts. This study compared the adult to fry reproductive success of natural-origin summer chum salmon (*Oncorhynchus keta*) with that of first- to third-generation hatchery-origin salmon in an experiment that included four replicate breeding groups. Hatchery- and natural-origin chum salmon exhibited similar reproductive success. Hatchery-

and natural-origin males obtained similar access to nesting females, and females of both types exhibited similar breeding behaviors and durations. Male body size was positively correlated with access to nesting females and reproductive success. The estimates of relative reproductive success (hatchery/natural = 0.83) in this study were similar to those in other studies of other anadromous salmonids in which the hatchery population was founded from the local natural population and much higher than those in studies that evaluated the lifetime relative reproductive success of nonlocal hatchery populations.

Binder, T.R., S.C. Riley, C.M. Holbrook, M.J. Hansen, R.A. Bergstedt, C.R. Bronte, J. He, and C.C. Krueger. 2016. Spawning site fidelity of wild and hatchery lake trout (*Salvelinus namaycush*) in northern Lake Huron. Canadian Journal of Fisheries and Aquatic Sciences, 73:18-34.

Abstract: Fidelity to high-quality spawning sites helps ensure that adults repeatedly spawn at sites that maximize reproductive success. Fidelity is also an important behavioural characteristic to consider when hatchery-reared individuals are stocked for species restoration, because artificial rearing environments may interfere with cues that guide appropriate spawning site selection. Acoustic telemetry was used in conjunction with Cormack–Jolly–Seber capture–recapture models to compare degree of spawning site fidelity of wild and hatchery-reared lake trout (*Salvelinus namaycush*) in northern Lake Huron. Annual survival was estimated to be between 77% and 81% and did not differ among wild and hatchery males and females. Site fidelity estimates were high in both wild and hatchery-reared lake trout (ranging from 0.78 to 0.94, depending on group and time filter), but were slightly lower in hatchery-reared fish than in wild fish. The ecological implication of the small difference in site fidelity between wild and hatchery-reared lake trout is unclear, but similarities in estimates suggest that many hatchery-reared fish use similar spawning sites to wild fish and that most return to those sites annually for spawning.

Brignon, W.R.. 2017. Spatial and Temporal Segregation of Wild and Hatchery Winter Steelhead Populations in Eagle Creek, Oregon. North American Journal of Fisheries Management 37:667-675.

Abstract: A segregated hatchery program promotes conservation by limiting the amount of overlap in return timing and spawning locations of hatchery- and natural-origin fish. The objective of the present study was to use radiotelemetry data collected from 2005 to 2007 to better understand the level of spatial and temporal segregation between hatchery and natural-origin steelhead *Oncorhynchus mykiss* in the Eagle Creek basin, Oregon. The analysis resulted in three key findings. First, hatchery-origin winter steelhead were unlikely to migrate into the North Fork Eagle Creek, a tributary that has historically lacked any hatchery releases or influence, suggesting a high level of segregation from the natural-origin population returning to that stream. Second, hatchery fish arrived at the lower fish ladder on Eagle Creek and at Eagle Creek National Fish Hatchery (NFH) earlier than natural-origin fish, suggesting that broodstock management practices to maintain an early returning hatchery stock (i.e., temporal segregation) have been somewhat successful. Finally, regardless of the differential arrival timing to Eagle Creek NFH, there is evidence of an increased probability of spatial and temporal overlap of the populations as the return progresses, and this may be explained by successful reproduction of hatchery-origin fish in main-stem Eagle Creek. Integrated and segregated hatchery programs should be monitored periodically to ensure that they are meeting their stated goals.

Brockmark, S., and J.I. Johnsson. 2010. Reduced hatchery rearing density increases social dominance, postrelease growth, and survival in brown trout (*Salmo trutta*). Canadian Journal of Fisheries and Aquatic Sciences, 67(2):288-295.

Synopsis: Hatchery fish reared for conservation or supplementation often have difficulties adapting to natural conditions, resulting in poor performance in the wild. In a standard hatchery, fish are confined at high densities, which creates a social environment different from that experienced after release. Here we investigated how rearing density influences social dominance, postrelease growth, and survival in brown trout (*Salmo trutta*). Fish were reared at three density treatments: conventional hatchery density, half of conventional hatchery density, and natural density. Four months after hatching, dominance status was determined, and 36 fish from each treatment were released into an enclosed stream and recaptured after 36 days. Trout reared at natural density had higher dominance status and grew faster, both in the hatchery and in the natural stream, than trout from higher densities. Moreover, trout reared at natural density were twice as likely to survive in the stream as trout from higher densities. These novel results suggest that more natural rearing densities would facilitate the development of adaptive behaviour in hatchery salmonids and, thereby, their contribution to natural production.

Busack, C., and C.M. Knudsen. 2007. Using factorial mating designs to increase the effective number of breeders in fish hatcheries. Aquaculture 273:24-32.

Abstract: We used Monte Carlo simulations to evaluate the potential of full- and partial-factorial mating designs to increase the effective number of breeders in fish hatchery operations, using two probability distributions (normal and uniform) to generate individual fitness values, two methods (multiplicative and additive) of combining fitness values in individual matings, four full-factorial designs (10×10, 20×20, 40×40, 120×120), and three partial-factorial designs (2×2, 5×5, 10×10). Nb under full-factorial mating was nearly linearly related to, and quite predictable from Nb under single-pair mating. The higher the variance of family size under single-pair mating, the greater the Nb benefit of full-factorial mating; and the larger the population, the greater the full-factorial benefit. Under assumptions of additive combination of fitness values, full-factorial mating resulted in an average Nb increase of 33%. Partial-factorial designs as small as 2×2 achieved on average 45% of the Nb advantage attainable under full-factorial mating. The proportionate incremental Nb benefit from partial-factorial designs diminishes rapidly as the size of the design increases, but designs as small as 10×10 may attain such a large proportion of the full-factorial benefit as to render larger designs unnecessary.

Busack, C., C.M. Knudsen, G. Hart, and P. Huffman. 2007. Morphological Differences Between Adult Wild and First-Generation Hatchery Upper Yakima River Spring Chinook Salmon. Transactions of the American Fisheries Society 136:1076–1087.

Abstract: Four-year-old adult wild spring Chinook salmon *Oncorhynchus tshawytscha* at a supplementation hatchery were compared morphologically with their first-generation hatchery counterparts over three consecutive brood years (BYs) using thin-plate spline analysis on 12 digitized landmarks and an analysis of 27 truss characters based on the landmarks. Canonical discriminant analysis (CDA) of sex-specific partial warp scores correctly classified females to origin (hatchery or wild) with 75% accuracy (up to 84% accuracy for one BY) and males to origin with 65% accuracy

(up to 89% accuracy for one BY). Classification to BY using sex- and BY-specific partial warps was 62% accurate for both females and males. The results of the truss analysis were very close to those from the thin-plate spline analysis. Sex-specific CDAs correctly classified 75% of females and 68% of males to origin. Correct classification to BY was 61% for females and 58% for males. Consensus shapes based on partial warps suggested that hatchery fish of both sexes have longer and deeper heads and shallower midbodies than wild fish. They also appear to be somewhat shorter in the posterior body. Analysis of variance of individual truss characters led to the same general conclusion but also provided evidence that hatchery fish have wider anal fins. There was no evidence of sex-specific differences between hatchery and wild fish. Body proportion differences between hatchery and wild fish at the eight most diagnostic truss characters averaged 0.31 standard deviations in females and 0.35 standard deviations in males. In terms of actual measurement, these differences amounted to an average of 1.4% of the wild mean, providing little discriminatory power.

Chamberlin, J.W., T.E. Essington, J.W. Ferguson, and T.P. Quinn. 2011. The Influence of Hatchery Rearing Practices on Salmon Migratory Behavior: Is the Tendency of Chinook Salmon to Remain within Puget Sound Affected by Size and Date of Release? *Transactions of the American Fisheries Society* 140:1398–1408.

Abstract: The marine migrations of Pacific salmon *Oncorhynchus* spp., and especially Chinook salmon *O. tshawytscha*, vary greatly in duration and spatial extent. In Puget Sound, Washington, most Chinook salmon migrate from freshwater to the coastal waters of the Pacific Ocean before returning to spawn in their natal streams. However, some leave freshwater but remain in the semi-estuarine waters of Puget Sound until they mature and then return to freshwater to spawn. The objective of our study was to determine the effect of rearing conditions and hatchery location on the prevalence of this alternative pattern of marine distribution by hatchery-produced Chinook salmon in Puget Sound. We used coded wire tag recovery data to analyze the effect of release region, age, size, and date of release on the proportion of fish showing resident-type behavior, defined as recovery in Puget Sound fisheries outside the period when maturing salmon return from the coast. Based on 226 different release groups from 26 hatcheries throughout Puget Sound from 1972 to 1993, 24% of the fish recovered were classified as residents, though this is not an actual estimate of the percentage of fish displaying this distribution pattern. The best single predictor of residency was release region, suggesting that where fish enter the marine environment had the largest influence on whether they adopted resident behavior or migrated directly to the ocean. The overall best model included an interactive effect between release region and size at release, revealing that the propensity of large fish to remain resident varied significantly among regions. The actual mechanisms that create the diversity of distribution patterns are still unknown, but the effects of rearing conditions and release location provide useful information for the management of these salmon populations.

Clarke, L.R., M.W. Flesher, T.A. Whitesel, G.R. Vonderohe, and R.W. Carmichael. 2010. Postrelease Performance of Acclimated and Directly Released Hatchery Summer Steelhead into Oregon Tributaries of the Snake River. *North American Journal of Fisheries Management* 30: 1098-1109.

Abstract: In a study using 14 paired-release groups over 10 release years, we compared the performance of hatchery summer steelhead *Oncorhynchus mykiss* that were acclimated as smolts (AC) for 16–57 d before release into ponds supplied with ambient stream water with that of fish

trucked from the hatchery and directly released (DR) into Spring, Deer, and Little Sheep creeks in northeastern Oregon. After releasing the fish into streams, we monitored out-migration travel times and survival to Lower Granite Dam (LGD) on the Snake River using freeze brand marks or implanted passive integrated transponder tags in a subsample of each release group. Across all release groups, travel time was significantly slower for AC fish (34.7 d) than for DR fish (31.8 d), though there was no significant difference in survival probability to LGD. We used recoveries of coded wire tags to estimate smolt-to-adult survival (SAS) and a stray rate index (SRI) for the AC and DR strategies. Across all release groups, SAS was 33% higher and SRI 42% lower for AC steelhead. At each release site acclimation increased average SAS by at least 11% and decreased SRI by at least 16.5%. We found a significant, negative linear relationship between travel time to LGD and SAS; however, there was no significant relationship between survival to LGD and SAS, which implies that judgments about the success or failure of a novel rearing or release strategy should not be made based on out-migration survival. Acclimating juvenile steelhead produced significantly higher SAS and lower SRI in the hatchery program we evaluated.

Cuenco, M. L., T. W. H. Backman, and P. R. Mundy. 1993. The use of supplementation to aid in natural stock restoration. Pages 269-293 in J. G. Cloud and G. H. Thorgaard, editors. Genetic conservation of salmonid fishes. Plenum Press, New York.

Synopsis: Defines supplementation and the parameters of a successful supplementation program. Note that this document was published by tribal scientists long before hatchery reform became popular and widely advocated. Many of the recommendations in this publication are being used in studies contained in this bibliography.

Dahl, J., E. Pettersson, J. Dannewitz, T. Järvi, and A-C Löf. 2006. No difference in survival, growth and morphology between offspring of wild-born, hatchery and hybrid brown trout (*Salmo trutta*). Ecology of Freshwater Fish 15:388-397.

Abstract: We studied survival, growth and morphological characters in the offspring of native hatchery and wild-born anadromous brown trout (*Salmo trutta*) and their hybrids (wild-born female × hatchery male and wild-born male × hatchery female) in a 1-year field experiment. We also conducted laboratory studies where we examined social interactions between the offspring of the same hatchery and wild-born trout. All offspring were raised in a hatchery and nose tagged before being released into the stream. In total, 1125 individuals were released into the stream (1999) and a total of 614 individuals were recovered (2000). We found no differences in growth and survival between the offspring of hatchery, wild-born and hybrid trout. Morphology was also similar among groups, where only 38% females and 36% males were classified into the right category, which were only 12% better than random classification. In the laboratory experiment, we compared only the offspring of hatchery and wild-born trout with respect to growth, dominance, aggressiveness, feeding and activity. We found small differences between the offspring of hatchery and wild-born fish with respect to growth but this effect was not found in the field experiment. Our result suggests that the offspring of hatchery trout and hybrids between hatchery and wild-born trout performed equally well to the offspring of wild-born trout.

Dannewitz, J., E. Petersson, T. Prestegard, and T. Jarvi. 2003. Effects of sea-ranching and family background on fitness traits in brown trout *Salmo trutta* reared under near-natural conditions.

Summary (Author's words taken directly from publication):

1. Many threatened populations of salmonids depend on supplemental releases of hatchery-produced fish. Laboratory studies suggest that altered selection regimes in the hatchery may result in evolutionary changes of traits connected to fitness. Such changes can have profound effects on the performance of the hatchery fish following release in the natural environment, and may also affect the genetic characteristics of locally adapted wild populations. However, surprisingly few studies have looked at the ability of hatchery fish to compete with wild conspecifics under natural conditions.
2. We studied growth, survival and life-history adoption of a wild and a multigeneration sea-ranched strain of brown trout *Salmo trutta* in a semi-natural stream. The fish were planted in the stream as eyed eggs and their family and strain origins were later revealed by microsatellite markers.
3. In the first experiment, in which the experimental fish originated from a full-sib mating design, there were strong family effects on both growth and survival over the first growth season. In the second experiment, in which the experimental fish originated from a half-sib mating design, there were significant male and female effects on growth parameters but not on survival over the first growth season.
4. When family and male–female effects were accounted for, there were no differences between wild and sea-ranched trout in body size and condition factor after the first growth season, or in survival up to this stage. Nor was there any difference between the groups in the proportions that metamorphosed into the migratory smolt phase at 1 year of age.
5. Synthesis and applications. Our results suggest that wild-born trout of sea-ranched origin can successfully compete with trout of wild origin under semi-natural conditions. This indicates that the impact of hatchery selection on the performance of sea-ranched fish in the wild may not be as pronounced as previously thought. It is suggested that for salmonid populations that depend on supplemental stocking, more effort should be paid to minimizing negative environmental effects during hatchery rearing. The observed differences in fitness characters between families suggest that family effects should be taken into account in stocking programmes because the amount of genetic variation maintained within populations is related to the variance in family performance.

Davis, J.L.D., A.C. Young-Williams, R. Aguilar, B.L. Carswell, M.R. Goodison, A.H. Hines, M.A. Kramer, Y. Zohar, O. Zmora. 2004. Differences between Hatchery-Raised and Wild Blue Crabs: Implications for Stock Enhancement Potential. *Transactions of the American Fisheries Society* 133:1-14.

Abstract: Stock enhancement of severely exploited, recruitment-limited fisheries has been controversial for several reasons, one of which is the lack of information about competency, competitiveness, and survivorship of hatchery-reared individuals released into the field. Because enhancement efforts have focused on finfish, even less information is available with which to assess enhancement potential of crustaceans. The Chesapeake Bay stock of blue crabs *Callinectes sapidus* has declined by more than 80% over the past 12 years and has exhibited recruitment limitation, leading to recent efforts to study the potential of enhancing populations with hatchery-reared juveniles. To assess how hatchery-raised juvenile blue crabs may fare after release into the Chesapeake Bay, we compared several aspects of hatchery and wild crabs. Hatchery crabs readily fed on natural prey, moved in the field similarly to wild crabs, and grew at rates similar to those of wild

crabs; however, the two crab groups differed in other factors important to field survival. Prerelease and laboratory-held hatchery crabs had different carapace morphology (smaller spines) than wild crabs, though spine lengths increased to normal proportions by several weeks after release. Hatchery crabs did not initially bury in sediment as often as wild crabs, suggesting inexperience with an important predator escape response. Hatchery crabs were also preyed upon at higher rates in the field than wild crabs. Conditioning experiments suggest that inexperience with sediment and low burial rates were not the main cause of higher predation. By identifying areas in which hatchery individuals may be relatively weak and deficits that can potentially be mitigated, studies such as this can lead to improving the success of hatchery-raised individuals in the field. On a broader scale, such studies also contribute to determining whether stock enhancement is possible in the case of the Chesapeake blue crab.

Dittman, A. H., D. May, D. A. Larsen, M. L. Moser, M. Johnston, and D. Fast. 2010. Homing and spawning site selection by supplemented hatchery- and natural-origin Yakima River spring Chinook salmon. *Transactions of the American Fisheries Society* 139:1014-1028.

Synopsis: This paper examined the homing patterns of supplemented Yakima River spring Chinook salmon releases from satellite acclimation facilities. The data indicated that supplementation increased the spatial range of spawning in the upper Yakima River. Natural- and hatchery-origin fish displayed similar spawning distributions within the upper Yakima Basin. Like their natural-origin counterparts, hatchery-origin fish demonstrated the ability to seek optimum spawning locations. This occurred especially in the absence of acceptable spawning conditions in their area of acclimation and release.

Eldridge, W.H. and K. Killebrew. 2008. Genetic diversity over multiple generations of supplementation: an example from Chinook salmon using microsatellite and demographic data. *Conservation Genetics* 9:13-28.

Abstract: We examined demographic data and microsatellite loci in a supplemented population of Chinook salmon (*Oncorhynchus tshawytscha*) seeking evidence of changes in genetic diversity or for reduction of the effective size (N_e) arising from supplementation (i.e., the Ryman-Laikre effect). A supplementation program in the North Fork Stillaguamish River (Washington State, USA) was intended to increase abundance (N) and maintain genetic diversity in the depressed population. Since supplementation expanded in 1986, about 9% of the population has been randomly collected for broodstock. The resulting progeny are released into the wild and comprised 10–60% of all returning adults. Genotypic data were obtained at 14 microsatellite loci from adult samples collected in four years between 1985 and 2001; these data indicated that the allelic richness and expected heterozygosity did not significantly change during this period and that genetic diversity in the captive and wild progeny was similar. The inbreeding and variance N_e estimated from adult escapement between 1974 and 2004 were different for the same generation, but the ratios of effective size to census size were very similar and decreased following supplementation. The variance N_e by the temporal method increased over time, but it is difficult to draw conclusions because of necessary assumptions made during the calculations. Based on these results we conclude that: (1) genetic diversity has been maintained over multiple generations of supplementation; (2) supplementation has not contributed to a loss of genetic diversity; and (3) monitoring genetic effects of supplementation is not straightforward, but it can be useful to look at both demographic and genetic data simultaneously.

Ford, M., Murdoch, A., Howard, S., 2012. Early male maturity explains a negative correlation in reproductive success between hatchery-spawned salmon and their naturally spawning progeny. *Conservation Letters* 5, 450–458.

Abstract: Adaptation of plants or animals to captivity is a risk associated with any captive breeding program that has the intent of returning organisms to the wild. The risk is particularly acute for species that are captively bred and released on a large scale, as is the case for many species of fish. Several studies, particularly in salmonids, have reported rapid adaptation of populations to captivity, but the mechanisms of such adaptations are not always clear. We evaluated a large three-generation pedigree of an artificially supplemented salmon population, and found that the fish with the highest reproductive success in captivity produce early maturing male offspring that have lower than average reproductive success in the wild. In contrast to an earlier study of steelhead trout, we found little evidence that parental origin of the captive spawners influenced the subsequent reproductive success of their naturally spawning progeny.

Fraser, D. J. 2008. How well can captive breeding programs conserve biodiversity? A review of salmonids. *Evolutionary Applications*, 1:535-586.

Synopsis: Review of existing literature relevant to genetic diversity and fitness issues in captive breeding and supplementation programs. Empirical and theoretical studies both suggest that most salmonid captive breeding programs can maintain genetic diversity over several captive generations. The apparent low N_e in some captive broodstocks might easily be avoided through the use of procedures that reduce genetic and other risks associated with captive breeding programs such as using local brood sources and minimizing generations in captivity. Many of the poorest performances of hatchery fish relative to wild fish involved nonlocal hatchery strains that had been in captivity for greater than five generations or that had undergone intentional artificial selection. There is little long-term evidence regarding whether captive-reared salmonids can or cannot be reintroduced as self-sustaining populations. There are numerous examples of the ability of salmonids to evolve rapidly in the wild over several generations. Certainly, then, the possibility exists that a reintroduced population based on captive-reared fish could re-adapt to the wild environment under a similar timeframe. There is only very limited empirical research to suggest that maintaining several small isolated populations with periodic mixing may be more effective at reducing losses of genetic diversity and fitness than maintaining a single large population.

Fritts, A.L., J.L. Scott, and T.N. Pearsons. 2007. The effects of domestication on the relative vulnerability of hatchery and wild spring Chinook salmon to predation. *Canadian Journal of Fisheries and Aquatic Sciences* 64:813-818.

Abstract: We tested whether one generation of state-of-the-art hatchery culture influenced the vulnerability of Chinook salmon (*Oncorhynchus tshawytscha*) fry to predators. Size-matched hatchery and wild origin spring Chinook salmon fry were exposed to rainbow trout (*Oncorhynchus mykiss*) and torrent sculpin (*Cottus rhotheus*) predators in 10.8 m³ net pens. The hatchery origin fry were the offspring of first generation hatchery-reared broodstock, and the wild origin fry had no history of hatchery culture; both originated from the same stock. Wild origin fry were found to have a 2.2% ($p = 0.016$) survival advantage over hatchery origin fry during 2 years of predation

challenges. The most important findings of this study are (i) domestication can affect the susceptibility to predators after only one generation of state-of-the-art hatchery culture practices, and (ii) the domestication effect was very small.

Gallinat, M.P. and W-Y. Chang. 2013. Phenotypic Comparisons among Natural-Origin, Hatchery-Origin, and Captive-Reared Female Spring Chinook Salmon from the Tucannon River, Washington, North American Journal of Aquaculture, 75:4, 572-581.

Abstract: We examined the effects of hatchery rearing on FL, weight, egg size, fecundity, relative fecundity, and reproductive mass of female spring Chinook Salmon *Oncorhynchus tshawytscha* from a population that had been in captivity for 0 (natural-origin), 18 (hatchery-origin), and 48 (captive-reared broodstock) months. Age-4 captive-reared broodstock females that were reared for their entire life in the hatchery environment had significantly lower mean FL, weight, fecundity, relative fecundity, and reproductive mass, but had significantly larger eggs than age-4 females from the other groups after correcting for body size. Hatchery-origin females had significantly lower fecundity than natural origin fish. Our findings illustrate a phenomenon of lower overall reproductive potential for hatchery-reared fish in the form of reduced fecundity that decreases as time spent in the hatchery environment increases. We also observed that progeny of captive-reared broodstock parents, released as smolts and recaptured as returning age-4 adults, have a size and fecundity distribution that is similar to the hatchery-origin adults, suggesting that the decrease in fecundity was not a genetically linked trait.

Habicht, C., T.M. Tobias, G. Fandrei, N. Webber, B. Lewis, and W.S. Grant. 2013. Homing of Sockeye Salmon within Hidden Lake, Alaska, Can Be Used to Achieve Hatchery Management Goals. North American Journal of Fisheries Management 33:777-782.

Abstract: The supplementation of natural populations of Pacific salmon *Oncorhynchus* spp. with hatchery fish poses unique management challenges. Two such challenges addressed in this study are limiting the number of hatchery fish spawning with natural-origin fish and maximizing the number of natural-origin fish in the supplementation broodstock. In this study, we focus on stock enhancement of Sockeye Salmon *O. nerka* in Hidden Lake, Alaska, where the Trail Lakes Hatchery supplements the natural population with hatchery-raised fry. Production in Hidden Lake is limited by the availability of spawning habitat and not by juvenile rearing capacity. The hatchery collects broodstock from the lake and releases fry with thermally marked otoliths at one of two primary natural spawning sites in Hidden Lake each year. During this study, an average of 58% of the fish returning to the lake through a weir on the outlet stream were of hatchery origin. However, an average of 88% of the fish at the release site were hatchery-origin fish, indicating a nonrandom distribution of hatchery-origin spawners. This pattern is consistent with homing to specific sites within the lake of either or both hatchery- and wild-origin fish. However, this distribution results in a larger-than-desirable proportion of hatchery-origin fish spawning with natural-origin fish at the release site. The proportion of hatchery-origin fish used for brood is also larger than desirable because the site is also the broodstock collection site. We propose that releasing hatchery fish at a new location removed from the primary spawning areas and the hatchery broodstock collection site will reduce the proportion of hatchery-origin fish spawning with wild-origin fish and increase the proportion of wild-origin fish in the broodstock, if our results are due, at least in part, to homing of hatchery fish.

Haponski, A.E., H. Dean, B.E. Blake, and C.A. Stepien. 2014. Genetic History of Walleyes Spawning in Lake Erie's Cattaraugus Creek: a Comparison of Pre- and Poststocking. *Transactions of the American Fisheries Society* 143:1295-1307.

Abstract: Fish stocking (artificial supplementation) has been used to augment populations and angling opportunities. However, genetic composition and adaptations of native fish populations may be affected, raising management concerns. From 1995 to 2000, the New York State Department of Environmental Conservation stocked Walleye *Sander vitreus* fry and fingerlings from the Maumee River (western Lake Erie) into Cattaraugus Creek (eastern Lake Erie). We analyzed nuclear microsatellite (sat) DNA and mitochondrial DNA (mtDNA) variation in Cattaraugus Creek Walleyes for comparisons between prestocking and poststocking groups, among annual spawning runs (1998–2011), among age cohorts, and between sexes. Results for genetic differentiation (index F_{ST}) were not significant between prestocking and poststocking groups (sat: $F_{ST} = 0.003$; mtDNA: $F_{ST} < 0.001$), and the two groups did not resemble stocked Maumee River fingerlings (sat: $F_{ST} = 0.003–0.012$; mtDNA: $F_{ST} = 0.076–0.090$). Tests for differentiation were not significant among annual spawning runs (sat: $F_{ST} = <0.001–0.007$; mtDNA: $F_{ST} = <0.001–0.049$), among age cohorts (sat: $F_{ST} = <0.001–0.006$; mtDNA: $F_{ST} = <0.001–0.097$), or between sexes (sat: $F_{ST} < 0.001$; mtDNA: $F_{ST} < 0.001$). Genetic diversity levels were high and consistent (sat: observed heterozygosity [mean \pm SE] = 0.71 ± 0.04 ; mtDNA: haplotype diversity = 0.79 ± 0.01). Thus, despite stocking, the genetic signature of the native spawning run remained distinctive. However, the genetic composition of the local wild population and the stocking source should be assessed prior to any future supplementation plans.

Hayes, S.A., M.H. Bond, C.V. Hanson, and R.B. MacFarlane. 2004. Interactions between endangered wild and hatchery salmonids: can the pitfalls of artificial propagation be avoided in small coastal streams? *Journal of Fish Biology*, 65 (s1):101-121.

Abstract: Hatchery and wild juvenile populations of steelhead *Oncorhynchus mykiss* and coho salmon *Oncorhynchus kisutch*, in a small coastal watershed in central California, were sampled throughout the year in a stream and at a hatchery. Both species grew faster in captivity than in the wild. Hatchery fish of both species had elevated gill Na^+ , K^+ -ATPase activity, and thus were ready to enter sea water when planted during the wild fish migration. Downstream migrant trapping and stream surveys indicated that hatchery smolts went to sea soon after planting, consequently avoiding the effects of competition and predation that commonly occur when hatchery-bred juveniles are released. Adult steelhead were also sampled throughout the watershed. The return of hatchery steelhead was highly synchronized with that of wild steelhead, indicating that hatchery propagation had no adverse effects on the timing of the run. A disproportionate number of hatchery steelhead returned to the tributary where the hatchery was located, despite being planted throughout the watershed. Hatchery steelhead did not differ in mean age or size from wild steelhead. Observations of spawning indicated that hatchery and wild steelhead interbreed. Competition for mates or spawning substratum was rarely observed between hatchery and wild steelhead. Many of the problems commonly associated with artificial propagation can be avoided in small coastal watersheds when wild broodstock are used and fish are released as smolts.

Heard, W.R., 2011. Overview of salmon stock enhancement in southeast Alaska and compatibility with maintenance of hatchery and wild stocks. *Environmental Biology of Fishes* 94, 273–283.

Abstract: Modern salmon hatcheries in Southeast Alaska were established in the 1970s when wild runs were at record low levels. Enhancement programs were designed to help rehabilitate depressed fisheries and to protect wild salmon stocks through detailed planning and permitting processes that included focused policies on genetics, pathology, and management. Hatcheries were located away from significant wild stocks, local sources were used to develop hatchery broodstocks, and juveniles are marked so management can target fisheries on hatchery fish. Initially conceived as a state-run system, the Southeast Alaska (SEAK) program has evolved into a private, non-profit concept centered around regional aquaculture associations run by fishermen and other stakeholders that pay for hatchery operations through landing fees and sale of fish. Today there are 15 production hatcheries and 2 research hatcheries in SEAK that between 2005 and 2009 released from 474 to 580 million (average 517 million) juvenile salmon per year. During this same period commercial harvest of salmon in the region ranged from 28 to 71 million salmon per year (average 49 million). Contributions of hatchery-origin fish to this harvest respectively averaged 2%, 9%, 19%, 20%, and 78% for pink, sockeye, Chinook, coho, and chum salmon. Both hatchery and wild salmon stocks throughout much of Alaska have experienced high marine survivals since the 1980s and 1990s resulting in record harvests over the past two decades. Although some interactions between hatchery salmon and wild salmon are unavoidable including increasing concerns over straying of hatchery fish into wild salmon streams, obvious adverse impacts from hatcheries on production of wild salmon populations in this region are not readily evident.

Hedrick, P.W., D. Hedgecock, S. Hamelberg, and S.J. Croci. 2000a. The impact of supplementation in winter-run chinook salmon on effective population size. *Journal of Heredity*, 91(2): 112-116.

Abstract: Supplementation of young raised at a protected site, such as a hatchery, may influence the effective population size of an endangered species. A supplementation program for the endangered winter-run chinook salmon from the Sacramento River, California, has been releasing fish since 1991. A breeding protocol, instituted in 1992, seeks to maximize the effective population size from the captive spawners by equaling their contributions to the released progeny. As a result, the releases in 1994 and 1995 appear not to have decreased the overall effective population size and may have increased it somewhat. However, mistaken use of non-winter-run chinook spawners resulted in artificial crosses between runs with fish on Battle Creek, the site of the hatchery, resulted in limiting the contribution of the released fish to the target mainstem population. Rapid genetic analysis of captured spawners and a new rearing facility on the Sacramento River should alleviate these problems and their negative effect on the effective population size in future years.

Hedrick, P.W., V.K. Rashbrook, and D. Hedgecock. 2000b. Effective population size of winter-run chinook salmon based on microsatellite analysis of returning spawners. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(12): 2368–2373.

Abstract: We previously estimated the predicted effective population size for the endangered winter-run chinook salmon, *Oncorhynchus tshawytscha*, based on a number of assumptions, including random survival and return of released fish. Here we present data from actual returning spawners, identified to family by microsatellite loci, and calculate the observed effective population size. In 1994 and 1995, the observed effective population sizes were 93.6 and 78.2% of predicted values, respectively, suggesting that the numbers of returning fish were very close to random expectations in 1994 and less close to random in 1995. The ratio of the effective population size to the adult number,

Ne/N, was greater than unity for 1994 and approximately 0.5 in 1995. The high ratio in 1994 reflects the success of the breeding protocol to equalize individual contributions and near random returns, while the lower number in 1995 appears to be the result of both less successful equalization and less close to random returns in that year. These findings provide an optimistic outlook for the success of this supplementation program and suggest that the overall effective population size has not been greatly reduced, since returning spawners represent a broad sample of parents and not fish from only a few families.

Heggenes, J., M. Beere, P. Tamkee, and E. B. Taylor. 2006. Genetic diversity in steelhead before and after conservation hatchery operation in a coastal, boreal river. *Transactions of the American Fisheries Society* 135:251-267.

Abstract: The objectives of this study were to (1) investigate the genetic diversity of wild steelhead populations in the river before hatchery stocking and (2) assess the potential genetic impacts of interbreeding of returning hatchery adult fish with wild spawners over almost 20 years of large-scale hatchery operation. The level of population subdivision among Kitimat River samples was low (0.004) and not significantly different from 0. Tests of population subdivision between pre-hatchery and post-hatchery operation indicated no significant changes. Similar results were obtained using other measures of genetic differentiation (principal components analysis of microsatellite allele frequencies and Cavalli-Sforza genetic distance). Our data, however, did indicate a slight but significant reduction in allelic richness after hatchery stocking. Pairwise tests for genetic differentiation among samples from different yearclasses were nonsignificant. We conclude that for the current management regime there is little apparent impact of hatchery practices on either the genetic structure or variation within the lower main-stem Kitimat River steelhead, but there may be a reduction in rare alleles. The practice of using substantial numbers of wild fish and multiple yearclasses in the hatchery may have minimized genetic changes via genetic drift.

Heggenes, J., M. Beere, P. Tamkee, and E. B. Taylor. 2011. Estimation of Genetic Diversity within and among Populations of *Oncorhynchus mykiss* in a Coastal River Experiencing Spatially Variable Hatchery Augmentation. *Transactions of the American Fisheries Society* 140:123-135.

Abstract: The allelic variation at 10 microsatellite loci was assayed in potentially wild rainbow trout *Oncorhynchus mykiss* and steelhead (anadromous rainbow trout) collected from 11 tributaries and three upper main-stem river sites (n = 547) in the Kitimat River, central British Columbia, and compared with the variation in steelhead from areas within the lower river (n = 333), where a hatchery has operated since 1984. The objective was to see whether the genetic structure of *O. mykiss* in the upper river was influenced by hatchery-reared fish stocked in the lower river. Measures of genetic diversity indicated that tributary and upper-river diversity were similar to what has previously been documented for wild populations. The level of genetic subdivision (θ) was significant ($\theta = 0.031$), indicating that genetic structure exists, and was higher than that among sites located in the lower main-stem river where the hatchery operates ($\theta = 0.004$). Bayesian assignment clustering suggested the existence of a genetic structure (K = 3) in *O. mykiss* in the upper river. The overall spatial pattern, however, identified no clearly separate genetic populations; rather, the genetic structure appeared to be an overlapping mosaic of modestly genetically divergent localities. We conclude that indigenous wild *O. mykiss* populations exist in the tributaries and the upper main-stem

river and its tributaries. These upper-river populations appear to have retained genetic diversity and differentiation despite extensive releases of hatchery fish in the lower river.

HSRG. 2005. Hatchery Scientific Review Group. Hatchery Reform in Washington State: Principles and Emerging Issues. Fisheries. Volume 30, Number 6. June 2005.

Synopsis: Makes recommendations for reforming hatchery operations to better meet goals of supporting sustainable fisheries and assisting with the conservation of natural populations. Many of the recommendations proposed by the HSRG were documented by Cuenco et al. in 1993 and are being used in studies contained in this bibliography.

Johnson, M.A. and T.A. Friesen. 2014. Genetic Diversity and Population Structure of Spring Chinook Salmon from the Upper Willamette River, Oregon. North American Journal of Fisheries Management. 34:853-862.

Abstract: Effective management of Pacific salmon requires an accurate understanding of both population genetic diversity and structure. Spring Chinook Salmon *Oncorhynchus tshawytscha* from the upper Willamette River (UWR), Oregon, are listed as threatened under the U.S. Endangered Species Act, and although this evolutionarily significant unit is recognized to be distinct from other Columbia River stocks, genetic relationships among its constituent hatchery and wild populations remain obscure. We used genotypic data from 13 microsatellite loci to test whether hatchery populations of UWR spring Chinook Salmon are most similar to wild populations within the same subbasin, or whether hatchery populations from different subbasins are more similar to each other than to local wild populations. We also tested for differences between the genetic diversities of hatchery and wild populations, as measured through heterozygosity and allelic richness. Our results suggest that populations are weakly structured among subbasins and, in all cases, hatchery populations are genetically most similar to local wild populations. We also found heterozygosity to be higher ($P = 0.009$) in hatchery populations (median, 81.5%) than in wild populations (median, 75.2%), but observed no significant difference with respect to allelic richness ($P = 0.406$). We conclude that hatchery-origin UWR spring Chinook Salmon represent genetically appropriate founder populations for ongoing reintroduction programs and recommend that the conservation and recovery of this stock proceed through management actions developed specifically for each subbasin. We further recommend that current restrictions on hatchery stock transfers among UWR subbasins be continued to preserve extant population genetic structure.

Johnson, S.L., J.H. Power, D.R. Wilson, and J. Ray. 2010. A Comparison of the Survival and Migratory Behavior of Hatchery-Reared and Naturally Reared Steelhead Smolts in the Alsea River and Estuary, Oregon, using Acoustic Telemetry. North American Journal of Fisheries Management 30:55-71.

Abstract: We tracked three groups of steelhead *Oncorhynchus mykiss* smolts implanted with acoustic transmitters to determine whether the degree of hatchery domestication or the juvenile rearing environment (hatchery raceway versus natural stream) influenced migration timing and survival in the Alsea River and estuary, Oregon. Two groups consisted of age-1 smolts reared in concrete raceways. One hatchery-reared group (traditional brood group) was derived from the traditional Alsea River broodstock initially developed in the 1950s. The second hatchery-reared group (new

brood group) was derived from naturally reared Alsea River adult steelhead that were captured and spawned at the hatchery beginning in the winter of 2000–2001. The third group (naturally reared group) consisted of age-2 naturally reared smolts captured in a downstream migrant trap located in a tributary stream near the hatchery. We placed transmitters in 74 traditional brood smolts, 76 new brood smolts, and 72 naturally reared smolts. Thirty-one acoustic receivers were located throughout the Alsea River and estuary and in the ocean offshore of the river mouth to monitor smolt movement. Neither the degree of hatchery domestication nor the juvenile rearing environment (hatchery raceway versus natural stream) appeared to influence the number of steelhead smolts that successfully migrated to the ocean. We found no significant difference between groups in their survival to the head of tide or to the mouth of the estuary. Most smolts from all three groups were detected at the head of tide (87% of fish from the traditional brood group, 78% from the new brood group, and 84% from the naturally reared group). However, survival was poor in the lower estuary for all three groups; we estimated that only 37% of the traditional brood group, 45% of the new brood group, and 47% of the naturally reared group survived to the ocean. The timing of migration through the river was highly variable in all three groups, and we found no significant differences in the rate of downstream movement from the release site to the head of tide. Mean residence time within the estuary was similar for all groups, although smolts from the naturally reared group showed less variability in estuary residence time than hatchery-reared smolts.

Kalinowski, S.T., D.M. Van Doornik, C.C. Kozfkay, and R. Waples. 2012. [Genetic diversity in the Snake River sockeye salmon captive broodstock program as estimated from broodstock records.](#) Conservation Genetics 13:1183-1193.

Synopsis: Assessing the magnitude of any of the future challenges to sockeye salmon in the Snake River, is difficult; predicting the cumulative impact of factors affecting survival is a formidable challenge. However, the results of this present investigation provide reason for optimism. Sockeye salmon in the Redfish Lake captive broodstock program appear to have retained approximately 95% of the genetic variation of the fish that founded the captive population, and we can hope that this is enough to avoid most of the harmful effects of inbreeding and to provide enough genetic variation for the population to adapt to future challenges.

Kassler, T.W. and C.A. Dean. 2010. Genetic Analysis of Natural-origin Spring Chinook and Comparison to Spring Chinook from an Integrated Supplementation Program and Captive Broodstock Program in the Tucannon River. Report to BPA, Project No. 2000-019-00, Contract Number 40744. WDFW, Olympia, WA.

Abstract: A collection of natural-origin spring Chinook from 1986 was compared to samples from two spawner groups (supplementation program and in-river spawners), and to collections of hatchery- and natural-origin from the Tucannon River. Samples from the captive brood program at the Tucannon River Hatchery were also compared. A microsatellite DNA analysis was conducted to determine if there have been any changes to the genetic diversity of spring Chinook in the Tucannon River. The measures of genetic diversity (heterozygosity and allelic richness) revealed similar levels within each spawner group and collection based on origin over time. Assessment of within population diversity indicates that the spawner groups and collections by origin have not undergone a loss of diversity and are not represented by family groups. We did detect that collections of the captive brood are not within Hardy-Weinberg proportions and have significant linkage

disequilibrium as a possible result of using equal numbers of individuals from two brood years that are differentiated. The collection of captive brood progeny returns in 2008; however is within expected proportions and indicates there has not been a genetic change to the spawner group collection or collections by origin. The pairwise F_{ST} values identify the variation between any two groups is approximately 1.0% or less indicating the differences among the groups is small. Factorial correspondence analysis identifies similarity among collections that are separated by four years and represent the genetic differences among primary brood years and not genetic changes to the natural-origin collection from 1986. The combination of all the results demonstrates that the genetic diversity of spring Chinook in the Tucannon River has not significantly changed as a result of the supplementation or captive brood programs.

Knudsen, C.M., S.L. Schroder, C. Busack, M.V. Johnston, T.N. Pearsons, and C.R. Strom. 2008. Comparison of Female Reproductive Traits and Progeny of First-Generation Hatchery and Wild Upper Yakima River Spring Chinook Salmon. *Transactions of the American Fisheries Society* 137:1433-1445.

Abstract: Hatchery and wild female spring Chinook salmon *Oncorhynchus tshawytscha* from the upper Yakima River were compared to determine whether their reproductive traits had diverged after a single generation of artificial propagation. Fecundity, relative fecundity, individual egg mass, and total gamete mass were all significantly correlated with body length, while reproductive effort (gonadosomatic index) was not. Regressions of trait versus body length often differed significantly among brood years. Hatchery spring Chinook salmon were significantly smaller than wild females over the four brood years examined. After brood year and body length (when necessary) were accounted for, wild females had an average of 8.8% more total gamete mass, 0.8% more individual egg mass, 7.7% greater fecundity, and 0.8% greater reproductive effort than hatchery females. Relative fecundity (the number of eggs per centimeter of body length) was on average 1.3% greater in hatchery females. We also compared body size at yolk absorption and egg-to-fry survival of the progeny from hatchery-by-hatchery and wild-by-wild matings. After differences in egg size were accounted for, hatchery fry were on average 1.0% heavier than wild fry. Egg-to-fry survival rates varied among years, with no consistent difference between hatchery and wild fry. The relationships between reproductive traits and body length were not significantly altered by a single generation of hatchery exposure. However, because hatchery females had smaller body sizes, the distributions of linked traits, such as total gamete mass and fecundity, differed by as much as 0.6 SD, probably resulting in some fitness loss. Our data support the idea that a single generation of state-of-the-art conservation hatchery propagation can produce fish with reproductive traits similar to those of wild fish, given comparable body size.

Lacroix, G.L. 2008. Influence of origin on migration and survival of Atlantic salmon (*Salmo salar*) in the Bay of Fundy, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 65:2063-2079.

Synopsis: Atlantic salmon smolts of wild and hatchery origin were tagged with ultrasonic transmitters and monitored at successive arrays of submerged receivers during migration from five watersheds in three regions of the Bay of Fundy, Canada. The early marine survival of migrating Atlantic salmon was estimated by monitoring their migration in estuarine and coastal habitats. Except in cases where hatchery fish were purposely forced to migrate later than their wild

counterparts, the migration success did not differ significantly between groups of wild and hatchery smolts for rivers where both were simultaneously monitored. The responses of hatchery fish to delays in release indicated that synchronizing the readiness and release time of hatchery smolts to the timing of wild smolt runs may be crucial to successful management of the depleted or endangered salmon populations being sustained by hatchery programs in the Bay of Fundy.

Lew, R.M., A.J. Finger, M.R. Baerwald, A. Goodbla, B. May, and M.H. Meek. 2015. Using Next-Generation Sequencing to Assist a Conservation Hatchery: a Single-Nucleotide Polymorphism Panel for the Genetic Management of Endangered Delta Smelt. *Transactions of the American Fisheries Society* 144: 767-779.

Abstract: The Delta Smelt *Hypomesus transpacificus*, listed as threatened under the California Endangered Species Act, has been cultured at a conservation hatchery since 2008 in response to significant declines in the wild. The conservation hatchery relies on accurate, efficacious, and reproducible molecular techniques to help maintain the captive population's overall genetic diversity and to minimize inbreeding. We created a panel of single-nucleotide polymorphisms (SNPs) to support broodstock pedigree reconstruction and improve upon current genetic management. For the SNP discovery, we sequenced 27 broodstock samples from the 2012 spawn by using restriction site-associated DNA sequencing (RAD-seq). We then created a linkage map by genotyping three single-pair crosses at 2,317 newly discovered loci with RAD-seq. We successfully mapped 1,123 loci and identified 26 linkage groups. Fluidigm SNP Type genotyping assays were developed for 104 mapped loci that were selected for minor allele frequencies (MAFs) greater than 0.20, neutrality (Hardy–Weinberg equilibrium), and marker location. Candidates for the genotyping panel were evaluated on a Fluidigm Integrated Fluidic Circuit 96.96 and were tested for marker accuracy and the ability to correctly assign parentage. When applied in conjunction with mating records, we found that a panel of 24 independent SNPs (mean MAF = 0.47) successfully assigned 100% of tested offspring if all of the samples were genotyped at a minimum of 18 loci. Given its capacity to streamline the screening of broodstock candidates, we foresee that the new SNP parentage panel will assume an integral role in genetic management of the Delta Smelt conservation hatchery. Furthermore, genomic resources created for this study have the potential to propel further advances in studying this imperiled species.

Marklevitz, S.A.C. and Y.E. Morbey. 2017. Habitat Use and Arrival Timing of Hatchery and Naturalized Chinook Salmon Spawning in a Great Lakes Tributary. *Transactions of the American Fisheries Society* 146: 567-583.

Abstract: Large-scale stocking programs have been used to introduce and maintain Chinook Salmon *Oncorhynchus tshawytscha* fisheries in the Laurentian Great Lakes since the late 1960s, with discoveries of naturalized populations in tributaries soon after the initial introduction. Characterizing ecological differences between hatchery and naturalized Chinook Salmon is becoming increasingly important for sustainable management of this species. We hypothesized that nonheritable traits (i.e., homing) and artificial selection might result in different habitat use and arrival timing between rearing origins occupying the same river, with the potential for reproductive isolation and divergence of naturalized and hatchery strains. In 2010 and 2011, using visual observations and PIT tags, we tracked individual hatchery and naturalized Chinook Salmon that spawned in the Sydenham River (Owen Sound, Ontario), one of the first tributaries in Lake Huron to be colonized by hatchery strays and establish a naturalized population. We estimated that 52–58% of the 3,200–3,300 fish returning

to spawn in 3.5 km of accessible spawning habitat were hatchery fish. In females, the extent of prespawning movement increased with arrival date, decreased with fish length, and was lower for hatchery fish. Hatchery females also displayed a higher probability of direct homing to the stocking site than naturalized females. Prespawning movements by males were extensive but did not depend on rearing origin, arrival timing, or body size. We found no evidence of reproductive isolation, however. Spatial distributions of spawning locations were independent of rearing origin for both sexes, and arrival timing in the river was similar between rearing origins for both sexes. The lack of reproductive isolation is likely attributable to the small area of suitable habitat in this river. Our study represents the first comprehensive comparison of spawning habitat use and timing by hatchery and naturalized Chinook Salmon in the Great Lakes.

Matala, A. P., W. Young, J. L. Vogel and S. Narum. 2012. Influences of Hatchery Supplementation, Spawner Distribution, and Habitat on Genetic Structure of Chinook Salmon in the South Fork Salmon River, Idaho. *North American Journal of Fisheries Management*. 32:346–359.

Synopsis: This study compared the genetic profile of Chinook salmon sampled below an exclusionary weir on the South Fork of the Salmon River, where supplementation has occurred for many years, with that of fish from above the weir, where only natural origin fish have access. They observed little genetic differentiation between the two groups, indicating that the supplementation program has not lead to a divergence with the wild population. They also compared these samples to samples from two neighboring populations, and observed significant differentiation inferring that despite substantial hatchery releases in the South Fork homogenization of fish across the basin has not occurred.

Monzyk, F.R., B.C. Jonasson, T.L. Hoffnagle, P.J. Keniry, R.W. Carmichael, and P.J. Cleary. 2009. Migration Characteristics of Hatchery and Natural Spring Chinook Salmon Smolts from the Grande Ronde River Basin, Oregon, to Lower Granite Dam on the Snake River. *Transactions of the American Fisheries Society* 138: 1093-1108.

Abstract: We investigated the patterns of travel time and survival of hatchery and natural smolts fitted with passive integrated transponder (PIT) tags through specific reaches of the migration corridor during the 2000–2006 migration years for two populations originating in the Grande Ronde River basin (Lostine River and Catherine Creek). For both populations, median travel times for natural smolts were significantly longer in the upper reaches of the migration corridor but shorter in the lower reaches than for their hatchery counterparts. Also, among both hatchery and natural smolts, smaller individuals spent more time in the upper reaches, presumably feeding to attain a larger size before continuing their migration. Within populations, both hatchery and natural smolts showed similar patterns of survival through the reaches of the migration corridor above Lower Granite Dam. Size-selective mortality was evident for hatchery and natural smolts from both populations, especially in the upper reaches, larger individuals experiencing higher survival.

Moyer, G.R., M.S. Blouin, and M.A. Banks. 2007. The influence of family-correlated survival on N_b/N for progeny from integrated multi- and single-generation hatchery stocks of coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Sciences* 64:1258-1265.

Abstract: There exist surprisingly few data on the final variance and mean of family sizes for hatchery-born fish at the adult stage. Thus, it is difficult to predict, for a conservation hatchery operation that minimizes the variance in progeny number, how much lower the true effective population size (N_e) of a cohort of hatchery-born adults will be than N_e predicted simply by the number of parents that produced them. We used parentage analysis to estimate the survival and N_e for two integrated stocks of hatchery coho salmon (*Oncorhynchus kisutch*). One hatchery is a multigeneration stock obtained by spawning 70% hatchery with 30% naturally reproducing fish, whereas the second is a single-generation stock derived from naturally reproducing coho. There was no significant difference in average overall survival between stocks, but observed N_e was significantly less than expected for each stock. Family-correlated survival contributed to roughly a 20% reduction in N_e over the freshwater and marine life stages. This reduction is similar to previous estimates and suggests a value that can be used when estimating the effective number of hatchery parents in applications of the Ryman-Laikre formula (at least for programs such as ours that attempt to equalize sex ratios and family sizes).

Moyer, G.R., J.D. Rousey, and M.A. Cantrell. 2009. Genetic Evaluation of a Conservation Hatchery Program for Reintroduction of Sicklefin Redhorse *Moxostoma* sp. in the Tuckasegee River, North Carolina. *North American Journal of Fisheries Management* 29: 1438-1443.

Abstract: Restoration and reintroduction efforts for the sicklefin redhorse *Moxostoma* sp. have been initiated by state, tribal, and federal agencies owing to the limited geographic distribution of this species and threats associated with the physical alteration of its habitat. A critical component of a successful reintroduction is that the source and recipient populations have similar genetic resources and life history patterns. We used 10 microsatellite loci to estimate and compare indices of genetic diversity between the Little Tennessee River population of wild adults and the hatchery broodstock being used for initial reintroduction efforts. We also compared relatedness values for the broodstock used for restoration efforts. There were no significant differences between hatchery broodstock and wild adults with respect to average gene diversity, but the average number of alleles for each brood year was significantly less than that for wild adults. While this trend persisted when the 2007 and 2008 brood years (combined) were compared with wild adults, the reduction was not significant. Finally, all hatchery crosses were among unrelated individuals. Our results highlight the importance of using genetic information to assist restoration and reintroduction efforts.

Nyqvist, D., S.D. McCormick, L. Greenberg, W.R. Ardren, E. Bergman, O. Calles, and T. Castro-Santos. 2017. Downstream Migration and Multiple Dam Passage by Atlantic Salmon Smolts. *North American Journal of Fisheries Management* 37: 816-828.

Abstract: The purpose of this study was to investigate behavior and survival of radio-tagged wild and hatchery-reared landlocked Atlantic Salmon *Salmo salar* smolts as they migrated past three hydropower dams equipped with fish bypass solutions in the Winooski River, Vermont. Among hatchery-reared smolts, those released early were more likely to initiate migration and did so after less delay than those released late. Once migration was initiated, however, the late-released hatchery smolts migrated at greater speeds. Throughout the river system, hatchery-reared fish performed similarly to wild fish. Dam passage rates varied between the three dams and was highest at the dam where unusually high spill levels occurred throughout the study period. Of the 50 fish that did migrate downstream, only 10% managed to reach the lake. Migration success was low despite the

presence of bypass solutions, underscoring the need for evaluations of remedial measures; simply constructing a fishway is not synonymous with providing fish passage.

Pearsons, T. N. and G. M. Temple. 2007. Impacts of Early Stages of Salmon Supplementation and Reintroduction Programs on Three Trout Species. *North American Journal of Fisheries Management* 27:1-20.

Abstract: Salmon supplementation and reintroduction programs have the potential to negatively impact other valued fish taxa that are not the targets of enhancement (nontarget taxa [NTT]). Impacts of the supplementation of spring Chinook salmon *Oncorhynchus tshawytscha* and the reintroduction of coho salmon *O. kisutch* (hereafter supplementation) on populations of rainbow trout *O. mykiss*, steelhead (anadromous rainbow trout), cutthroat trout *O. clarkii*, and bull trout *Salvelinus confluentus* were evaluated after 5 years of stocking approximately 1 million yearling smolts in the upper Yakima River basin between 1999 and 2003. Field methods included backpack electrofishing and snorkeling in tributaries and drift-boat electrofishing in the main stem. We used three sequential steps in our evaluation: (1) we determined whether spatial overlap occurred between supplemented fish and NTT; (2) if overlap occurred, we determined whether a change in abundance, size, or biomass occurred during supplementation; and (3) if a change occurred, we determined whether the change could be reasonably attributed to supplementation. Salmon rarely overlapped cutthroat trout or bull trout in tributaries, but some overlap with cutthroat trout occurred in relatively high elevations of the main stem and considerable overlap with rainbow trout occurred in tributaries and the main stem. Except in steelhead, the lower 90% confidence limit (CL) of abundance, size, and biomass was above the containment objective for NTT that overlapped significantly with salmon. We used rainbow trout as an analog for steelhead. The lower 90% CL of rainbow trout abundance and size in tributaries and the main stem and biomass in the main stem was below the containment objective for steelhead. However, comparisons of rainbow trout abundance, size, and biomass between tributaries and main-stem sections with relatively high and low salmon abundances revealed that the change was probably not the result of supplementation (before–after control–impact paired site analysis: $P > 0.05$). Our data indicate that early stages of salmon supplementation have not impacted trout species in the upper Yakima River basin beyond predetermined containment objectives.

Pearsons, T.N., A.L. Fritts, and J.L. Scott. 2007. The effects of hatchery domestication on competitive dominance of juvenile spring Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 64:803-812.

Abstract: We tested the null hypotheses that competitive dominance among juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in contest and scramble experiments would not be affected by domestication selection after one generation of state-of-the-art hatchery culture. Dyadic challenges of size-matched juvenile fish were conducted after a 6-day acclimation in 113.4 L aquaria. Differences in dominance and frequency of different types of agonistic interactions used were not significantly different in contest ($n = 505$) or scramble ($n = 363$) competition experiments ($P > 0.05$). However, wild origin fish were more aggressive than hatchery origin fish in both types of experiments ($P \leq 0.05$). Furthermore, wild origin fish gained more weight than hatchery origin fish during contest experiments, and hatchery origin fish lost less weight than wild origin fish in scramble experiments ($P \leq 0.05$). Dominant fish, regardless of origin, grew more than subordinate fish in both contest and scramble experiments ($P \leq 0.05$). Our results indicate that aggression, and growth

mediated by competition, can be affected by domestication after only one generation of state-of-the-art hatchery culture; however, impacts to competitive dominance appear to be small.

Richins, S.M. and J.R. Skalski. 2018. Steelhead Overshoot and Fallback Rates in the Columbia–Snake River Basin and the Influence of Hatchery and Hydrosystem Operations. *North American Journal of Fisheries Management* 38:1122-1137.

Abstract: Tributary overshoot occurs when adult salmonids homing to natal sites continue upstream past the mouth of their natal stream. Although overshooting is a common behavior by steelhead *Oncorhynchus mykiss* in the Columbia River basin, it has not been adequately quantified or explained. Using multistate release–recapture models, we examined the prevalence of overshooting and fallback to natal tributaries by 37,806 PIT-tagged steelhead from 14 tributaries of the Columbia River basin during 2005–2015. Eight populations had overshooting rates exceeding 50% in at least 1 year. Source of hatchery stock, rearing location, and release practices were found to have appreciable effects on overshoot rates. Overshooting was elevated in hatchery stocks reared upstream of release sites, but this effect may be lessened by utilizing endemic broodstocks and acclimating juveniles within the release basin. **For one population of hatchery steelhead, acclimation within the release basin was found to decrease overshooting from 81% to 40%.** Across both hatchery and wild populations, successful homing was found to decline 4 percentage points for every 5-percentage-point increase in overshoot rate. Average annual fallback probabilities ranged from 0.18 for Walla Walla River hatchery steelhead to 0.75 for Umatilla River wild steelhead. Fish stocks with the greatest fallback probabilities also had the greatest interannual variability in fallback rates. For John Day River wild steelhead and Tucannon River hatchery steelhead, the interannual range in fallback probabilities exceeded 0.50. We found evidence that spill at dams during March may enhance the fallback of overshooting steelhead and contribute to increased homing to natal tributaries. Therefore, additional attention should be paid to facilitating downstream dam passage of adult salmon.

Rosenberger, S.J., W.P. Connor, C.A. Peery, D.J. Milks, M.L. Schuck, J.A. Hesse, and S.G. Smith. 2013. Acclimation enhances postrelease performance of hatchery fall Chinook salmon subyearlings while reducing the potential for interaction with natural fish. *North American Journal of Fisheries Management* 33:519-528.

Abstract: One form of prerelease acclimation of hatchery anadromous salmonid *Oncorhynchus* spp. juveniles is to truck the fish to remote points for extended holding at low densities in rearing vessels (e.g., tanks, raceways, or in-ground ponds) supplied with river water. We conducted a 3-year study to determine whether such acclimation enhanced the postrelease performance of hatchery fall Chinook Salmon *O. tshawytscha* subyearlings and reduced the potential for interaction with natural fall Chinook Salmon subyearlings. In comparison with hatchery subyearlings that were released directly into the lower Snake River just downstream of the acclimation facility, acclimated hatchery subyearlings (1) passed downstream to Lower Monumental Dam (the third dam encountered during seaward migration) faster, (2) passed the dam earlier, and (3) survived from release to the dam tailrace at higher rates. The differences in downstream passage rate and dam passage timing were also much greater between acclimated hatchery subyearlings and natural subyearlings than between directly released hatchery

subyearlings and natural subyearlings. Thus, acclimation provided a survival advantage to the hatchery fish while reducing the potential for (1) aggressive and nonaggressive social interactions with natural fish while in transit through the reservoirs associated with Lower Granite, Little Goose, and Lower Monumental dams; and (2) confinement with natural fish at those three dams, where fish collection and raceway holding were followed by transport in tanker trucks. Our findings support acclimation as a method for enhancing postrelease performance of hatchery fall Chinook Salmon subyearlings and reducing their potential interactions with natural conspecifics.

Rosengren, M., E. Kvingedal, J. Näslund, J.I. Johnsson, and K. Sundell. 2017. Born to be wild: effects of rearing density and environmental enrichment on stress, welfare, and smolt migration in hatchery-reared Atlantic salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 74:396-405.

Abstract: Hatchery-reared salmonids released into the wild generally have poor survivability compared with wild conspecifics. To assess potential hatchery rearing improvements, behavioral and physiological effects of reducing animal density and adding in-tank shelter were investigated. Atlantic salmon (*Salmo salar*) parr were placed in barren or shelter-enriched tanks at high or low density up until release as smolts. Lowered density rendered positive effects on growth and intestinal barrier function, and both lowered density and shelter decreased conspecific aggression, as inferred by fin damage. Furthermore, while the presence of shelter decreased stress hormone levels following human disturbance, it also decreased growth and smolt migration success, an effect particularly pronounced at high densities. Therefore, we suggest that this type of structural enrichment should be avoided for Atlantic salmon smolts held at high densities and conclude that a lowered animal density with or without shelter has the highest potential in producing a more resilient smolt for stocking.

Sard, N.M., K.G. O'Malley, D.P. Jacobson, M.J. Hogansen, M.A. Johnson, and M.A. Banks. 2015. Factors influencing spawner success in a spring Chinook salmon (*Oncorhynchus tshawytscha*) reintroduction program. *Canadian Journal of Fisheries and Aquatic Sciences*, 72:1390-1397.

Abstract: Dams have contributed to the decline of migratory fishes by blocking access to historical habitat. The active transport (trap and haul) of migratory fish species above existing dams can sometimes support population recovery when the use of fish ladders or dam removal is infeasible. However, little is known about the efficacy of trap and haul conservation strategies. Here we used genetic parentage assignments to evaluate the efficacy of reintroducing adult Chinook salmon (*Oncorhynchus tshawytscha*) above Cougar Dam on the South Fork McKenzie River, Oregon, USA, from 2008 to 2011. We found that mean reproductive success (RS) declined as adults were released later in the spawning season in 2009 and 2010; however, release location did not affect RS. In 2010 and 2011, we tested for RS differences between hatchery and natural origin (HOR and NOR, respectively) adults. HOR males were consistently less fit than NOR males, but little evidence for fitness differences was apparent between HOR and NOR females. Interestingly, the effect of origin on RS was not significant after accounting for variation explained by body length. Our results indicate that release date and location have inconsistent or no effect on the reproductive success of reintroduced adults when active transport strategies are employed for migratory fishes.

Schroder, S. L., C. M. Knudsen, T. N. Pearsons, T. W. Kassler, S. F. Young, C. A. Busack, and D. E.

Fast. 2008. Breeding Success of Wild and First-Generation Hatchery Female Spring Chinook Salmon Spawning in an Artificial Stream. Transactions of the American Fisheries Society, 137:1475-1489.

Abstract: First generation hatchery and wild spring Chinook salmon from the upper Yakima River, Washington State were placed into an artificial stream and allowed to spawn. Seven independent test groups were placed into the stream from 2001 through 2005. No differences were detected in the egg deposition rates of wild and hatchery females. Pedigree assignments based on microsatellite DNA, however, showed that the eggs deposited by wild females survived to the fry stage at a 5.6% higher rate than those spawned by hatchery females. Subtle differences between hatchery and wild females in redd abandonment, egg burial, and redd location choice may have been responsible for the difference observed. Body size did not affect the ability of females to spawn or the survival of their deposited eggs. How long a female lived was positively related to her breeding success but female origin did not affect longevity. The density of females spawning in portions of the stream affected both egg deposition and egg-to-fry survival. No difference, however, was found in the overall distribution patterns of the two types of females. Other studies that have examined the effects of a single generation of hatchery culture on upper Yakima River Chinook have disclosed similar low-level effects on adult and juvenile traits. The cumulative impact of such differences will need to be considered when hatcheries are used to restore depressed populations of salmon.

Schroder, S. L., C. M. Knudsen, T. N. Pearsons, T. W. Kassler, S. F. Young, E.P. Beall, and D. E. Fast. 2010. Behavior and Breeding Success of Wild and First-Generation Hatchery Male Spring Chinook Salmon Spawning in an Artificial Stream. Transactions of the American Fisheries Society, 139:989-1003.

Abstract: Spring Chinook salmon *Oncorhynchus tshawytscha* native to the upper Yakima River, Washington, were placed into an artificial stream to evaluate the effect of a single generation of hatchery culture on their spawning behavior and ability to produce offspring. From 2001 to 2005, seven independent test groups containing wild and hatchery fish were placed into the stream. The effects of body weight, spawning ground longevity, attack frequency, social dominance, courting frequency, and mate number on breeding success in hatchery and wild males were evaluated. Differences in male agonism due to male origin were found. Wild males exhibited higher attack rates and greater social dominance than did hatchery males. However, the observed inequalities in agonism and dominance appeared to be largely caused by differences in body weight between the two types of males: wild males were, on average, 9% heavier than hatchery males. Wild and hatchery males did not differ in the frequency of courting behaviors or in the number of mates. Pedigree analyses based on DNA showed that hatchery and wild males had comparable breeding success values. Consequently, a single generation of hatchery exposure appeared to have a low effect on spring Chinook salmon male breeding success in our experimental setting.

Selly, S-L. C., J. Hickey, and J. R. Stevens. 2014. A tale of two hatcheries: Assessing bias in the hatchery process for Atlantic salmon (*Salmo salar* L.). Aquaculture, 434:254-263.

Abstract: Stock enhancement of Atlantic salmon (*Salmo salar* L.), a fish of considerable economic and social importance, is commonplace. Supportive-breeding is a well-recognized method of enhancement which, when compared with traditional hatchery practices, is thought to reduce the

severity of selection pressures on broodstock fish. Critically, in supportive-breeding programmes, the eggs and sperm used in the breeding process are taken from wild adult fish originating from the same catchment that resulting juvenile fish are subsequently stocked into, thereby avoiding problems associated with a lack of local adaptation in the stocked fish. Previous studies have indicated that sex bias during the hatchery process may result in reduced genetic diversity of the offspring. Utilising 16 microsatellite loci and two expressed sequence tag (EST) loci, we examined progeny from two hatcheries located on the rivers Exe and Tamar in southwest England, assessing the genetic diversity and parental contribution at each. Two strains were assessed within each hatchery. Genetic diversity was found to be reduced in offspring compared with that of the parent fish. This is likely the result of utilising a small number of broodstock in combination with parental bias. In the four hatchery strains studied (Bar, LEx, Lyd and TXL), parental contribution ranged between 2.1 and 29.2%, 12.2–51.0%, 2.0–70.0% and 4.0–40.0%, respectively. If this practice is to be continued, efforts should be made to improve adherence to national rearing guidelines by increasing the number of broodstock fish utilised and ensuring a more balanced contribution of all adults during the crossing process. Ultimately, we suggest a need to review the suitability of current national Atlantic salmon hatchery guidelines, particularly with regard to their use and relevance in small European rearing systems.

Sharma, R, G. Morishima, S. Wang, A. Talbot, and L. Gilbertson. 2006. An evaluation of the Clearwater River supplementation program in western Washington. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(2): 423-437.

Synopsis: After three generations of study, an integrated coho supplementation program in a Washington coastal stream documented no empirical evidence that the program negatively affected the fitness of the target population. This study demonstrates that a supplementation (hatchery) program, in this case following new and innovative operational protocols, can produce smolts that have nearly the same survival rate to adults as that of wild smolts and can result in more adult coho returning to the Clearwater basin. This benefit appears possible without short-term adverse impacts to either intrinsic productivity or the number of naturally produced smolts.

Sharpe, C.S., P.L. Hulett, C.W. Wagemann, M.P. Small and A.R. Marshall. 2010. Natural Reproductive Success of First-generation Hatchery Steelhead Spawning in the Kalama River: A Progress Report. Washington Department of Fish and Wildlife, Fish Program, Fish Science Division. (<http://wdfw.wa.gov/publications/00969/wdfw00969.pdf>)

Synopsis: The goal of the Kalama research program is to identify and empirically quantify risks imposed by hatchery programs on natural production of anadromous salmonids, and identify strategies to manage those risks. Studies of steelhead genetics, ecology, and life history have been ongoing in the Kalama River since the mid-1970's. A primary objective of Kalama research work has been to assess the relative reproductive performance and contribution of hatchery and wild steelhead spawning in the wild. We did not detect a difference in reproductive success of the wild broodstock hatchery spawners: the proportions of offspring from Hatchery \times Hatchery (HH), Hatchery \times Wild (HW), and Wild \times Wild (WW) spawners closely approximated the proportions expected under the null hypothesis with reproductive success of hatchery spawners equal to that of wild spawners. Reproductive success of first-generation wild broodstock hatchery fish appeared to be similar to that of wild fish in the first replicate of our experiment. The outcome is in agreement with initial results from a similar reproductive success study on the Hood River, Oregon (Araki et al. 2006), where first

generation wild-broodstock winter-run steelhead appeared to be as reproductively competent as the wild fish from which they were derived (but see Araki et al. 2007 and Araki et al. 2008). Because we present results from only the first of three replicates the results should be considered preliminary.

Small, M.P., K. Currens, T.H. Johnson, A.E. Frye, and J.F. Von Bargaen. 2009. Impacts of supplementation: genetic diversity in supplemented and unsupplemented populations of summer chum salmon (*Oncorhynchus keta*) in Puget Sound (Washington, USA). *Canadian Journal of Fisheries and Aquatic Sciences*, 66:1216-1229.

Abstract: In supplementation programs, hatcheries employ wild-origin fish as brood stock and their offspring are allowed into wild spawning areas. Resource managers use supplementation to support imperiled salmonid populations, seeking to increase census size and possibly effective population size (N_e), while minimizing risks of genetic diversity loss and domestication from hatchery intervention. Here we document impacts of 5–10 years of supplementation on threatened summer-run chum salmon (*Oncorhynchus keta*) in Hood Canal (HC) and Strait of Juan de Fuca (SJF) in Washington State and compare them genetically with unsupplemented summer- and fall-run chum salmon from HC and South Puget Sound. Microsatellite allele frequencies identified four run-timing and geographic groups. HC and SJF summer chum salmon genetic relationships followed a metapopulation pattern of isolation by distance, similar to patterns prior to supplementation, suggesting that supplementation minimally impacted population structure. In most supplemented subpopulations, we detected no effects on diversity and N_e , but high variance in individual pairwise relatedness values indicated over-representation of family groups. In two subpopulations, hatchery impacts (decreased diversity and lower N_e) were confounded with extreme bottlenecks. Rebounds in census sizes in all subpopulations suggest that general survivorship has improved and that possible hatchery effects on genetic diversity will be overcome.

Smith, C.T., R. French, J. Lovtang, and D. Hand. 2014. Genetic Composition of the Warm Springs River Chinook Salmon Population Maintained following Eight Generations of Hatchery Production. *Transactions of the American Fisheries Society*, 143:1280-1294.

Abstract: Balancing the disparate objectives of fishery augmentation and conservation of an endemic fish population presents a substantial challenge. In the case of Warm Springs National Fish Hatchery (Warm Springs Hatchery), strategies for achieving both objectives included incorporation of natural fish into the hatchery broodstock and restricting proportions of hatchery fish on the spawning grounds. The hatchery has been more successful in implementing the latter than the former. We analyzed 76 single nucleotide polymorphism markers in Spring Chinook Salmon *Oncorhynchus tshawytscha* collected from the Warm Springs River in 1976–1977 (prior to hatchery production) and 2001–2011 (posthatchery) to examine whether the genetic characteristics of the endemic population had changed during that time. Pre- and posthatchery collections clustered together when compared with those from Round Butte Hatchery, which has a nearby segregated program, and other Columbia River populations. The difference between pre- and posthatchery collections was nonsignificant, but posthatchery samples exhibited significantly lower expected heterozygosity. We observed some evidence of reduced effective size and increased genetic drift in fish produced at Warm Springs Hatchery (relative to natural-origin fish) and even stronger evidence of this in fish produced at Round Butte Hatchery. We conclude that natural-origin Chinook Salmon returning to the Warm Springs River form a distinct group within the interior Columbia Basin spring-run lineage and have changed

very little over the past eight generations. We further speculate that differences between hatchery- and natural-origin fish at Warm Springs Hatchery are expected to increase if hatchery operations remain static (i.e., little integration of natural-origin fish and incorporation of Round Butte Hatchery fish in the broodstock).

Stephenson, S.M., M.D. Neufeld, S.C. Ireland, S. Young, R.S. Hardy, and P. Rust. 2013. Survival and Dispersal of Sonic-Tagged, Hatchery-Reared Burbot Released into the Kootenay River. *Transactions of the American Fisheries Society*, 142:1671-1679.

Abstract: As part of recovery efforts for the Kootenay population of Burbot *Lota lota*, we monitored 109 sonic-tagged, hatchery-reared Burbot released at 1–3 years of age throughout Kootenay Lake and the Kootenay River over a 3-year period. Our objectives were to evaluate broodstock choice, assess differences in survival and dispersal by release site and age, and evaluate spawning movements. Overall, release survival was high (66%) and there was dispersal throughout the system (up to 235 km), involving both lacustrine and riverine habitat. Spawning movements were extensive (up to 59 km/d upstream) and suggest the use of known spawning locations. However, most age-1 releases had lower survival and remained in the release tributaries for 1 year postrelease, which was longer than expected and which warrants further investigation. Overall, this telemetry study provides a positive outlook on the current aquaculture rehabilitation efforts for Kootenay Burbot and provides direction for further work.

Sturdevant, M.V., Fergusson, E., Hillgruber, N., Reese, C., Orsi, J., Focht, R., Wertheimer, A., Smoker, B., 2011. Lack of trophic competition among wild and hatchery juvenile chum salmon during early marine residence in Taku Inlet, Southeast Alaska. *Environmental Biology of Fishes* 94, 101–116.

Abstract: Early marine trophic interactions of wild and hatchery chum salmon (*Oncorhynchus keta*) were examined as a potential cause for the decline in harvests of adult wild chum salmon in Taku Inlet, Southeast Alaska. In 2004 and 2005, outmigrating juvenile chum salmon were sampled in nearshore habitats of the inlet (spring) and in epipelagic habitat at Icy Strait (summer) as they approached the Gulf of Alaska. Fish were frozen for energy density determination or preserved for diet analyses, and hatchery stocks were identified from the presence of thermal marks on otoliths. We compared feeding intensity, diets, energy density, and size relationships of wild and hatchery stocks (n=3123) across locations and weeks. Only hatchery fish feeding intensity was negatively correlated with fish abundance. In both years, hatchery chum salmon were initially larger and had greater energy density than wild fish, but lost condition in early weeks after release as they adapted to feeding on wild prey assemblages. Diets differed between the stocks at all inlet locations, but did not differ for hatchery salmon between littoral and neritic habitats in the outer inlet, where the stocks overlapped most. Both diets and energy density converged by late June. Therefore, if density-dependent interactions affect wild chum salmon, these effects must be very rapid because survivors in Icy Strait showed few differences. Our study also demonstrates that hatchery release strategies used near Taku Inlet successfully promote early spatial segregation and prey partitioning, which reduce the probability of competition between wild and hatchery chum salmon stocks.

Suk, H.Y., B.D. Neff, K. Quach, and Y.E. Morbey. 2011. Evolution of introduced Chinook salmon (*Oncorhynchus tshawytscha*) in Lake Huron: emergence of population genetic structure in less than 10 generations. *Ecology of Freshwater Fish*, 21:235-244, corrigendum 21:494.

Abstract: Population genetic structure was detected in Chinook salmon *Oncorhynchus tshawytscha* in their non-native range of Lake Huron using microsatellite DNA. All Chinook salmon in this system descend from Green River, Washington cohorts, originally transplanted to Michigan hatcheries in the late 1960s. We tested for population genetic differentiation of age 0 fish collected from 13 rivers and two hatcheries in 2007. The amount of genetic differentiation among collection sites was low but statistically significant, with F_{ST} values ranging from 0.036 to 0.133 and R_{ST} values ranging from 0.008 to 0.157 for specific loci. Based on pairwise F_{ST} and R_{ST} values and Bayesian cluster analysis, the Maitland River population in the Main Basin of Lake Huron was genetically distinct from the remaining collection sites. Based on analysis of bycatch data from commercial gill net fisheries, Chinook salmon likely colonised the Main Basin by 1975 (10 generations ago) and the North Channel and southern Georgian Bay regions by 1980 (eight generations ago). Thus, population genetic structure has emerged in Lake Huron Chinook salmon in <10 generations.

Tatara, C.P., S.C. Riley, and B.A. Berejikian. 2011. Effects of Hatchery Fish Density on Emigration, Growth, Survival, and Predation Risk of Natural Steelhead Parr in an Experimental Stream Channel. *North American Journal of Fisheries Management* 31:224-235.

Abstract: Hatchery supplementation of steelhead *Oncorhynchus mykiss* raises concerns about the impacts on natural populations, including reduced growth and survival, displacement, and increased predation. The potential risks may be density dependent. We examined how hatchery stocking density and the opportunity to emigrate affect the responses of natural steelhead parr in an experimental stream channel and after 15 d found no density-dependent effects on growth, emigration, or survival at densities ranging from 1-6 hatchery parr/m². The opportunity for steelhead parr to emigrate reduced predation by coastal cutthroat trout *O. clarkii clarkii* on both hatchery and natural steelhead parr. The cutthroat trout exhibited a type-I functional response (constant predation rate with increased prey density) for the hatchery and composite populations. In contrast, the predation rate on natural parr decreased as hatchery stocking density increased. Supplementation with hatchery parr at any experimental stocking density reduced the final natural parr density. This decline was explained by increased emigration from the supplemented groups. Natural parr had higher mean instantaneous growth rates than hatchery parr. The proportion of parr emigrating decreased as parr size increased over successive experimental trials. Smaller parr had lower survival and suffered higher predation. The final density of the composite population, a measure of supplementation effectiveness, increased with the hatchery steelhead stocking rate. Our results indicate that stocking larger hatchery parr (over 50 d postemergence) at densities within the carrying capacity would have low short-term impact on the growth, survival, and emigration of natural parr while increasing the density of the composite population; in addition, a stocking density greater than 3 fish/m² might be a good starting point for the evaluation of parr stocking in natural streams.

Tatara, C.P., M.R. Cooper, W. Gale, B.M. Kennedy, C.R. Pasley, and B.A. Berejikian. 2017. Age and Method of Release Affect Migratory Performance of Hatchery Steelhead. *North American Journal of Fisheries Management* 37:700-713.

Abstract: Hatchery programs that are designed to aid recovery of natural populations of anadromous salmonids, including steelhead *Oncorhynchus mykiss*, require locally derived, natural-origin broodstock. In such programs, achieving smoltification size thresholds may require extending hatchery rearing beyond age 1. We compared out-migration survival and travel rates of 142,990 PIT-tagged steelhead smolts released at age 1 (S1 rearing strategy) or age 2 (S2 rearing strategy) over five release years at Winthrop National Fish Hatchery (WNFH, Okanogan County, Washington). An S2 rearing cycle produced larger smolts with more uniform size distributions, resulting in higher survival during the first portion of their out-migration than for S1 smolts in three of the five release years. The S2 smolts migrated more rapidly to the ocean than S1 smolts in all years except 2011 and arrived in the Columbia River estuary 5.4 d earlier on average than the S1 smolts. The S1 steelhead that did not leave during the volitional release were subsequently forced from the hatchery to measure their survival. Nonvolitional S1 migrants were smaller and had survival rates that were 2.3–66.3 times lower than those of S1 steelhead that left WNFH on their own. The same was true for S2 steelhead, but the magnitude of the survival difference between volitional migrants and fish forced from the raceways was less variable and ranged from 2.5- to 4.6-fold. We conclude that S2 rearing can be a successful strategy for producing smolts from local natural-origin broodstock, with out-migration survival and travel times that are equivalent to or better than those of S1 smolts produced from nonlocal broodstock.

Temple, G.M. and T.N. Pearsons. 2012. Risk management of non-target fish taxa in the Yakima River Watershed associated with hatchery salmon supplementation. *Environmental Biology of Fishes* 94:67–86.

Abstract: Hatchery cultured salmon have the potential to interact strongly with other valued fish taxa (nontarget taxa; NTT) in the natural environment. Monitoring and managing adverse interactions between hatchery supplemented salmon and NTT is one unique characteristic of a hatchery salmon supplementation program in the Yakima River, Washington. In this study, we evaluate impacts of spring Chinook salmon *Oncorhynchus tshawytscha* and coho salmon *O. kisutch* reintroduction to 15 NTT after 11 years of stocking approximately one million yearling smolts annually in the upper Yakima Basin between 1999 and 2009. Our risk management monitoring indicated changes in important response variables for NTT were within acceptable limits. Rigorous pre-implementation planning likely prevented many undesirable ecological impacts from the hatchery supplementation program. We illustrate a number of important features associated with risk management of hatchery and wild fish interactions. First, pre-project planning can eliminate many risks of concern and substantially reduce the need for risk containment during project implementation. Second, the sieve approach for monitoring impacts provided an acceptable balance between monitoring effort and risk containment ability, although in some cases, we would not detect impacts of interest. Third, rare and dispersed species that cannot be monitored effectively benefit from risk averse hatchery release strategies. Fourth, risk containment monitoring programs can be used to refute unsubstantiated claims of undesirable impacts. In short, our experience suggests that risk management of ecological interactions can occur by using a combination of pre-project adjustments through risk assessment and risk reduction, and by cost-effective risk containment monitoring and management.

Van Doornik, D.M., R.S. Waples, M.C. Baird, P. Moran, and E.A. Berntson. 2011. Genetic Monitoring Reveals Genetic Stability within and among Threatened Chinook Salmon

Populations in the Salmon River, Idaho. *North American Journal of Fisheries Management* 31:96-105.

Abstract: Identifying and understanding temporal genetic changes within fish populations is important for the management of these populations, especially those of conservation concern. Such changes are often the result of genetic drift, which can be exacerbated when the size of a population decreases. Using molecular-genetics techniques, we monitored nine populations of Chinook salmon *Oncorhynchus tshawytscha* in the Salmon River, Idaho, to determine how the genetic characteristics within and among these populations have changed over time. We found no evidence of change in the level of heterozygosity or allelic richness over three to four generations in eight of the populations. This is probably due to the fact that the populations all maintained a sufficiently large effective size, even though a few of the populations did show a decline in effective size. Also, the genetic structure among the populations did not change appreciably over time. Populations that had been supplemented with hatchery-reared fish showed genetic similarity to the within-basin hatchery source population, presumably because of the extensive use of native fish for hatchery brood stocks and minimal out-of-basin stock transfers. The lack of a detectable decline in these populations' levels of genetic diversity is encouraging, given the species' threatened status under the U.S. Endangered Species Act.

Van Doornik, D.M., D.L. Eddy, R.S. Waples, S.J. Boe, T.L. Hoffnagle, E.A. Berntson, and P. Moran. 2013. Genetic Monitoring of Threatened Chinook Salmon Populations: Estimating Introgression of Nonnative Hatchery Stocks and Temporal Genetic Changes. *North American Journal of Fisheries Management* 33:693-706.

Abstract: Conservation efforts aimed at Pacific salmon (*Oncorhynchus* spp.) populations have frequently utilized artificial propagation in an attempt to increase fish abundance. However, this approach carries the risk of unwanted changes in the genetic characteristics of the target population and perhaps others that might incidentally be affected. We used genetic monitoring techniques to estimate the amount of introgression that has occurred from nonnative hatchery stocks into native populations and to determine the extent of genetic changes that have occurred in association with supplementation efforts over the past 20–50 years in Snake River Chinook Salmon *O. tshawytscha* populations from northeastern Oregon. A total of 4,178 fish from 13 populations were genotyped for 12 microsatellite DNA loci. Expected heterozygosity values for each sample ranged from 0.707 to 0.868. Estimates of the effective number of breeders per year in the naturally spawning populations ranged from 20.6 to 459.1, whereas in the hatchery populations they ranged from 33.8 to 1,118.8. We found that introgression from the Rapid River Hatchery stock was particularly noticeable in the early 1990s but that it appears to have had a substantial effect on only two of the native populations (Lookingglass Creek and the upper Grande Ronde River) despite the ample opportunities for introgression to occur. All seven of the native populations sampled have maintained their levels of within-population genetic diversity throughout the sampling period. Overall, this region's supplementation efforts appear to have had a minimal effect on the genetic diversity of its Chinook Salmon populations.

Van Doornik, D.M., M.A. Hess, M.A. Johnson, D.J. Teel, T.A. Friesen, and J.M. Myers. 2015. Genetic Population Structure of Willamette River Steelhead and the Influence of Introduced Stocks. *Transactions of the American Fisheries Society* 144:150-162.

Abstract: Conservation genetics studies are frequently conducted on Pacific salmon *Oncorhynchus* spp. to delineate their population structure and to quantify their genetic diversity, especially for populations that have experienced declines in abundance and are subject to anthropogenic activities. One such group of salmonids is steelhead *O. mykiss* (anadromous Rainbow Trout) from the Willamette River, a tributary of the Columbia River. Within the Willamette River there are multiple steelhead life history and run-timing types, some of which originated from nonnative populations. Late winter-run steelhead and Rainbow Trout are native to the Willamette River, whereas early winter-run and summer-run steelhead have been introduced into the system via releases from artificial propagation efforts. We conducted genetic analyses of Willamette River steelhead to determine the effect that nonnative steelhead released into the Willamette River basin have had on the genetic population structure of native steelhead. We found genetic differentiation among the samples that separated steelhead into four population groups that corresponded to run type. Possibly due to local adaptation, the native run type has retained its genetic distinctiveness from the introduced types, despite there being opportunities for gene flow among all types. Introduced early winter-run steelhead appear to be the origin of steelhead inhabiting certain Willamette River tributaries where native steelhead did not historically spawn.

Venditti, D.A., R.N. Kinzer, K.A. Apperson, B. Barnett, M. Belnap, T. Copeland, M.P. Corsi, W.T. Gross, L. Janssen, R. Santo, K. Tardy, and A. Teton. 2015. Idaho Supplementation Studies Project Completion Report, 1991-2014.
<https://nwcouncil.app.box.com/s/gsolcxk9nv1w3897am4th5nl7xe6108g>

Synopsis: This supplementation study incorporated 27 streams and spanned 23 years. There were nine supplemented and four reference streams in the Clearwater River basin, and four supplemented and 10 reference streams in the Salmon River basin. The project consisted of a baseline data collection phase (1992-1995), a supplementation phase (1996-2007), and a post-supplementation evaluation phase (2008-2012). Supplementation resulted in a population boost that did not persist after supplementation ceased. Abundance, as measured by redd counts, increased across both basins but supplemented streams increased more than reference streams. The observed abundance increase diminished through the life cycle (emigrants, smolts, and adult progeny) and this trend was consistent across the Clearwater and Salmon basins. Similar overall patterns were observed when addressing effects of non-treatment hatchery fish on redd abundance, but positive effects of these fish were not observed in juvenile life stages or in adult progeny. After supplementation, abundance at each life stage in treated and reference streams returned to their pre-supplementation relationships, suggesting supplementation did not have a lasting influence on abundance. Unless factors limiting abundance are ameliorated, increases resulting from supplementation are unlikely to persist. Supplementation had few effects on population productivity. Supplementation is useful as part of an integrated management approach to maintain population abundance in the face of poor conditions. Post-supplementation results show that temporary benefits can be achieved while keeping ecological costs low. However, supplementation alone is not a panacea because it does not correct fundamental limiting factors; these limiting factors must be addressed to achieve population levels capable of sustaining ecological function and management opportunities such as harvest.

Waters, C.D., J.J. Hard, M.S.O. Briec, D.E. Fast, K.I. Warheit, R. Waples, C.M. Knudsen, W.J. Bosch, and K.A. Naish. 2015. Effectiveness of managed gene flow in reducing genetic divergence associated with captive breeding. *Evolutionary Applications* 8:956-971. [DOI:](#)

Abstract: Captive breeding has the potential to rebuild depressed populations. However, associated genetic changes may decrease restoration success and negatively affect the adaptive potential of the entire population. Thus, approaches that minimize genetic risks should be tested in a comparative framework over multiple generations. Genetic diversity in two captive-reared lines of a species of conservation interest, Chinook salmon (*Oncorhynchus tshawytscha*), was surveyed across three generations using genome-wide approaches. Genetic divergence from the source population was minimal in an integrated line, which implemented managed gene flow by using only naturally-born adults as captive broodstock, but significant in a segregated line, which bred only captive-origin individuals. Estimates of effective number of breeders revealed that the rapid divergence observed in the latter was largely attributable to genetic drift. Three independent tests for signatures of adaptive divergence also identified temporal change within the segregated line, possibly indicating domestication selection. The results empirically demonstrate that using managed gene flow for propagating a captive-reared population reduces genetic divergence over the short term compared to one that relies solely on captive-origin parents. These findings complement existing studies of captive breeding, which typically focus on a single management strategy and examine the fitness of one or two generations.

If there are negative hatchery effects, are they reversible?

Bosch, W. J., T. H. Newsome, J. L. Dunnigan, J. D. Hubble, D. Neeley, D. T. Lind, D. E. Fast, L. L. Lambull, and J. W. Blodgett. 2007. Evaluating the Feasibility of Reestablishing a Coho Salmon Population in the Yakima River, Washington. *North American Journal of Fisheries Management* 27:198-214.

Abstract: Historical returns of coho salmon to the Yakima River Basin were estimated to range from 45,000 to 100,000 fish annually but declined to zero by the 1980s after decades of overexploitation of fishery, water, and habitat resources. In 1996 the Yakama Nation and cooperators initiated a project to determine the feasibility of reestablishing a naturally spawning coho population in the Yakima River. The Yakima coho project explored whether successful recolonization was feasible when multi-generational, hatchery-reared coho were reintroduced to native habitats. After 10-20 years of outplanting, we compared data for adult returns of known natural- and hatchery-origin coho. We found that natural-origin coho returned at a significantly larger size than hatchery-origin coho. Mean egg mass and mean egg size of natural-origin females were greater than those of hatchery-origin females, though the differences were statistically significant for only one of three sample years. Natural-origin adults returned (2 to 9 days) and spawned (5 days) later than their hatchery-origin counterparts. Preliminary indices of smolt-to-adult survival for natural-origin coho were 3.5 to 17.0 times survival indices of hatchery-origin coho. The number of coho returning to historical native spawning habitats in upriver areas generally increased. Spawning surveys demonstrated the existence of robust and sustainable spawning aggregates in various locations in the basin. Hatchery releases from local brood source parents had significantly higher smolt-to-smolt survival than releases from out-of-basin hatchery broodstock, but some of these observed differences in survival could have been due in part to differences in smolt size. We conclude that hatchery-origin coho, with a legacy of as

many as 10 to 30 generations of hatchery-influence, demonstrated their ability to reestablish a naturalized population after as few as 3 to 5 generations of outplanting in the wild.

Note that natural-origin coho adult returns to spawning areas above Willamette Falls confirm these results. After decades of outplanting hatchery-origin coho from multiple hatcheries including Oregon coastal hatcheries, releases above Willamette Falls were terminated in 1998. Now, 3-4 coho generations after hatchery-origin releases were terminated, adult coho returns to Willamette Falls numbered 25,300 in 2009 and will likely exceed 30,000 in 2010.

Campbell, N.R., C. Kamphaus, K. Murdoch, and S.R. Narum. 2017. Patterns of genomic variation in Coho salmon following reintroduction to the interior Columbia River. *Ecology and Evolution* 7:10350-10360.

Abstract: Coho salmon were extirpated in the mid-20th century from the interior reaches of the Columbia River but were reintroduced with relatively abundant source stocks from the lower Columbia River near the Pacific coast. Reintroduction of Coho salmon to the interior Columbia River (Wenatchee River) using lower river stocks placed selective pressures on the new colonizers due to substantial differences with their original habitat such as migration distance and navigation of six additional hydropower dams. We used restriction site-associated DNA sequencing (RAD-seq) to genotype 5,392 SNPs in reintroduced Coho salmon in the Wenatchee River over four generations to test for signals of temporal structure and adaptive variation. Temporal genetic structure among the three broodlines of reintroduced fish was evident among the initial return years (2000, 2001, and 2002) and their descendants, which indicated levels of reproductive isolation among broodlines. Signals of adaptive variation were detected from multiple outlier tests and identified candidate genes for further study. This study illustrated that genetic variation and structure of reintroduced populations are likely to reflect source stocks for multiple generations but may shift over time once established in nature.

Carmona-Catot, G, P.B. Moyle, and R.E. Simmons. 2012. Long-term captive breeding does not necessarily prevent reestablishment: lessons learned from Eagle Lake rainbow trout. *Reviews in Fish Biology and Fisheries*, 2012, Volume 22, Number 1, Pages 325-342.

Abstract: Captive breeding of animals is often cited as an important tool in conservation, especially for fishes, but there are few reports of long-term (<50 years) success of captive breeding programs, even in salmonid fishes. Here we describe the captive breeding program for Eagle Lake rainbow trout, *Oncorhynchus mykiss aquilarum*, which is endemic to the Eagle Lake watershed of northeastern California. The population in Eagle Lake has been dependent on captive breeding for more than 60 years and supports a trophy fishery in the lake. Nevertheless, the basic life history, ecological, and genetic traits of the subspecies still seem to be mostly intact. Although management has apparently minimized negative effects of hatchery rearing, reestablishing a wild population would ensure maintenance of its distinctive life history and its value for future use as a hatchery fish. An important factor that makes reestablishment possible is that the habitat in Eagle Lake is still intact and that Pine Creek, its major spawning stream, is recovering as habitat. With the exception of an abundant alien brook trout (*Salvelinus fontinalis*) population in Pine Creek, the habitat factors that led to the presumed near-extinction of Eagle Lake rainbow trout in the early twentieth century have been ameliorated, although the final stages of reestablishment (eradication of brook trout, unequivocal demonstration of successful spawning migration) have still not been completed. The

Eagle Lake rainbow trout story shows that long-term captive breeding of migratory salmonid fishes does not necessarily prevent reestablishment of wild populations, provided effort is made to counter the effects of hatchery selection and that natural habitats are restored for reintroduction. Long-term success, however, ultimately depends upon eliminating hatchery influences on wild-spawning populations. Extinction of Eagle Lake rainbow trout as a wild species becomes increasingly likely if we fail to act boldly to protect it and the Eagle Lake watershed.

Conover, D. O., S. B. Munch, and S. A. Arnott. 2009. Reversal of evolutionary downsizing caused by selective harvest of large fish. *Proceedings of the Royal Society B*. doi:10.1098/rspb.2009.0003.

Synopsis: Evolutionary responses to the long-term exploitation of individuals from a population may include reduced growth rate, age at maturation, body size and productivity. Theoretical models suggest that these genetic changes may be slow or impossible to reverse but rigorous empirical evidence is lacking. Here, we provide the first empirical demonstration of a genetically based reversal of fishing-induced evolution. We subjected six populations of silverside fish (*Menidia menidia*) to three forms of size-selective fishing for five generations, thereby generating twofold differences among populations in mean weight and yield (biomass) at harvest. This was followed by an additional five generations during which size-selective harvest was halted. We found that evolutionary changes were reversible. Populations evolving smaller body size when subjected to size-selective fishing displayed a slow but significant increase in size when fishing ceased. Neither phenotypic variance in size nor juvenile survival was reduced by the initial period of selective fishing, suggesting that sufficient genetic variation remained to allow recovery. These results show that populations have an intrinsic capacity to recover genetically from harmful evolutionary changes caused by fishing, even without extrinsic factors that reverse the selection gradient.

Doyle, R.M., R. Perez-Enriquez, M. Takagi, and N. Taniguchi. 2001. Selective recovery of founder genetic diversity in aquacultural broodstocks and captive, endangered fish populations. *Genetica* 111:291-304.

Abstract: Hatchery broodstocks used for genetic conservation or aquaculture may represent their ancestral gene pools rather poorly. This is especially likely when the fish that found a broodstock are close relatives of each other. We re-analysed microsatellite data from a breeding experiment on red sea bream to demonstrate how lost genetic variation might be recovered when gene frequencies have been distorted by consanguineous founders in a hatchery. A minimal-kinship criterion based on a relatedness estimator was used to select subsets of breeders which represented the maximum number of founder lineages (i.e., carried the fewest identical copies of ancestral genes). UPGMA clustering of Nei's genetic distances grouped these selected subsets with the parental gene pool, rather than with the entire, highly drifted offspring generation. The selected subsets also captured much of the expected heterozygosity and allelic diversity of the parental gene pool. Independent pedigree data on the same fish showed that the selected subsets had more contributing parents and more founder equivalents than random subsets of the same size. The estimated mean coancestry was lower in the selected subsets, meaning that inbreeding in subsequent generations would be lower if they were used as breeders. The procedure appears suitable for reducing the genetic distortion due to consanguineous and over-represented founders of a hatchery gene pool.

Evans, M., J.J. Hard, A. Black, N.M. Sard, and K.G. O'Malley. 2019. A quantitative genetic analysis of life-history traits and lifetime reproductive success in reintroduced Chinook salmon. *Conservation Genetics* <https://doi.org/10.1007/s10592-019-01174-4>.

Abstract: Reintroductions are widely implemented as a means of reestablishing wild populations and genetic parentage methods can be used in concert with these efforts to monitor and evaluate efficacy. In addition to understanding demographic outcomes, reconstructed pedigrees, when combined with phenotypic data, can provide insight into the adaptive potential of reintroduced individuals. Here, we examined the heritability and evolvability of life-history traits and lifetime reproductive success in two threatened Chinook salmon populations undergoing reintroduction to historical habitats above dams in Oregon, USA, using previously-developed multigenerational genetic pedigrees. All of the examined life-history traits: length-at-maturity, age-at-maturity, and arrival timing to the spawning grounds, and lifetime reproductive success exhibited significant narrow-sense heritabilities and evolvabilities. There was also a detectable influence of parental effects (i.e., paternal or maternal effects) on life-history trait variation, suggesting that in addition to genetic effects, nongenetic inheritance mechanisms are influencing life-history diversity in the populations. Additionally, our analyses revealed evidence of natural selection on the date of reintroduction, although the form and intensity of selection differed between the two populations; the forms of selection also point to the potential for phenotype-environment mismatch under some conditions. Overall, our results suggest that these threatened Chinook salmon populations exhibit significant adaptive potential, a factor that should be important to the longer-term success of recovery efforts.

Fraser, D. J. 2008. How well can captive breeding programs conserve biodiversity? A review of salmonids. *Evolutionary Applications*, 1:535-586.

Galbreath, P.F., M.A. Bisbee Jr., D.W. Dompier, C.M. Kamphaus, and T.H. Newsome. 2014. Extirpation and Tribal Reintroduction of Coho Salmon to the Interior Columbia River Basin. *Fisheries*, 39:77-87.

Abstract: Harvest of anadromous salmonids in the Columbia River basin has been fundamental to the nutrition, economy, and cultural and religious beliefs of the regional Native American tribes. Agricultural development, dam construction, urbanization, and overharvest following colonization by European-origin settlers, however, resulted in dramatic reductions in salmon runs and negative impacts to the well-being of tribal peoples. Federal and state fishery agencies attempted to mitigate for the loss and to rebuild some salmonid populations but deemed Coho Salmon of lesser importance for upriver fisheries and allowed them to go functionally extinct. In the mid-1990s, fishery agencies of the Columbia River Treaty tribes spearheaded efforts to reestablish the extirpated Coho Salmon, beginning in the Yakima, Wenatchee, Methow, and Clearwater rivers. The programs were initiated with juveniles from composite lower Columbia River hatchery stocks, acclimated or direct released near potential spawning habitat, then were transitioned to producing juveniles with broodstock collected in-basin. Increasing numbers of fish are now returning to these rivers, a portion of which is the product of natural spawning. Results suggest that the Coho Salmon are adapting to their new environments and founding local naturalized populations.

Tymchuk, W. E., C. Biagi, R. Withler, and R. H. Devlin. 2006. Growth and behavioral

consequences of introgression of a domesticated aquaculture genotype into a native strain of coho salmon. *Transactions of the American Fisheries Society* 135:442-455.

Abstract: Selective breeding for enhanced growth in Pacific salmon *Oncorhynchus* spp. and other fish typically involves use of the largest mature individuals to breed for future generations of aquaculture broodstock. Owing to an altered selection regime, faster-growing fish may not be as adapted to the natural environment as wild fish. To increase understanding of the genetic changes underlying selection for enhanced growth that results in phenotypic differentiation of farmed from wild Pacific salmon, multiple generations of pure and hybrid families were generated for coho salmon *O. kisutch*, including pure farm (D), pure native (Ch; a natural strain propagated by wild and hatchery production), F₁ and F₂ hybrids, and F₁ × wild backcross (B_{Ch}) genotypes. The family groups were reared in the laboratory under controlled conditions as (1) individual genotypic groups, (2) mixed groups under culture conditions, and (3) mixed groups under enriched (seminatural) conditions. The growth of the fish was tracked until smoltification. There was a significant genotype effect on growth performance (mass and length), with rankings as follows: D > F₂ > F₁ > B_{Ch} > Ch. This ranking remained the same in all three rearing environments. Behavioral differences were observed among the families, the fast-growing domesticated families showing a reduced antipredator response relative to the slow-growing wild families. Expression of the phenotypic differences in the hybrids and backcrosses, together with the results from a joint-scale analysis on line means, suggests that additive genetic effects contribute significantly to the divergence between the fast- and slow-growing strains. As phenotypic differences between strains are largely a consequence of additive gene action, the phenotypic effects of domestication are largely diluted within two generations of backcrossing to wild salmon. Knowledge of the genetic changes responsible for altered growth rates is crucial to our ability to predict the consequences of introgression of domestic strains into wild populations of salmon.

Kitada, S., H. Kishino, and K. Hamasaki. 2011. Bias and significance of relative reproductive success estimates based on steelhead trout (*Oncorhynchus mykiss*) data: a Bayesian meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 68:1827-1835.

Abstract: The evaluation of the reproductive success (RS) of hatchery fish in the wild is one of the most important issues in hatchery supplementation, aquaculture, and conservation. Estimates of the relative reproductive success (RRS) have been used to evaluate RS. Because RRS may vary greatly depending on cross, years of release, and environmental conditions, we introduced a log-normal distribution to quantify the variation. The classical estimator of RRS based on multiple measurements is contrasted with the mean of this distribution. We derived the mean, variance, and relative bias and applied our Bayesian hierarchical model to 42 empirical RRS estimates of steelhead trout (*Oncorhynchus mykiss*) in the Hood River, Oregon, USA. The RRS estimate generally had an upward bias. Although the average level of RRS implied the reproductive decline of hatchery fish and wild-born hatchery descendants, we could not reject the null hypothesis that hatchery fish and their descendants have the same chance of having smaller RS than wild fish as they do of having larger RS than wild fish.

Neville, H.M. and L. Bernatchez. 2013. Coding Gene Single Nucleotide Polymorphism Population Genetics of Nonnative Brook Trout: The Ghost of Introductions Past. *Transactions of the American Fisheries Society*, 142: 1215-1231.

Abstract: Fish have been translocated throughout the world, and introductions often have been executed repeatedly and have used mixtures of different strains from the native range. This history might have contributed to their invasive potential by allowing introduced and invading populations to circumvent expected reductions in genetic diversity from founder effects in a scenario termed the “genetic paradox” of invasions. We characterize patterns of genetic diversity in nonnative Brook Trout *Salvelinus fontinalis*, which have been introduced across the western United States for over a century but have also invaded broadly and pose a primary threat to native trout. We analyzed 155 coding gene single nucleotide polymorphisms (SNPs) in 34 nonnative Brook Trout populations sampled across eight large river systems as well as samples from the only four hatchery strains with documented use in Idaho. We uncovered similar within-population genetic diversity and large effective population sizes in naturalized populations compared with hatchery samples. Naturalized populations also showed substantial genetic structuring (maximum pairwise $F_{ST} = 0.23$) across and even within watersheds and indicated suggestions of admixture in certain regions. Assignment probabilities confirmed two main hatcheries as the origin of most fish collected in the field; however, the four hatcheries were excluded as being the origin for 8% of individuals, mirroring results from clustering analyses and suggesting the influence of an additional unsampled hatchery source or sources. Simulated admixtures of hatchery samples produced genetic patterns similar to those observed in field samples, further supporting an influence of multiple historic hatchery stocks on the contemporary genetic structure of Brook Trout in Idaho. Our study highlights the potential contribution of historic hatchery and introduction practices in creating genetically variable and structured naturalized Brook Trout populations across Idaho, which may have allowed these fish to defy the “genetic paradox” early on in their nonnative history and set the stage for successful establishment and subsequent invasion.

Are hatchery effects genetically based? Could deleterious effects attributed to hatchery programs be due to environmental or other factors?

Abadia-Cardoso, A., E. C. Anderson, D. E. Pearse, and J. Carlos-Garza. 2013. Large-scale parentage analysis reveals reproductive patterns and heritability of spawn timing in a hatchery population of steelhead (*Oncorhynchus mykiss*). *Molecular Ecology* 22:4733-4746. [doi: 10.1111/mec.12426](https://doi.org/10.1111/mec.12426).

Abstract: Understanding life history traits is an important first step in formulating effective conservation and management strategies. The use of artificial propagation and supplementation as such a strategy can have numerous effects on the supplemented natural populations and minimizing life history divergence is crucial in minimizing these effects. Here, we use single nucleotide polymorphism (SNP) genotypes for large-scale parentage analysis and pedigree reconstruction in a hatchery population of steelhead the anadromous form of rainbow trout. Nearly complete sampling of the broodstock for several consecutive years in two hatchery programmes allowed inference about multiple aspects of life history. Reconstruction of cohort age distribution revealed a strong component of fish that spawn at 2 years of age, in contrast to programme goals and distinct from naturally spawning steelhead in the region, which raises a significant conservation concern. The first estimates of variance in family size for steelhead in

this region can be used to calculate effective population size and probabilities of inbreeding, and estimation of iteroparity rate indicates that it is reduced by hatchery production. Finally, correlations between family members in the day of spawning revealed for the first time a strongly heritable component to this important life history trait in steelhead and demonstrated the potential for selection to alter life history traits rapidly in response to changes in environmental conditions. Taken together, these results demonstrate the extraordinary promise of SNP-based pedigree reconstruction for providing biological inference in high-fecundity organisms that is not easily achievable with traditional physical tags.

Baudron, A.R., C.L. Needle, A.D. Rijnsdorp, C.T. Marshall. 2014. Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. *Global Change Biology*. doi: [10.1111/gcb.12514](https://doi.org/10.1111/gcb.12514).

Abstract: Decreasing body size has been proposed as a universal response to increasing temperatures. The physiology behind the response is well established for ectotherms inhabiting aquatic environments: as higher temperatures decrease the aerobic capacity, individuals with smaller body sizes have a reduced risk of oxygen deprivation. However, empirical evidence of this response at the scale of communities and ecosystems is lacking for marine fish species. Here, we show that over a 40-year period six of eight commercial fish species in the North Sea examined underwent concomitant reductions in asymptotic body size with the synchronous component of the total variability coinciding with a 1–2 °C increase in water temperature. Smaller body sizes decreased the yield-per-recruit of these stocks by an average of 23%. Although it is not possible to ascribe these phenotypic changes unequivocally to temperature, four aspects support this interpretation: (i) the synchronous trend was detected across species varying in their life history and life style; (ii) the decrease coincided with the period of increasing temperature; (iii) the direction of the phenotypic change is consistent with physiological knowledge; and (iv) no cross-species synchrony was detected in other species-specific factors potentially impacting growth. Our findings support a recent model-derived prediction that fish size will shrink in response to climate-induced changes in temperature and oxygen. The smaller body sizes being projected for the future are already detectable in the North Sea.

Beacham, T. D. 2010. Revisiting Trends in the Evolution of Egg Size in Hatchery-Enhanced Populations of Chinook Salmon from British Columbia. *Transactions of the American Fisheries Society*, 139: 579-585.

Synopsis: Hatchery enhancement has been reported to result in an increase in egg size in coho salmon *Oncorhynchus kisutch* and a decline in egg size in Chinook salmon *O. tshawytscha*. Egg size may be directly influenced by selection, a larger egg size evolving as a consequence of hatchery incubation. Alternatively, a smaller egg size could evolve as a correlated response to fecundity selection, and a unidirectional change in egg size over time may reflect selection and an underlying genetic change in the population. To address this question, temporal trends in egg size were investigated for two hatchery-enhanced populations of Chinook salmon from Vancouver Island, British Columbia. After the effect of female length variation was removed by standardizing egg sizes to a female of common length (the overall mean for each population), there was no temporal trend in egg size from the 1970s to 2008 for any of the hatchery-enhanced populations evaluated. These

results do not support a previous report of genetically based declines in egg size in hatchery-enhanced Chinook salmon populations from this region.

Bellinger, K. B., G. H. Thorgaard, and P. A. Carter. 2014. Domestication is associated with reduced burst swimming performance and increased body size in clonal rainbow trout lines. *Aquaculture* 420–421 (2014) 154–159.

Abstract: Domestication selection combined with inadvertent selection for high growth rate and large body size are common in hatchery salmonids. However, evolutionary trade-offs of various fitness components with body size and domestication are likely. This study explores potential trade-offs between growth and sprint swim performance among five clonal lines of rainbow trout (*Oncorhynchus mykiss*), varying in the number of generations under domestication. We hypothesized that clonal lines of trout derived from highly domesticated populations would have higher growth rates but slower sprint swimming performance relative to clonal lines derived from less domesticated populations. Individuals from each of the five lines were repeatedly measured for body size and sprint swimming performance over 10–15 weeks. Our findings indicate significant differences in body size and sprint swimming performances between the less-domesticated and the more-domesticated lines, with more domesticated lines being larger but poorer swimmers. Implications for the survival and reproduction of hatchery salmonids released into the wild are explored.

Breckenridge, J.K., S.M. Bollens, G. Rollwagen-Bollens, and G.C. Roegner. 2014. Plankton Assemblage Variability in a River-Dominated Temperate Estuary During Late Spring (High-flow) and Late Summer (Low-flow) Periods. *Estuaries and Coasts*, May 2014, doi:DOI 10.1007/s12237-014-9820-7.

Abstract: Seasonally variable freshwater flows are known to influence estuarine plankton assemblages. There has been little recent study of the plankton dynamics of the Columbia River Estuary (CRE), a large, river-dominated estuary that has experienced great modification to its hydrological cycle. Zooplankton (>75 µm) were collected during four late spring (high-flow) cruises and three late summer (low-flow) cruises in 2005 and 2006. Surface-water microplankton (5–200 µm) were collected during cruises in 2005. Zooplankton and phytoplankton assemblage composition varied along an axial salinity gradient and between flow periods. Estuarine zooplankton were strongly seasonal and dominated by the calanoid copepod *Eurytemora affinis* in the late spring, high-flow period and by the invasive calanoid *Pseudodiaptomus forbesi* in the late summer, low-flow period. The phytoplankton assemblage was dominated by freshwater diatoms, primarily *Aulacoseira* spp. The ciliate *Mesodinium rubrum* (= *Myrionecta rubra*) reached high densities during the low-flow period, but otherwise, distinct high-flow and low-flow phytoplankton assemblages were not detected. Comparison to prior studies in the CRE suggests that the plankton assemblage composition during the low-flow period has undergone considerable change, which may in turn have important trophic implications.

Brodeur, R. D., M. E. Hunsicker, A. Hann, and T. W. Miller. 2018. Effects of warming ocean conditions on feeding ecology of small pelagic fishes in a coastal upwelling ecosystem: a shift to gelatinous food sources. *Marine Ecology Progress Series*: <https://doi.org/10.3354/meps12497>.

Abstract: Forage fish play a central role in the transfer of energy from lower to higher trophic levels. Ocean conditions may influence this energy pathway in the Northern California Current (NCC) ecosystem, and we may expect it to differ between warm and cold periods in the northeast Pacific Ocean. The recent unprecedented warming in the NCC provides a unique opportunity to better understand the connection between ocean conditions and forage fish feeding habits and the potential consequences for predators that depend on them for sustenance. Here we present findings from gut content analysis to examine food sources of multiple forage fishes (northern anchovy *Engraulis mordax*, Pacific sardine *Sardinops sagax*, jack mackerel *Trachurus symmetricus*, Pacific herring *Clupea pallasii*, surf smelt *Hypomesus pretiosus*, and whitebait smelt *Allosmerus elongatus*) off the Washington and Oregon coasts. Analyses were applied to fish collected in May and June during recent warm years (2015 and 2016) and compared to previous collections made during cool (2011, 2012) and average (2000, 2002) years. Results of the diet analysis indicate that fish feeding habits varied significantly between cold and both average and warm periods. Euphausiids, decapods, and copepods were the main prey items of the forage fishes for most years examined; however, gelatinous zooplankton were consumed in much higher quantities in warm years compared to cold years. This shift in prey availability was also seen in plankton and trawl surveys in recent years and suggests that changing ocean conditions are likely to affect the type and quality of prey available to forage fish. Although gelatinous zooplankton are generally not believed to be suitable prey for most fishes due to their low energy content, some forage fishes may utilize this prey in the absence of more preferred prey resources during anomalously warm ocean conditions.

Buckland-Nicks, J.A., M. Gillis, and T.E. Reimchen. 2011. Neural network detected in a presumed vestigial trait: ultrastructure of the salmonid adipose fin. *Proceedings of the Royal Society, Series B Biology* : [rspb.2011.1009v1-rspb20111009](https://doi.org/10.1098/rspb.2011.1009).

Synopsis: If the adipose fin is in fact functioning as a precaudal flow sensor, allowing optimal maneuverability in turbulent water, ... then it is logical that swimming in non-turbulent waters would be largely unaffected by removal of the adipose fin. This hypothesis could explain why previous studies found that clipping of the adipose fin had no effect on stamina, susceptibility to predation or growth, as these studies were conducted in non-turbulent water. Other research, however, did find that growth was significantly affected by adipose fin clipping when fish were swimming in turbulent water. There are also suggestions that the adipose fin has a potential role during courtship as males have a larger fin than females and the latter appear to prefer males with a relatively larger adipose fin. Past research has proposed that both these factors may reflect a selective landscape in streams where males are subject to greater swimming demands than that of females. The occurrence of a larger adipose fin in males may relate to hydrodynamic functionality owing to the greater complexity and density of the nerve net in a larger fin.

Chen, W. and J.D. Olden. 2017. Designing flows to resolve human and environmental water needs in a dam-regulated river. *Nature Communications* 8, article 2158, [doi:10.1038/s41467-017-02226-4](https://doi.org/10.1038/s41467-017-02226-4).

Abstract: Navigating trade-offs between meeting societal water needs and supporting functioning ecosystems is integral to river management policy. Emerging frameworks provide the opportunity to

consider multiple river uses explicitly, but balancing multiple priorities remains challenging. Here we quantify relationships between hydrologic regimes and the abundance of multiple native and nonnative fish species over 18 years in a large, dryland river basin in southwestern United States. These models were incorporated into a multi-objective optimization framework to design dam operation releases that balance human water needs with the dual conservation targets of benefiting native fishes while disadvantaging nonnative fishes. Predicted designer flow prescriptions indicate significant opportunities to favor native over nonnative fishes while rarely, if ever, encroaching on human water needs. The predicted benefits surpass those generated by natural flow mimicry, and were retained across periods of heightened drought. We provide a quantitative illustration of theoretical predictions that designer flows can offer multiple ecological and societal benefits in human-altered rivers.

Chittenden, C.M., C.A. Biagi, J.G. Davidsen, H. Kondo, A. McKnight, O.P. Pedersen, P.A. Raven, A.H. Rikardsen, J.M. Shrimpton, B. Zuehlke, R.S. McKinley, and R.H. Devlin. 2010. Genetic versus rearing-environment effects on phenotype: hatchery and natural rearing effects on hatchery- and wild-born coho salmon. [PLoS One](#). 2010 Aug 19;5(8):e12261.

Abstract: With the current trends in climate and fisheries, well-designed mitigative strategies for conserving fish stocks may become increasingly necessary. The poor post-release survival of hatchery-reared Pacific salmon indicates that salmon enhancement programs require assessment. The objective of this study was to determine the relative roles that genotype and rearing environment play in the phenotypic expression of young salmon, including their survival, growth, physiology, swimming endurance, predator avoidance and migratory behaviour. Wild- and hatchery-born coho salmon adults (*Oncorhynchus kisutch*) returning to the Chehalis River in British Columbia, Canada, were crossed to create pure hatchery, pure wild, and hybrid offspring. A proportion of the progeny from each cross was reared in a traditional hatchery environment, whereas the remaining fry were reared naturally in a contained side channel. The resulting phenotypic differences between replicates, between rearing environments, and between cross types were compared. While there were few phenotypic differences noted between genetic groups reared in the same habitat, rearing environment played a significant role in smolt size, survival, swimming endurance, predator avoidance and migratory behaviour. The lack of any observed genetic differences between wild- and hatchery-born salmon may be due to the long-term mixing of these genotypes from hatchery introgression into wild populations, or conversely, due to strong selection in nature--capable of maintaining highly fit genotypes whether or not fish have experienced part of their life history under cultured conditions.

Copeland, T., D.A. Venditti, and B.R. Barnett. 2014. The Importance of Juvenile Migration Tactics to Adult Recruitment in Stream-Type Chinook Salmon Populations. *Transactions of the American Fisheries Society* 143:1460-1475.

Abstract: The existence of multiple migration tactics within a population has been observed for several fish species, and they may contribute differentially to adult recruitment. Relative contribution by juveniles using the same habitats on different schedules is variable; therefore, understanding and conserving this diversity should be important to fisheries managers. We investigated adult recruitment by two distinct juvenile migration tactics in several spawning populations of stream-type Chinook Salmon *Oncorhynchus tshawytscha* in Idaho: those leaving the spawning grounds as

subyearlings during June through November (downstream rearing, or DSR, type) and those emigrating from natal areas 1 year after emergence (natal reach rearing, or NRR, type). The DSR type had greater juvenile abundance in all populations, although the NRR type exhibited better survival from the natal reach to the migratory corridor. The DSR type had greater survival from smoltification to adult return to freshwater compared with the NRR type. More DSR emigrants than NRR emigrants returned to freshwater as adults, although the difference was influenced by cohort and population. Adult recruits to stream-type Chinook Salmon populations in Idaho are comprised mostly of DSR emigrants, i.e., fish that dispersed from their natal habitats and reared in reaches downstream. This finding is ubiquitous, although the size of the effect depends on cohort and population. We demonstrated that juvenile Chinook Salmon in Idaho do indeed use downstream rearing habitats effectively, thereby increasing recruitment of adults back to the spawning gravels in these populations. This study illustrates how dispersive life histories are essential to achieve the full productive potential of migratory stream fish populations.

Courter, I.I., G.J. Wyatt, R.W. Perry, J.M. Plumb, F.M. Carpenter, N.K. Ackerman, R.B. Lessard, and P.F. Galbreath. 2019. A Natural-Origin Steelhead Population's Response to Exclusion of Hatchery Fish. *Transactions of the American Fisheries Society* 148:339-351.

Abstract: It is asserted that reduction or elimination of hatchery stocking will increase natural-origin salmon *Oncorhynchus* spp. and steelhead *O. mykiss* production. We conducted an analysis of steelhead population census data (1958–2017) to determine whether elimination of summer steelhead stocking in the upper Clackamas River in 1998 increased the productivity of natural-origin winter steelhead. A Bayesian state–space stock–recruitment model was fitted to the adult steelhead data set, and productivity was estimated as a function of hatchery-origin spawner abundance as well as other environmental factors. When used as a predictive variable in our model, the abundance of hatchery summer steelhead spawners (1972–2001) did not have a negative effect on winter steelhead recruitment. However, spill at North Fork Dam (the gateway to the upper Clackamas River basin) and the Pacific Decadal Oscillation (an index of ocean conditions) were both negatively associated with winter steelhead recruitment. Moreover, winter steelhead abundance in the upper Clackamas River basin failed to rebound to abundances observed in years prior to the hatchery program, and fluctuations in winter steelhead abundance were correlated with those of other regional winter steelhead stocks. Our assessment underscores the need for studies that (1) directly quantify the effects of hatchery fish on the production of natural-origin salmon and steelhead, (2) empirically test published theories about mechanisms of hatchery fish impacts on natural-origin populations, and (3) document population responses to major changes in hatchery programs.

Feist, B.E., E.R. Buhle, D.H. Baldwin, J.A. Spromberg, S.E. Damm, J.W. Davis, and N.L. Scholz. 2017. Roads to ruin: conservation threats to a sentinel species across an urban gradient. *Ecological Applications* doi:10.1002/eap.1615.

Abstract: Urbanization poses a global challenge to species conservation. This is primarily understood in terms of physical habitat loss, as agricultural and forested lands are replaced with urban infrastructure. However, aquatic habitats are also chemically degraded by urban development, often in the form of toxic stormwater runoff. Here we assess threats of urbanization to coho salmon throughout developed areas of the Puget Sound Basin in Washington, USA. Puget Sound coho are a

sentinel species for freshwater communities and also a species of concern under the U.S. Endangered Species Act. Previous studies have demonstrated that stormwater runoff is unusually lethal to adult coho that return to spawn each year in urban watersheds. To further explore the relationship between land use and recurrent coho die-offs, we measured mortality rates in field surveys of 51 spawning sites across an urban gradient. We then used spatial analyses to measure landscape attributes (land use and land cover, human population density, roadways, traffic intensity, etc.) and climatic variables (annual summer and fall precipitation) associated with each site. Structural equation modeling revealed a latent urbanization gradient that was associated with road density and traffic intensity, among other variables, and positively related to coho mortality. Across years within sites, mortality increased with summer and fall precipitation, but the effect of rainfall was strongest in the least developed areas and was essentially neutral in the most urbanized streams. We used the best-supported structural equation model to generate a predictive mortality risk map for the entire Puget Sound Basin. This map indicates an ongoing and widespread loss of spawners across much of the Puget Sound population segment, particularly within the major regional north-south corridor for transportation and development. Our findings identify current and future urbanization-related threats to wild coho, and show where green infrastructure and similar clean water strategies could prove most useful for promoting species conservation and recovery.

Fisk III, J.M., T.J. Kwak, and R.J. Heise. 2015. Effects of Regulated River Flows on Habitat Suitability for the Robust Redhorse. *Transactions of the American Fisheries Society* 144:792-806.

Abstract: The Robust Redhorse *Moxostoma robustum* is a rare and imperiled fish, with wild populations occurring in three drainages from North Carolina to Georgia. Hydroelectric dams have altered the species' habitat and restricted its range. An augmented minimum-flow regime that will affect Robust Redhorse habitat was recently prescribed for Blewett Falls Dam, a hydroelectric facility on the Pee Dee River, North Carolina. Our objective was to quantify suitable spawning and nonspawning habitat under current and proposed minimum-flow regimes. We implanted radio transmitters into 27 adult Robust Redhorses and relocated the fish from spring 2008 to summer 2009, and we described habitat at 15 spawning capture locations. Nonspawning habitat consisted of deep, slow-moving pools (mean depth = 2.3 m; mean velocity = 0.23 m/s), bedrock and sand substrates, and boulders or coarse woody debris as cover. Spawning habitat was characterized as shallower, faster-moving water (mean depth = 0.84 m; mean velocity = 0.61 m/s) with gravel and cobble as substrates and boulders as cover associated with shoals. Telemetry relocations revealed two behavioral subgroups: a resident subgroup (linear range [mean \pm SE] = 7.9 \pm 3.7 river kilometers [rkm]) that remained near spawning areas in the Piedmont region throughout the year; and a migratory subgroup (linear range = 64.3 \pm 8.4 rkm) that migrated extensively downstream into the Coastal Plain region. Spawning and nonspawning habitat suitability indices were developed based on field microhabitat measurements and were applied to model suitable available habitat (weighted usable area) for current and proposed augmented minimum flows. Suitable habitat (both spawning and nonspawning) increased for each proposed seasonal minimum flow relative to former minimum flows, with substantial increases for spawning sites. Our results contribute to an understanding of how regulated flows affect available habitats for imperiled species. Flow managers can use these findings to regulate discharge more effectively and to create and maintain important habitats during critical periods for priority species.

Gow, J.L., P. Tamkee, J. Heggenes, G.A. Wilson, and E.B. Taylor. 2011. Little impact of hatchery supplementation that uses native broodstock on the genetic structure and diversity of steelhead trout revealed by a large-scale spatio-temporal microsatellite survey. *Evolutionary Applications*, Volume 4, Issue 6, pages 763-782.

Abstract: Artificial breeding programs initiated to enhance the size of animal populations are often motivated by the desire to increase harvest opportunities. The introduction of non-native genotypes, however, can have negative evolutionary impacts. These may be direct, such as introgressive hybridization, or indirect via competition. Less is known about the effects of stocking with native genotypes. We assayed variation at nine microsatellite loci in 902 steelhead trout (*Oncorhynchus mykiss*) from five rivers in British Columbia, Canada. These samples were collected over 58 years, a time period that spanned the initiation of native steelhead trout broodstock hatchery supplementation in these rivers. We detected no changes in estimates of effective population size, genetic variation or temporal genetic structure within any population, nor of altered genetic structure among them. Genetic interactions with nonmigratory *O. mykiss*, the use of substantial numbers of primarily native broodstock with an approximate 1:1 male-to-female ratio, and/or poor survival and reproductive success of hatchery fish may have minimized potential genetic changes. Although no genetic changes were detected, ecological effects of hatchery programs still may influence wild population productivity and abundance. Their effects await the design and implementation of a more comprehensive evaluation program.

Harnish, R.A., R. Sharma, G.A. McMichael, R.B. Langshaw, and T.N. Pearsons. 2014. Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population. *Canadian Journal of Fisheries and Aquatic Sciences*, 71:602-615.

Abstract: Altering the timing and magnitude of discharge fluctuations can minimize the adverse effects of operating hydroelectric dams on the productivity of downstream salmon populations. Hydroelectric operations at Priest Rapids Dam during the mid-1970s resulted in dewatering of fall Chinook salmon (*Oncorhynchus tshawytscha*) redds, causing mortality of intragravel life stages. Since then, a series of operational constraints have been implemented at Priest Rapids Dam to reduce the effects of discharge fluctuations on the population of fall Chinook salmon that spawns and rears downstream from the dam. Initial protections that focused on preventing redd dewatering were subsequently increased to include postemergence life stages. We used stock–recruit analyses to identify changes to the population’s freshwater productivity that occurred over a 30-year period and coincided with changes to dam operations. We observed a 217% increase in productivity that corresponded with constraints enacted to prevent redd dewatering and an additional 130% increase that coincided with enactment of constraints to limit stranding and entrapment of juveniles. The information gained from this study may be used to guide efforts elsewhere to mitigate the effects of hydroelectric dam operations on downstream fish populations.

Haskell, C.A., K.F. Tiffan, and D.W. Rondorf. 2013. The Effects of Juvenile American Shad Planktivory on Zooplankton Production in Columbia River Food Webs. *Transactions of the American Fisheries Society*, 142: 606-620.

Abstract: Columbia River reservoirs support a large population of nonnative American Shad *Alosa sapidissima* that consume the zooplankton that native fishes also rely on. We hypothesized that the unprecedented biomass of juvenile American Shad in John Day Reservoir is capable of altering the zooplankton community if these fish consume a large portion of the zooplankton production. We derived taxon-specific estimates of zooplankton production using field data and a production model from the literature. Empirical daily ration was estimated for American Shad and expanded to population-level consumption using abundance and biomass data from hydroacoustic surveys. *Daphnia* spp. production was high in early summer but declined to near zero by September as shad abundance increased. American Shad sequentially consumed *Daphnia* spp., copepods, and *Bosmina* spp., which tracked the production trends of these taxa. American Shad evacuation rates ranged from 0.09 to 0.24/h, and daily rations ranged from 0.008 to 0.045 g·g⁻¹·d⁻¹ (dry weight) over all years. We observed peak American Shad biomass (45.2 kg/ha) in 1994, and daily consumption (1.6 kg/ha) approached 30% (5.3 kg/ha) of zooplankton production. On average, American Shad consumed 23.6% of the available zooplankton production (range, <1–83%). The changes in the zooplankton community are consistent with a top-down effect of planktivory by American Shad associated with their unprecedented biomass and consumption, but the effects are likely constrained by temperature, nutrient flux, and the seasonal production patterns of zooplankton in John Day Reservoir. American Shad add to the planktivory exerted by other species like *Neomysis mercedis* to reduce the capacity of the reservoir to support other planktivorous fishes. The introduction of American Shad and other nonnative species will continue to alter the food web in John Day Reservoir, potentially affecting native fishes, including Pacific salmon *Oncorhynchus* spp.

Haxton, T., M. Friday, T. Cano, and C. Hendry. 2015. Assessing the Magnitude of Effect of Hydroelectric Production on Lake Sturgeon Abundance in Ontario. *North American Journal of Fisheries Management* 35: 930-941.

Abstract: The presence of hydroelectric power generating facilities has been identified as the primary factor affecting the variation in relative abundance of Lake Sturgeon *Acipenser fulvescens* in rivers across Ontario. Qualitatively, these facilities are known to have impacts on the aquatic environment, and they can be inferred to have effects on Lake Sturgeon; however, few studies quantifying these effects are available. Our objectives were to (1) determine and compare the magnitude of effect (*d*) of hydroelectric facility operating regimes on Lake Sturgeon abundance; (2) compare Lake Sturgeon biological responses among river systems with different operating regimes in order to understand the potential limiting factors within these systems; and (3) assess the effectiveness of mitigation efforts where they have been employed. A standardized index netting program targeting juveniles and adults was conducted over two field seasons at 23 river sites across Ontario. The magnitude of effect on abundance (as indicated by *d*) was lowest in run-of-the-river systems and was considered large in peaking systems and winter reservoir systems. Relative abundance was significantly greater in unregulated rivers than in regulated rivers. Juvenile abundance was significantly greater in run-of-the-river systems than in peaking systems and winter reservoirs and was significantly greater in peaking systems than in winter reservoirs. Adult abundance did not significantly differ among operating regimes. Growth was faster and condition was significantly greater in unregulated systems than in regulated systems. Recruitment of Lake Sturgeon was highly variable in both regulated and unregulated systems, whereas recruitment failure was more evident in regulated systems, particularly in peaking systems.

Hinrichsen, R.A., D.J. Hasselman, C.C. Ebbesmeyer, and B.A. Shields. 2013. The Role of Impoundments, Temperature, and Discharge on Colonization of the Columbia River Basin, USA, by Nonindigenous American Shad. *Transactions of the American Fisheries Society*, 142: 887-900.

Abstract: Ecologists have become increasingly aware of the combined effects of habitat disturbance and climate change on the establishment and proliferation of invasive species. Long-term data on the population of the invasive American Shad *Alosa sapidissima* in the U.S. portion of the Columbia River basin provide an opportunity to examine how habitat disturbances affect the abundance and spatial distribution of an invasive species in a heavily modified environment. After the establishment of American Shad in the Columbia River in the late 1800s, the drainage was transformed from its natural lotic state to a series of reservoirs, with concomitant changes to discharge and temperature regimes, which are confounded by climate change. As the Columbia River was dammed, American Shad extended its range and increased in abundance. A large and rapid increase in spawning population abundance (recruits per spawner = 63) followed completion of The Dalles Dam in 1957, which inundated Celilo Falls, a natural barrier to upriver American Shad migration. Regressions revealed that the annual percentage of American Shad migrating upstream from McNary Dam varied with water temperature and discharge ($R^2 = 0.72$), but not population density. When Atlantic coast rivers were dammed, however, American Shad lost spawning habitat and declined in abundance. Understanding the rapid colonization of the Columbia River by American Shad may reveal ways to help American Shad recolonize rivers where they are native. Understanding the roles of water temperature and discharge may allow us to project effects of climate change on the future distribution and abundance of American Shad in the Columbia River basin. Our results suggest that dam construction and alterations to the temperature and discharge regimes of the Columbia River have contributed to the increase in abundance and spatial distribution of American Shad. These changes might have improved the reproductive success of American Shad by providing access to additional spawning grounds and creating suitable juvenile rearing conditions.

Hoffnagle, T.L., R.W. Carmichael, K.A. Frenyea, and P.J. Keniry. 2008. Run timing, spawn timing, and spawning distribution of hatchery- and natural-origin spring Chinook salmon in the Imnaha River, Oregon. *North American Journal of Fisheries Management* 28:148-164.

Abstract: We evaluated 16 years (1990–2005) of weir collection and spawning ground survey data to examine differences in run timing, spawn timing, and spawning distribution between naturally and hatchery-reared Chinook salmon *Oncorhynchus tshawytscha* in the Imnaha River, Oregon, and to look for changes in these variables over time. We compared run timing based on arrival time at the weir and found that naturally reared Chinook salmon arrived earlier than hatchery-reared fish in all 16 years. Carcasses of naturally reared fish of either or both sexes were recovered on the spawning grounds earlier than carcasses of hatchery-reared fish for all years combined and during 5 of 16 years, indicating earlier spawning by naturally reared fish. We compared spawning distribution using the percent of female carcasses recovered in each spawning ground survey reach. The percent recovery of the carcasses of naturally reared females was greater in reaches above the weir than below the weir and these carcasses were farther upstream than those of hatchery-reared females. For females of hatchery origin, carcasses were more commonly found in reaches closer to and below the weir (the smolt release location). Alternate management strategies designed to improve the maintenance of genetic integrity and life history characteristics of the Imnaha River Chinook salmon

population should be considered, implemented, and evaluated. Collection strategies should be modified to ensure that the hatchery broodstock is representative of the entire natural run, and release strategies should be developed to promote a spawning distribution of hatchery adults that mimics the distribution of natural Imnaha River Chinook salmon.

Hogg, R.S., S.M. Coghlan Jr., J. Zydlewski, and C. Gardner. 2015. Fish Community Response to a Small-Stream Dam Removal in a Maine Coastal River Tributary. *Transactions of the American Fisheries Society*, 144: 467-479.

Abstract: Sedgeunkedunk Stream, a third-order tributary to the Penobscot River in Maine, historically has supported several anadromous fishes including Atlantic Salmon *Salmo salar*, Alewife *Alosa pseudoharengus*, and Sea Lamprey *Petromyzon marinus*. Two small dams constructed in the 1800s reduced or eliminated spawning runs entirely. In 2009, efforts to restore marine–freshwater connectivity in the system culminated in removal of the lowermost dam (Mill Dam) providing access to 4.7 km of lotic habitat and unimpeded passage into the lentic habitat of Fields Pond. In anticipation of these barrier removals, we initiated a modified before-after-control-impact study, and monitored stream fish assemblages in fixed treatment and reference sites. Electrofishing surveys were conducted twice yearly since 2007. Results indicated that density, biomass, and diversity of the fish assemblage increased at all treatment sites upstream of the 2009 dam removal. No distinct changes in these metrics occurred at reference sites. We documented recolonization and successful reproduction of Atlantic Salmon, Alewife, and Sea Lamprey in previously inaccessible upstream reaches. These results clearly demonstrate that dam removal has enhanced the fish assemblage by providing an undisrupted stream gradient linking a small headwater lake and tributary with a large coastal river, its estuary, and the Atlantic Ocean.

Hughes, R.M., S. Dunham, K.G. Maas-Hebner, J.A. Yeakley, C. Schreck, M. Harte, N. Molina, C.C. Schock, V.W. Kaczynski, and J. Schaeffer. 2014. A review of urban water body challenges and approaches: (1) rehabilitation and remediation. *Fisheries*, 39:18-29.

Abstract: We review how urbanization alters aquatic ecosystems, as well as actions that managers can take to remediate urban waters. Urbanization affects streams by fundamentally altering longitudinal and lateral processes that in turn alter hydrology, habitat, and water chemistry; these effects create physical and chemical stressors that in turn affect the biota. Urban streams often suffer from multiple stressor effects that have collectively been termed an “urban stream syndrome,” in which no single factor dominates degraded conditions. Resource managers have multiple ways of combating the urban stream syndrome. These approaches range from whole-watershed protection to reach-scale habitat rehabilitation, but the prescription must be matched to the scale of the factors that are causing the problem, and results will likely not be immediate because of lengthy recovery times. Although pristine or reference conditions are far from attainable, urban stream rehabilitation is a worthy goal because appropriate actions can provide ecosystem improvements as well as increased ecosystem service benefits for human society.

Hughes, M.S. and A.R. Murdoch. 2017. Spawning Habitat of Hatchery Spring Chinook Salmon and Possible Mechanisms Contributing to Lower Reproductive Success. *Transactions of the American Fisheries Society*, 146: 1016-1027.

Abstract: Spawning is a critical stage in the life history of salmonids. Spawning location has been

reported to be a significant factor in the fitness differences between natural- and hatchery-origin (natural and hatchery, respectively) female spring Chinook Salmon *Oncorhynchus tshawytscha*, although the mechanisms responsible remain uncertain. The objectives of this study were to compare the spawning distributions of hatchery and natural female spring Chinook salmon within the Chiwawa River, Washington, and determine whether spawning characteristics differ between hatchery and natural female Chinook Salmon or between channel types within the Chiwawa River. Over a 10-year period, locations of female carcasses were examined to assess differences in the spawning distribution of hatchery and natural females. Additionally, a suite of metrics was measured from redds of known origin females to characterize the spawning location and redd characteristics. A greater proportion of hatchery females spawned in the lower watershed within plane-bed channels than spawned upstream. Conversely, the majority of natural females spawned farther upstream in pool-riffle channels. The distribution of hatchery fish was presumably strongly influenced by the hatchery acclimation–release location in the lower river. Given the geomorphic characteristics of plane-bed channels, salmon were unable to build redds there similar to those in more typical pool-riffle channels. Redds constructed in plane-bed channels were smaller, shallower, and closer to stream banks than redds in pool-riffle channels. Limited differences were detected in redd characteristics between natural and hatchery females in pool-riffle channels. Smaller hatchery females constructed smaller redds with lower tailspill relief than did larger natural fish. As the results of differences in spawning distribution and fish size, redds constructed by hatchery females were more susceptible to environmental sources of mortality than were redds constructed by natural females. This study provides insight into the possible mechanisms responsible for the reported lower reproductive success among hatchery females spawning in the natural environment.

Johnson, L., B. Anulacion, M. Arkoosh, O.P. Olson, C. Sloan, S.Y. Sol, J. Spromberg, D.J. Teel, G. Yanagida, and G. Ylitalo. 2013. Persistent Organic Pollutants in Juvenile Chinook Salmon in the Columbia River Basin: Implications for Stock Recovery. *Transactions of the American Fisheries Society*, 142: 21-40.

Abstract: Among the populations of Pacific salmon and steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) that inhabit the Columbia River basin there are currently 13 Evolutionarily Significant Units listed as threatened or endangered under the U.S. Endangered Species Act. While habitat loss, dams, overharvest, and climate change have been implicated in declining abundance of Chinook Salmon *O. tshawytscha* in the Columbia River, chemical contaminants represent an additional, yet poorly understood, conservation threat. In this study we measured concentrations of persistent organic pollutants in juvenile Chinook Salmon from various Columbia River stocks and life history types to evaluate the potential for adverse effects in these threatened and endangered fish. Polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDTs), recognized contaminants of concern in the Columbia basin, are the primary focus of this paper; other contaminants found in these fish, such as polybrominated diphenyl ethers and polycyclic aromatic hydrocarbons, are described in other publications. We frequently detected PCBs and DDTs in juvenile salmon and salmon diet samples from the lower Columbia River and estuary. In some cases, concentrations in salmon were above estimated thresholds for effects on growth and survival. The tidal freshwater portion of the estuary, between Portland, Oregon, and Longview, Washington, appeared to be an important source of contaminants for juvenile salmon and a region in which salmon were exposed to toxicants associated with urban development and industrial activity. Highest concentrations of PCBs were found in fall Chinook

Salmon stocks with subyearling life histories, including populations from the upper Columbia and Snake rivers, which feed and rear in the tidal freshwater and estuarine portions of the river for extended periods. Spring Chinook Salmon stocks with yearling life histories that migrate more rapidly through the estuary generally had low PCB concentrations, but high concentrations of DDTs. Lipid content was low (<1%) in many of the fish examined, contributing to high lipid-adjusted contaminants concentrations in some samples.

Jones, M.H., J.E. Seeb, K.I. Warheit, T.R. Seamons, T.P. Quinn, and L.W. Seeb. 2015. Consequences of Emergence Timing for the Growth and Relative Survival of Steelhead Fry from Naturally Spawning Wild and Hatchery Parents. *Transactions of the American Fisheries Society*, 144: 977-989.

Abstract: For many fishes, reproducing early in the year may present tradeoffs for the offspring: the drawbacks associated with harsh environmental conditions may be offset by advantages in competition for food and space. We investigated this tradeoff in a system where hatchery-origin steelhead *Oncorhynchus mykiss* were bred to spawn about 4 months earlier than wild-origin fish. Hatchery-origin adults were released into the wild and spawned in common with wild steelhead. Naturally spawned offspring from these matings were assigned to hatchery, wild, and hybrid lineages by using a panel of 96 single-nucleotide polymorphisms. We then evaluated whether fry abundance, body size and condition, and geographic distribution differed based on parental lineage. The observed mixture proportions were 0.007 hatchery-lineage, 0.289 hybrid, and 0.704 wild-lineage juveniles, despite the predominance of hatchery-origin parents. There were significant differences in FL (hatchery > hybrid > wild) but no difference in body condition. We modeled the emergence dates of the sampled fry and estimated that 96.0% of wild-lineage fish emerged after the arrival of temperate spring conditions (reduced flows and warmer temperatures) compared with 80.4% of hybrids and 41.2% of hatchery-lineage fish. We hypothesize that the low abundance of pure hatchery-lineage fry may be due to a mismatch between the timing of breeding by the parents and suitable river conditions, resulting in low survival and physical displacement of hatchery-lineage fry from the system. Thus, the advantages of early emergence and large size associated with hatchery origin did not mitigate the disadvantages of early spawning in this case.

Kennedy, T.A., J.D. Muehlbauer, C.B. Yackulic, D.A. Lytle, S.W. Miller, K.L. Dibble, E.W. Kortenhoeven, A.N. Metcalfe, and C.V. Baxter. 2016. Flow Management for Hydropower Extirpates Aquatic Insects, Undermining River Food Webs. *BioScience* 66:561-575. <https://bioscience.oxfordjournals.org/content/66/7/561.full>

Abstract: Dams impound the majority of rivers and provide important societal benefits, especially daily water releases that enable on-peak hydroelectricity generation. Such “hydropeaking” is common worldwide, but its downstream impacts remain unclear. We evaluated the response of aquatic insects, a cornerstone of river food webs, to hydropeaking using a life history–hydrodynamic model. Our model predicts that aquatic-insect abundance will depend on a basic life-history trait—adult egg-laying behavior—such that open-water layers will be unaffected by hydropeaking, whereas ecologically important and widespread river-edge layers, such as mayflies, will be extirpated. These predictions are supported by a more-than-2500-sample, citizen-science data set of aquatic insects from the Colorado River in the Grand Canyon and by a survey of insect diversity and hydropeaking intensity across dammed rivers of the Western United States. Our study reveals a hydropeaking-related life history bottleneck that precludes viable populations of many aquatic insects from

inhabiting regulated rivers.

KozfKay, C.C., M. Peterson, B.P. Sandford, E.L. Johnson, and P. Kline. The Productivity and Viability of Snake River Sockeye Salmon Hatchery Adults Released into Redfish Lake, Idaho. Transactions of the American Fisheries Society, 148: 308-323.

Abstract: In 1991, the Snake River Sockeye Salmon Captive Broodstock Program was initiated to prevent the extinction and preserve the genetic diversity of this evolutionarily significant unit protected by the Endangered Species Act. At the time of listing, the Redfish Lake Sockeye Salmon *Oncorhynchus nerka* population was considered functionally extinct. One of the recovery strategies entails the release of adults for volitional spawning in Redfish Lake, Idaho, for rebuilding of the natural population. In this paper, we describe the productivity metrics from this strategy. We evaluated eight spawn years to address three primary questions: (1) What metrics for eggs to smolts, smolts per female, and smolt-to-adult returns (SARs) result from recent adult releases? (2) How do these metrics compare with historical estimates for Redfish Lake and estimates for other Sockeye Salmon populations throughout the range? and (3) Does the current combination of smolts per female and SARs result in population replacement? Replacement was determined as two adult recruits per female assuming an even sex ratio. We found that the reintroduced adults, despite being derived from a multigenerational captive broodstock, were able to successfully spawn and produce offspring that migrated to the ocean and returned as adults. Smolt abundance, size, and age data suggest that the population is functioning below density dependence. However, increased smolt production did not translate into greater adult returns and this is likely due to out-of-basin factors. Productivity metrics were similar to those of the wild population in Redfish Lake during the 1950s and 1960s. However, both current and historic productivity estimates were near the low end of the range for other Sockeye Salmon populations and have not resulted in population replacement. Until freshwater and out-of-basin survival can be improved, our data suggest that adult releases will continue to be an important recovery strategy to prevent cohort collapse and to rebuild naturally spawning populations.

Lister, D.B. 2014. Natural Productivity in Steelhead Populations of Natural and Hatchery Origin: Assessing Hatchery Spawner Influence. Transactions of the American Fisheries Society, 143: 1-16. (See also 2015 Comments by Carmichael et al. and Lister Response in Transactions 144:1292-1300).

Abstract: Natural productivity, the number of natural-origin adult recruits per parent, is an important parameter for assessing population status of steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) and Pacific salmon *Oncorhynchus* spp. listed under the U.S. Endangered Species Act. Hatchery-origin adults comprise a majority of many salmon and steelhead spawning populations. In such cases, the utility of natural productivity estimates is affected by uncertain reproductive fitness of hatchery spawners and by possible ecological or genetic interactions among hatchery and natural fish. This study examined options for analyzing population census data to assess hatchery spawner effects on natural productivity of mixed steelhead populations including spawners of hatchery and natural origin. It compared productivity in three mixed and reference (natural) population pairs, and estimated productivity as natural recruits per total spawners of natural and hatchery origin ($Rnat/Stot$) or as natural recruits per natural spawner ($Rnat/Snat$). Natural productivity estimated as $Rnat/Stot$ reflected hatchery program scale, not productive capacity of natal streams. This analytical approach masked natural production dynamics in populations with a major hatchery spawner proportion, and was therefore of limited use for determining hatchery spawner influence. Productivity estimated as

Rnat/Snat indicated similar productivity of reference and mixed populations, and an absence of hatchery spawner effect, in the case of (1) a large hatchery stray component, and (2) a hatchery supplementation program. In the third pairing, *Rnat/Snat* productivity of the mixed population significantly exceeded that of the reference population, suggesting natural spawner abundance is below carrying capacity. Hatchery spawners contributed to natural productivity in that case, but in the presence of reduced natural spawner density. These findings suggest that hatchery spawners are unlikely to affect natural production of a mixed steelhead population unless natural spawner abundance is below carrying capacity.

Mackey, G., J.E. McLean, and T.P.Quinn. 2001. Comparisons of Run Timing, Spatial Distribution, and Length of Wild and Newly Established Hatchery Populations of Steelhead in Forks Creek, Washington. *North American Journal of Fisheries Management* 21: 717-724.

Synopsis: In Washington State, the approach to management of wild and hatchery steelhead trout *Oncorhynchus mykiss* has been to separate the timing of return and spawning by the two groups through selective breeding for early timing in hatchery fish. However, overlap in timing and spatial distribution could permit genetic and ecological interactions. To evaluate this management approach, we compared the timing, spatial distribution, and size of adult steelhead in the wild and newly established hatchery populations of Forks Creek, Washington. Hatchery fish tended to return and spawn about 3 months before wild fish but there was some temporal overlap. Radio-tracking indicated that the spatial distributions of the populations overlapped considerably, permitting interbreeding and ecological interactions. However, the hatchery fish tended to stay closer to the hatchery, consistent with olfactory imprinting on the hatchery's water supply. Wild females were larger than hatchery females (median fork lengths were 670 and 644 mm, respectively), and wild males and females varied more in length than did hatchery fish of the same sex. In the first year in which naturally spawned offspring of hatchery fish might have returned, we observed a marked increase in early-returning unmarked (i.e., naturally spawned) adults, suggesting that some hatchery fish spawned successfully in the creek.

McIntyre, J. K., J. I. Lundin, J. R. Cameron, M. I. Chow, J. W. Davis, J. P. Incardona, and N. L. Scholz. 2018. Interspecies variation in the susceptibility of adult Pacific salmon to toxic urban stormwater runoff. *Environmental Pollution* 238:196-203. Available: <https://doi.org/10.1016/j.envpol.2018.03.012>

Abstract: Adult coho salmon (*Oncorhynchus kisutch*) prematurely die when they return from the ocean to spawn in urban watersheds throughout northwestern North America. The available evidence suggests the annual mortality events are caused by toxic stormwater runoff. The underlying pathophysiology of the urban spawner mortality syndrome is not known, and it is unclear whether closely related species of Pacific salmon are similarly at risk. The present study co-exposed adult coho and chum (*O. keta*) salmon to runoff from a high traffic volume urban arterial roadway. The spawners were monitored for the familiar symptoms of the mortality syndrome, including surface swimming, loss of orientation, and loss of equilibrium. Moreover, the hematology of both species was profiled by measuring arterial pH, blood gases, lactate, plasma electrolytes, hematocrit, and glucose. Adult coho developed behavioral symptoms within a few hours of exposure to stormwater. Various measured hematological parameters were significantly altered compared to coho controls, indicating a blood acidosis and ionoregulatory disturbance. By contrast, runoff-exposed chum

spawners showed essentially no indications of the mortality syndrome, and measured blood hematological parameters were similar to unexposed chum controls. We conclude that contaminant(s) in urban runoff are the likely cause of the disruption of ion balance and pH in coho but not chum salmon. Among the thousands of chemicals in stormwater, future forensic analyses should focus on the gill or cardiovascular system of coho salmon. Because of their distinctive sensitivity to urban runoff, adult coho remain an important vertebrate indicator species for degraded water quality in freshwater habitats under pressure from human population growth and urbanization.

McManamay, R.A., B.K. Peioles, D.J. Orth, C.A. Dolloff, and D.C. Matthews. 2015. Isolating causal pathways between flow and fish in the regulated river hierarchy. *Canadian Journal of Fisheries and Aquatic Sciences*, 72:1731-1748.

Abstract: Unregulated river systems are organized in a hierarchy in which large-scale factors (i.e., landscape and segment scales) influence local habitats (i.e., reach, meso-, and microhabitat scales), and both differentially exert selective pressures on biota. Dams, however, create discontinua in these processes and change the hierarchical structure. We examined the relative roles of hydrology and other instream factors, within a hierarchical landscape context, in organizing fish communities in regulated and unregulated tributaries to the Upper Tennessee River, USA. We used multivariate regression trees to identify factors that partition fish assemblages based on trait similarities, irrespective of spatial scale. We then used classical path analysis and structural equation modeling to evaluate the most plausible hierarchical causal structure of specific trait-based community components, given the data. Both statistical approaches suggested that river regulation affects stream fishes through a variety of reach-scale variables, not always through hydrology itself. Although we observed different changes in flow, temperature, and biotic responses according to regulation types, the most predominant path in which dam regulation affected biota was via temperature alterations. Diversion dams had the strongest effects on fish assemblages. Diversion dams reduced flow magnitudes, leading to declines in fish richness but increased temperatures, leading to lower abundances in equilibrium species and nest guards. Peaking and run-of-river dams increased flow variability, leading to lower abundances in nest-guarding fishes. Flow displayed direct relationships with biotic responses; however, results indicated that changes in temperature and substrate had equal, if not stronger, effects on fish assemblage composition. The strength and nature of relationships depended on whether flow metrics were standardized for river size. We suggest that restoration efforts in regulated rivers focus on improving flow conditions in conjunction with temperature and substrate restoration.

Meador, J.P. 2014. Do chemically contaminated river estuaries in Puget Sound (Washington, USA) affect the survival rate of hatchery-reared Chinook salmon? *Canadian Journal of Fisheries and Aquatic Sciences*, 71:162-180.

Abstract: This study examined the rate of survival for hatchery-reared, ocean-type juvenile Chinook salmon (*Oncorhynchus tshawytscha*) to the adult life stage in relation to contamination status for estuaries where they temporarily reside. The hypothesis tested here is that juvenile Chinook from Puget Sound (Washington, USA) area hatcheries exhibit differential survival as categorized by the state of contamination in their respective natal estuaries. Data were examined from 20 hatcheries that released fish to 14 local estuaries in the Greater Puget Sound area over 37 years (1972–2008). A parallel analysis was also conducted for coho salmon (*Oncorhynchus kisutch*) outmigrating from

many of the same hatcheries. For all years combined, juvenile Chinook transiting contaminated estuaries exhibited an overall rate of survival that was 45% lower than that for Chinook moving through uncontaminated estuaries, which was confirmed when tested year by year. The results for coho originating from the same hatcheries and sharing a similar marine distribution indicated no substantial differences among estuaries. These observations have important implications for wild juvenile Chinook that spend more time in the estuary compared with hatchery-reared fish.

Meredith, C., B. Roper, and E. Archer. 2014. Reductions in Instream Wood in Streams near Roads in the Interior Columbia River Basin. *North American Journal of Fisheries Management*, 34:493-506.

Abstract: Despite the success of recent management efforts to reduce streamside logging, instream wood recovery may be limited by the presence of near-stream roads. We investigated the relationships between the presence of near-stream roads and the frequency and volume of different size-classes of wood in streams in the interior Columbia River basin. We developed models to evaluate the average reduction in instream wood for streams near roads (<30 m or 30–60 m). We compared this with the changes in wood frequency and volume related to changes in environmental conditions such as precipitation, bank-full width, gradient, and forest cover as well as to changes in grazing-related management. In order to extrapolate our findings to the entire study area, we used a GIS approach to determine the distance to roads for randomly selected sites throughout the study area. Sites <30 m from a road had 65 (26%) fewer pieces of total wood, 33 (34%) fewer pieces of coarse wood, 31 (37%) fewer pieces of pool-forming wood, and 37 m³ (42%) less wood volume per kilometer than sites >60 m from a road. We also observed significant reductions at sites 30–60 m from a road, but these were about half those documented for sites <30 m. Changes in environmental conditions and grazing intensity had effects similar to those of being near a road. Based on our GIS analysis, approximately 29% of the sites in the study area are within 60 m of a road, and this percentage is even greater if unroaded catchments are excluded. Our results provide strong evidence that the presence of roads has significantly reduced habitat conditions for salmonids in the interior Columbia River basin and illustrate the need for road removal or relocation projects to increase wood in streams.

Milbrink, G., T. Vrede, L.J. Tranvik, and E. Rydin. 2011. Large-scale and long-term decrease in fish growth following the construction of hydroelectric reservoirs. *Canadian Journal of Fisheries and Aquatic Sciences*, 68:2167-2173.

Abstract: Hydroelectric reservoirs retain large volumes of water and have a global impact on sea level, elemental cycles, and biodiversity. Using data from a total of 90 historical and recent surveys in nine regulated and eight unregulated alpine and subalpine lakes, we show an additional large effect of reservoirs, i.e., that impoundment causes drastically decreased fish growth and thereby great negative consequences for inland fisheries in Scandinavia. Following a long period (40–65 years) after impoundment, the length and mass of Arctic charr (*Salvelinus alpinus*) of the single age class 4+ years was, on average, 35% and 72% lower, respectively, in impounded versus natural lakes in northern Scandinavia. The effect was stronger at higher altitudes and can be mitigated by addition of inorganic nutrients. We suggest that the decreased fish growth is a consequence of lowered

ecosystem productivity, oligotrophication, caused by impoundment, resulting in erosion and loss of the littoral ecosystem as well as delayed flooding and leakage of nutrients from the riparian zone until after the growing season.

Nakamura, T. 2013. Effects of Flow Reduction on a Whitespotted Char Population in a Japanese Mountain Stream. *North American Journal of Fisheries Management* 33: 1142-1148.

Abstract: I evaluated the effects of long-term (about 270 d/year) and large-volume (83.3% at mean flow) reductions in stream flow on a population of Whitespotted Char *Salvelinus leucomaenis*. I compared a range of biological parameters (density, biomass, condition factor, and age composition) between populations of char in the free-flowing (above dam) and regulated (below dam) sections of a Japanese mountain stream over a 4-year period. The density and biomass of age-1 and older fish was significantly lower in the regulated section than in the free-flowing section: 32.8% reduction in density and 42.5% in biomass. The mean condition factor of age-1 and older fish was significantly lower in the regulated section. In addition, the percentage of age-2 and older fish in the total catch was significantly lower in the regulated section. Except for flow, the physical environment was similar in both the free-flowing and regulated sections. Thus, the changes I observed in the regulated section were likely caused by flow reduction. I hypothesize that a decrease in food availability associated with the reduction in flow caused the decrease in density and condition factor in the regulated section. I also speculate that an increase in density in the pools due to flow reduction resulted in increased aggression among conspecifics. In turn, this results in an increase in the emigration of individuals, particularly older and larger fish, in the regulated section. The decreases in the density, condition factor, and the number of older and larger fish following the reduction in flow probably explain the decrease in biomass in the regulated section.

Neuswanger, J.R., M.S. Wipfli, M.J. Evenson, N.F. Hughes, and A.E. Rosenberger. 2015. Low productivity of Chinook salmon strongly correlates with high summer stream discharge in two Alaskan rivers in the Yukon drainage. *Canadian Journal of Fisheries and Aquatic Sciences*, 72:1125-1137.

Abstract: Yukon River Chinook salmon (*Oncorhynchus tshawytscha*) populations are declining for unknown reasons, creating hardship for thousands of stakeholders in subsistence and commercial fisheries. An informed response to this crisis requires understanding the major sources of variation in Chinook salmon productivity. However, simple stock–recruitment models leave much of the variation in this system’s productivity unexplained. We tested adding environmental predictors to stock–recruitment models for two Yukon drainage spawning streams in interior Alaska — the Chena and Salcha rivers. Low productivity was strongly associated with high stream discharge during the summer of freshwater residency for young-of-the-year Chinook salmon. This association was more consistent with the hypothesis that sustained high discharge negatively affects foraging conditions than with acute mortality during floods. Productivity may have also been reduced in years when incubating eggs experienced major floods or cold summers and falls. These freshwater effects — especially density dependence and high discharge — helped explain population declines in both rivers. They are plausible as contributors to the decline of Chinook salmon throughout the Yukon River drainage.

Nielsen, J.L., S.M. Turner, and C.E. Zimmerman. 2011. Electronic tags and genetics explore variation in migrating steelhead kelts (*Oncorhynchus mykiss*), Ninilchik River, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences*, 68:1-16.

Synopsis: Fine-scale tag data on kelt movements, life history analyses, and genetics from this study suggest that steelhead have multiple migratory and reproductive phenotypes that contribute to reproductive success and population structure over time. Conservation and management of one or two reproductive phenotypes may not be sufficient in this complex species.

Nielsen, E.B. and J.L. Morace. 2014. Foodweb transfer, sediment transport, and biological impacts of emerging and legacy organic contaminants in the lower Columbia River, Oregon and Washington, USA: Contaminants and Habitat (ConHab) Project. *Science of the Total Environment*, 484:319-321.

Synopsis: The investigation began with scientific researchers measuring for contaminants, including pesticides, flame retardant compounds, and ingredients from common household products, in the water and osprey eggs at 10 different locations along the Columbia River. The study states that several chemicals have been found at levels that exceed screening level values in Oregon Department of Environmental Quality guidance. Along with human health concerns, these contaminants may also have an adverse effect on the river system's food web in general. Results show that fish become more stressed and contaminated further downstream in the Columbia River, as more urban runoff enters the river.

Perkin, J.S., Z.R. Shattuck, J.E. Gerken and T.H. Bonner. 2013. Fragmentation and Drought Legacy Correlate with Distribution of Burrhead Chub in Subtropical Streams of North America. *Transactions of the American Fisheries Society*, 142: 1287-1298.

Abstract: Burrhead Chub *Macrhybopsis marconis* is a species of special concern endemic to subtropical streams in south Texas. We documented life history attributes and historical patterns in abundance and distribution to aid in understanding range-wide declines of the species among the Colorado and Guadalupe-San Antonio River systems. Life history results suggest Burrhead Chub lives for 2 years, reaches sexual maturity at age-1, and spawns multiple clutches during March–September. Review of museum vouchers revealed Burrhead Chub is now missing from 26% of its historical range, including most impounded stream segments. There was a significant difference in the size of stream fragments for which Burrhead Chub is missing or still persists. Timing of many extirpations occurred after fragmentation and coincided with a record drought (1949–1959) when range-wide stream flows were exceedingly low during the Burrhead Chub reproductive season. Furthermore, extensive historical collections taken during 1950–1961 in the Guadalupe River revealed a decline in relative abundance in upstream reaches as the drought continued. Based on these data, we hypothesize that Burrhead Chub experienced range-wide declines associated with historical drought conditions in desiccated stream fragments. Following the drought, stream flows recovered but recolonization by Burrhead Chub was blocked by impoundments in many fragments. These findings support previous linkages between stream connectivity, flow magnitude, and the persistence of fish populations while providing insight into the mechanisms driving freshwater fish declines in the plains of North America.

Sabal, M., S. Hayes, J. Merz and J. Setka. 2016. Habitat Alterations and a Nonnative Predator, the

Striped Bass, Increase Native Chinook Salmon Mortality in the Central Valley, California.
North American Journal of Fisheries Management, 36: 309-320.

Abstract: Anthropogenic stressors are the leading causes of species and biodiversity declines, driving wide-scale ecosystem changes. Additionally, synergistic effects of multiple anthropogenic modifications, including species introductions and habitat alterations, can have complex outcomes for native species. We assessed how a nonnative predator (the Striped Bass *Morone saxatilis*) and habitat alterations (a small diversion dam and other altered habitats) interacted to influence mortality of native juvenile Chinook Salmon *Oncorhynchus tshawytscha* during their emigration from the lower Mokelumne River, California. Relative abundance and diet surveys across natural and human-altered habitats were used to assess Striped Bass functional and aggregative responses. Per capita consumption (PCC) of juvenile salmon and behavioral aggregation (CPUE) by Striped Bass at a small diversion dam (Woodbridge Irrigation District Dam [WIDD]) were elevated in comparison with those at other altered and natural habitats (WIDD: PCC = 3.54 juvenile salmon, CPUE = 0.189 Striped Bass/s of electrofishing; other altered habitats: PCC = 0 juvenile salmon, CPUE = 0.0024 Striped Bass/s; natural habitats: PCC = not estimable, CPUE = 0.0003 Striped Bass/s). Increased aggregative and functional predator responses created a localized area of heightened predation at WIDD. At this predation hot spot, we used three approaches (experimental Striped Bass removals, diet energetic analysis, and before–after impact assessment) to estimate Striped Bass consumption at 8–29% of the emigrating juvenile salmon population. Striped Bass PCC rates for juvenile salmon as determined by the three approaches were 0.92% (predator removals), 0.71–1.20% (diet energetic analysis), and 0.96–1.11% (before–after impact assessment). Our results (1) illustrate how the synergistic effect of habitat modification and a nonnative predator can exacerbate the mortality of native juvenile salmon during their emigration and (2) highlight the importance of considering interactions among stressors when planning local management strategies and assessing population-level impacts on salmon.

Seamons, T.R., L. Hauser, K.A. Naish, and T.P. Quinn. 2012. Can interbreeding of wild and artificially propagated animals be prevented by using broodstock selected for a divergent life history? [Evolutionary Applications, 5:705-719](#).

Abstract: Two strategies have been proposed to avoid negative genetic effects of artificially propagated individuals on wild populations: (i) integration of wild and captive populations to minimize domestication selection and (ii) segregation of released individuals from the wild population to minimize interbreeding. We tested the efficacy of the strategy of segregation by divergent life history in a steelhead trout, *Oncorhynchus mykiss*, system, where hatchery fish were selected to spawn months earlier than the indigenous wild population. The proportion of wild ancestry smolts and adults declined by 10–20% over the three generations since the hatchery program began. Up to 80% of the naturally produced steelhead in any given year were hatchery/wild hybrids. Regression model selection analysis showed that the proportion of hatchery ancestry smolts was lower in years when stream discharge was high, suggesting a negative effect of flow on reproductive success of early-spawning hatchery fish. Furthermore, proportions of hybrid smolts and adults were higher in years when the number of naturally spawning hatchery-produced adults was higher. Divergent life history failed to prevent interbreeding when physical isolation was ineffective, an inadequacy that is likely to prevail in many other situations.

Schoenfuss, H.L., E.T. Furlong, P.J. Phillips, T-M Scott, D.W. Kolpin, M. Cetkovic-Cvrlje, K.E. Lesteberg, and D.C. Rearick. 2015. Complex mixtures, complex responses: Assessing pharmaceutical mixtures using field and laboratory approaches. [Environmental Toxicology and Chemistry doi:10.1002/etc.3147](https://doi.org/10.1002/etc.3147).

Abstract: Pharmaceuticals are present in low concentrations (<100 ng/L) in most municipal wastewater effluents but may be elevated locally because of factors such as input from pharmaceutical formulation facilities. Using existing concentration data, the authors assessed pharmaceuticals in laboratory exposures of fathead minnows (*Pimephales promelas*) and added environmental complexity through effluent exposures. In the laboratory, larval and mature minnows were exposed to a simple opioid mixture (hydrocodone, methadone, and oxycodone), an opioid agonist (tramadol), a muscle relaxant (methocarbamol), a simple antidepressant mixture (fluoxetine, paroxetine, venlafaxine), a sleep aid (temazepam), or a complex mixture of all compounds. Larval minnow response to effluent exposure was not consistent. The 2010 exposures resulted in shorter exposed minnow larvae, whereas the larvae exposed in 2012 exhibited altered escape behavior. Mature minnows exhibited altered hepatosomatic indices, with the strongest effects in females and in mixture exposures. In addition, laboratory-exposed, mature male minnows exposed to all pharmaceuticals (except the selective serotonin reuptake inhibitor mixture) defended nest sites less rigorously than fish in the control group. Tramadol or antidepressant mixture exposure resulted in increased splenic T lymphocytes. Only male minnows exposed to whole effluent responded with increased plasma vitellogenin concentrations. Female minnows exposed to pharmaceuticals (except the opioid mixture) had larger livers, likely as a compensatory result of greater prominence of vacuoles in liver hepatocytes. The observed alteration of apical endpoints central to sustaining fish populations confirms that effluents containing waste streams from pharmaceutical formulation facilities can adversely impact fish populations but that the effects may not be temporally consistent. The present study highlights the importance of including diverse biological endpoints spanning levels of biological organization and life stages when assessing contaminant interactions.

Snow, C.G., A.R. Murdoch, and T.H. Kahler. 2013. Ecological and Demographic Costs of Releasing Nonmigratory Juvenile Hatchery Steelhead in the Methow River, Washington. *North American Journal of Fisheries Management* 33: 1100-1112.

Abstract: We classified juvenile hatchery summer steelhead *Oncorhynchus mykiss* released from Wells Hatchery, Washington, from three brood years (2002–2004) as those that migrated volitionally (VM) from rearing ponds or as those that were forced out of rearing ponds after volitional migration concluded (NM). Fish were implanted with PIT tags prior to release and we used recreational angling equipment to recapture tagged fish to estimate the relative contribution rates of VM and NM release groups to the stream-resident population of juvenile hatchery summer steelhead in the Twisp River. We also evaluated the survival for each group from release to McNary Dam, and from release to adult return (SAR) at Bonneville and Wells dams on the Columbia River. Overall, we estimated that 82% of stream-resident hatchery juvenile summer steelhead originated from releases of NM fish. The probability of survival from release to McNary Dam was significantly greater for VM groups (mean, 0.4817; SE, 0.023) than for NM groups (mean, 0.2182; SE, 0.021) within each year. The mean SAR to Bonneville and Wells dams was 1.54% and 1.26%, respectively, for VM fish and 0.37% and 0.32%, respectively, for NM fish; the differences were significant between groups within each year. As an index of release strategy performance, VM releases resulted in one stream-resident fish

recaptured for every 7.8 adults returned, while NM releases produced one stream-resident fish recaptured for every 0.48 adults returned. These results suggest that managers employ a volitional release strategy to significantly reduce the abundance of stream-resident juvenile hatchery steelhead by not releasing NM fish into waters inhabited by anadromous fishes, thereby reducing negative ecological interactions between hatchery residual steelhead and wild salmonids at little cost to adult returns.

Spromberg, J.A., D.H. Baldwin, S.E. Damm, J.K. McIntyre, M. Huff, C.A. Sloan, B.F. Anulacion, J.W. Davis, and N.L. Scholz. 2015. Coho salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal storm water impacts. *Journal of Applied Ecology* doi:[10.1111/1365-2664.12534](https://doi.org/10.1111/1365-2664.12534)

Summary:

1. Adult coho salmon *Oncorhynchus kisutch* return each autumn to freshwater spawning habitats throughout western North America. The migration coincides with increasing seasonal rainfall, which in turn increases storm water run-off, particularly in urban watersheds with extensive impervious land cover. Previous field assessments in urban stream networks have shown that adult coho are dying prematurely at high rates (>50%). Despite significant management concerns for the long-term conservation of threatened wild coho populations, a causal role for toxic run-off in the mortality syndrome has not been demonstrated.
2. We exposed otherwise healthy coho spawners to: (i) artificial storm water containing mixtures of metals and petroleum hydrocarbons, at or above concentrations previously measured in urban run-off; (ii) undiluted storm water collected from a high traffic volume urban arterial road (i.e. highway run-off); and (iii) highway run-off that was first pre-treated via bioinfiltration through experimental soil columns to remove pollutants.
3. We find that mixtures of metals and petroleum hydrocarbons – conventional toxic constituents in urban storm water – are not sufficient to cause the spawner mortality syndrome. By contrast, untreated highway run-off collected during nine distinct storm events was universally lethal to adult coho relative to unexposed controls. Lastly, the mortality syndrome was prevented when highway run-off was pretreated by soil infiltration, a conventional green storm water infrastructure technology.
4. Our results are the first direct evidence that: (i) toxic run-off is killing adult coho in urban watersheds, and (ii) inexpensive mitigation measures can improve water quality and promote salmon survival.
5. *Synthesis and applications.* Coho salmon, an iconic species with exceptional economic and cultural significance, are an ecological sentinel for the harmful effects of untreated urban run-off. Wild coho populations cannot withstand the high rates of mortality that are now regularly occurring in urban spawning habitats. Green storm water infrastructure or similar pollution prevention methods should be incorporated to the maximal extent practicable, at the watershed scale, for all future development and redevelopment projects, particularly those involving transportation infrastructure.

Stich, D.S., M.M. Bailey, C.M. Holbrook, M.T. Kinnison, and J.D. Zydlewski. 2015. Catchment-wide survival of wild- and hatchery-reared Atlantic salmon smolts in a changing system. *Canadian Journal of Fisheries and Aquatic Sciences*, 72:1352-1365.

Abstract: We developed a hierarchical multistate model to estimate survival of Atlantic salmon (*Salmo salar*) smolts in the Penobscot River, USA, over a decade during which two mainstem dams were removed from the catchment. We investigated effects of (i) environmental factors, (ii) rearing history, and (iii) management actions, including dam removal, turbine shutdown, and installation of new powerhouses. Mean \pm SD smolt survival per kilometre was higher through free-flowing reaches of the catchment ($0.995 \pm 0.004 \cdot \text{km}^{-1}$) than through reaches containing dams that remain in the system ($0.970 \pm 0.019 \cdot \text{km}^{-1}$). We observed maximum survival between 12 and 17 °C and at intermediate discharges ($1200 \text{ m}^3 \cdot \text{s}^{-1}$). Smolt survival increased concurrent with dam removal and decreased following increases in hydropower generation. The greatest increase in smolt survival followed seasonal turbine shutdowns at a dam located on the largest tributary to the Penobscot River, while other shutdowns had little influence. Our model provides a useful tool for assessing changes to survival of migratory species and will be useful for informing stocking plans to maximize numbers of smolts leaving coastal systems.

Tian, Z., Z. Haoqi, K. T. Peter, M. Gonzalez, J. Wetzel, C. Wu, X. Hu, J. Prat, E. Mudrock, R. Hettinger, A. E. Cortina, R. G. Biswas, F. V. C. Kock, R. Soong, A. Jenne, B. Du, F. Hou, H. He, R. Lundeen, A. Gilbreath, R. Sutton, N. L. Scholz, J. W. Davis, M. C. Dodd, A. Simpson, J. K. McIntyre, and E. P. Kolodziej. 2020. A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon. *Science* 03Dec2020, DOI: 10.1126/science.abd6951.

Abstract: In U.S. Pacific Northwest coho salmon (*Oncorhynchus kisutch*), stormwater exposure annually causes unexplained acute mortality when adult salmon migrate to urban creeks to reproduce. By investigating this phenomenon, we identified a highly toxic quinone transformation product of N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), a globally ubiquitous tire rubber antioxidant. Retrospective analysis of representative roadway runoff and stormwater-impacted creeks of the U.S. West Coast indicated widespread occurrence of 6PPD-quinone ($<0.3\text{-}19 \mu\text{g/L}$) at toxic concentrations (LC_{50} of $0.8 \pm 0.16 \mu\text{g/L}$). These results reveal unanticipated risks of 6PPD antioxidants to an aquatic species and imply toxicological relevance for dissipated tire rubber residues.

Thériault, V., G.R. Moyer, and M.A. Banks. 2010. Survival and life history characteristics among wild and hatchery coho salmon (*Oncorhynchus kisutch*) returns: how do unfed fry differ from smolt releases? *Canadian Journal of Fisheries and Aquatic Sciences*, 67:486-497.

and

Thériault, V., G.R. Moyer, L.S. Jackson, M.S. Blouin, and M.A. Banks. 2011. Reduced reproductive success of hatchery coho salmon in the wild: insights into most likely mechanisms. *Molecular Ecology* 20:1860-1869.

Synopsis: Molecular parentage analysis was used to evaluate the lifetime reproductive success of hatchery- and natural-origin coho salmon allowed to reproduce in the wild in the Umpqua River Basin, Oregon. Relative reproductive success for hatchery-origin fish released as smolts and returning as age-3 adults was significantly less than that of natural-origin coho in 2 of 3 study brood years for females and in all 3 study broods for males. However, returning hatchery-origin adult coho (released as smolts) were significantly smaller than natural-origin returns. The smaller size of adult

returns could explain the observed differences in reproductive success (e.g., smaller females could have fewer eggs and smaller males may not compete as successfully for mates). The study found no significant difference in reproductive success between hatchery-origin fish with two hatchery-origin parents and those with two natural-origin parents. This indicates that any differences in reproductive success in the wild were not passed on to progeny (i.e., observed differences were likely due to environmental and not genetic effects).

Tiffan, K.F. and W.P. Connor. 2011. Distinguishing between Natural and Hatchery Snake River Fall Chinook Salmon Subyearlings in the Field Using Body Morphology. *Transactions of the American Fisheries Society*, 140: 21-30.

Abstract: We used body morphology to distinguish between natural- and hatchery-origin subyearling fall Chinook salmon *Oncorhynchus tshawytscha* in rearing areas of the Snake River and at a downstream dam during seaward migration. Using subjective eye and body shape characteristics, field personnel correctly classified 88.9-100% of natural subyearlings (N = 626) and 90.0-100% of hatchery subyearlings (N = 867) in rearing areas from 2001 to 2008. The morphological characteristics used by these personnel proved to have a quantitative basis, as was shown by digital photography and principal components analysis. Natural subyearlings had smaller eyes and pupils, smaller heads, deeper bodies, and shorter caudal peduncles than their hatchery counterparts during rearing and at the dam. A discriminant function fitted from this set of morphological characteristics classified the origin of fish during rearing and at the dam with over 97% accuracy. We hypothesize that these morphological differences were primarily due to environmental influences during incubation and rearing because it is highly probable that a large portion of the natural juveniles we studied were the offspring of hatchery x hatchery mating in the wild. The findings in this paper might provide guidance for others seeking to differentiate between natural and hatchery fish.

Tiffan, K.F., J.M. Erhardt, and S.J. St. John. 2014. Prey Availability, Consumption, and Quality Contribute to Variation in Growth of Subyearling Chinook Salmon Rearing in Riverine and Reservoir Habitats. *Transactions of the American Fisheries Society*, 143: 219-229.

Abstract: We examined prey availability, prey consumed, and diet energy content as sources of variation in growth of natural fall Chinook Salmon *Oncorhynchus tshawytscha* subyearlings rearing in riverine and reservoir habitats in the Snake River. Subyearlings in riverine habitat primarily consumed aquatic insects (e.g., Diptera, Ephemeroptera, Trichoptera), of which a high proportion was represented by adult, terrestrial forms. In the reservoir, subyearlings also consumed aquatic insects but also preyed heavily at times on nonnative lentic amphipods *Corophium* spp. and the mysid *Neomysis mercedis*, which were absent in riverine habitats. The availability of prey was typically much higher in the reservoir due to *N. mercedis* often composing over 90% of the biomass, but when this taxon was removed from consideration, biomass estimates were more often higher in the riverine habitat. Subyearling diets during 2009–2011 were generally 17–40% higher in energy in the riverine habitat than in the reservoir. Observed growth in both length and weight were significantly higher in the riverine habitat than in the reservoir. Little is known about how temporal and spatial changes in the food web in large river landscapes influence populations of native anadromous fishes. Our results provide a glimpse of how the spread and establishment of nonnative prey species can reduce juvenile salmon growth in a large river impoundment, which in turn can affect migration timing and survival.

Torterotot, J-B, C. Perrier, N.E. Bergeron, and L. Bernatchez. 2014. Influence of Forest Road Culverts and Waterfalls on the Fine-Scale Distribution of Brook Trout Genetic Diversity in a Boreal Watershed. *Transactions of the American Fisheries Society*, 143: 1577-1591.

Abstract: Habitat fragmentation has become an increasing concern in conservation biology and is of prime importance with the expansion of forest road networks toward boreal and arctic regions. The aim of this study was to evaluate the effects of artificial and natural barriers to fish movement on the fine-scale distribution of genetic diversity in Brook Trout *Salvelinus fontinalis*. We genotyped 995 individuals sampled from 25 locations in a boreal watershed fragmented by culverts and natural waterfalls. Using a landscape genetics approach, we tested whether the presence of both types of barrier resulted in decreased genetic diversity and increased divergence within isolated locations. Results showed that genetic divergence was enhanced between sites separated by barriers and that genetic diversity was reduced within sites located upstream of barriers. Moreover, the observed changes in levels of divergence and diversity were correlated with the number of barriers. Overall, our results suggested that the effects of culverts and natural waterfalls were similar. To our knowledge, this is the first study illustrating the effects of forest road culverts and natural waterfalls on the distribution of genetic diversity in Brook Trout within a boreal watershed. We discuss our results in the context of boreal forest road network expansion and in light of the need to better understand the potential impacts of road infrastructure on the long-term persistence of fish populations.

Trushenski, J.T., G.E. Whelan, and J.D. Bowker. 2018. Why Keep Hatcheries? Weighing the Economic Cost and Value of Fish Production for Public Use and Public Trust Purposes. *Fisheries*, 43: 284-293.

Abstract: Resource allocation for fisheries management and conservation in the United States has not grown substantially in recent years, and there is ongoing debate over how limited resources should be used to create, maintain, or restore fisheries. Hatcheries have been in existence in North America since 1848, but their organization and role in fisheries management are not widely understood or appreciated. The continuing debate about hatcheries has painted them in broad strokes, with critics suggesting that hatcheries are altogether ineffective, unnecessary, too costly to operate, or do more harm than good to wild populations. Such characterizations fail to capture the diversity of hatchery operations and do not acknowledge the hatchery reform initiatives of the past 20 years or public expectations and legal requirements that influence the production and use of hatchery-origin fish. In this paper, we describe the current number and distribution of fish hatcheries operated for public purposes in North America, provide insights on the costs and benefits of hatcheries operated for public use and other public trust purposes, provide initial cost comparisons to habitat rehabilitation or restoration, and consider the role of hatcheries into the future as a fisheries management tool.

Trushenski, J.T., D.A. Larsen, M.A. Middleton, M. Jakaitis, E.L. Johnson, C.C. Kozfkay, and P.A. Kline. 2019. Search for the Smoking Gun: Identifying and Addressing the Causes of Postrelease Morbidity and Mortality of Hatchery-Reared Snake River Sockeye Salmon Smolts. *Transactions of the American Fisheries Society*, 148:875-895.

Abstract: As part of the Snake River Sockeye Salmon *Oncorhynchus nerka* recovery effort, a dedicated smolt rearing facility was constructed in 2013 near Springfield, Idaho. In-hatchery performance and survival were typical for the species, but unexpectedly high mortality rates were observed in the first cohorts of Springfield-reared smolts upon release into Redfish Lake Creek (RFLC) and during out-migration. In response, a series of iterative experiments was conducted to identify the cause of the morbidity and mortality observed and to test a range of strategies to mitigate effects on postrelease survival. In the search for possible contributing factors, a difference in water chemistry was noted: whereas Springfield Hatchery's water source is “hard” and has high calcium concentrations, water at the RFLC release site is “soft” and has very low calcium concentrations. In both manipulative experiments and field evaluations, we demonstrated that juvenile Snake River Sockeye Salmon are profoundly affected by instantaneous transitions from high- to low-hardness water. Furthermore, we established a causal link between differences in water chemistry, the associated physiological stress, and morbidity/mortality observed during smolt releases and subsequent out-migration. A variety of mitigation strategies, including water mixing and water softening, was tested, but stepwise acclimation from high- to medium-hardness water and then from medium- to low-hardness water proved to be the most biologically and logistically effective means of addressing the identified water chemistry differences. Estimates of postrelease survival to Lower Granite Dam (~430 river kilometers downstream) indicated significantly higher survival for acclimated groups (68.7–75.5%) compared to smolts directly released into RFLC (18.1%). Although Snake River Sockeye Salmon smolt survival rates will undoubtedly fluctuate annually with environmental conditions, it is clear that the elevated morbidity and mortality observed in previous years can be addressed through proper acclimation of smolts prior to release.

Walsworth, T.E. and P. Budy. 2015. Integrating Nonnative Species in Niche Models to Prioritize Native Fish Restoration Activity Locations along a Desert River Corridor. *Transactions of the American Fisheries Society*, 144: 667-681.

Abstract: The efficient allocation of restoration resources is critical for the effective conservation of species. Here, we developed an ecological niche model to predict the response of three imperiled desert fishes to potential restoration actions along the longitudinal gradient of a desert river. The San Rafael River, Utah, is home to a complex of three endemic fishes (Flannelmouth Sucker *Catostomus latipinnis*, Bluehead Sucker *C. discobolus*, and Roundtail Chub *Gila robusta*; referred to as the “three species”). Like many Colorado River basin tributaries, the river is overallocated for human use, has experienced extensive physical degradation, and is now home to several nonnative fish species. To determine the factors most limiting to the three species, we first fit random forest models to fish CPUE and habitat data. We next combined these models with a longitudinal habitat survey and modeled nonnative species abundance to predict the continuous distribution of the three species in the lower San Rafael River, under current conditions and following simulated restoration. Nonnative fishes were important negative predictors of Flannelmouth Sucker and Bluehead Sucker relative abundance, and broadscale habitat variables were important positive predictors for all of the three species. Each of the three species was predicted to experience a significant increase in abundance following simulated eradication of nonnative fishes. Responses to simulated reach-specific habitat restoration were dependent on the reach restored, demonstrating that the choice of restoration location is critical. Nonnative species removal and restoring degraded reaches near already suitable habitat were predicted to be the most beneficial to the three species. Ecological niche models developed at the river scale, and incorporating both physical and biotic predictor variables, can

provide spatially explicit information that appropriately parallels the spatial distribution of the needs of endemic fishes and can facilitate effective management and conservation decisions.

Ward, E.J., J.H. Anderson, T.J. Beechie, G.R. Pess, and M.J. Ford. 2015. Increasing hydrologic variability threatens depleted anadromous fish populations. *Global Change Biology*, doi: 10.1111/gcb.12847.

Abstract: Predicting effects of climate change on species and ecosystems depend on understanding responses to shifts in means (such as trends in global temperatures), but also shifts in climate variability. To evaluate potential responses of anadromous fish populations to an increasingly variable environment, we performed a hierarchical analysis of 21 Chinook salmon populations from the Pacific Northwest, examining support for changes in river flows and flow variability on population growth. More than half of the rivers analyzed have already experienced significant increases in flow variability over the last 60 years, and this study shows that this increase in variability in freshwater flows has a more negative effect than any other climate signal included in our model. Climate change models predict that this region will experience warmer winters and more variable flows, which may limit the ability of these populations to recover.

Watson, J.M., S.M. Coghlan, J. Zydlewski, D.B. Hayes, and I.A. Kiraly. 2018. Dam Removal and Fish Passage Improvement Influence Fish Assemblages in the Penobscot River, Maine. *Transactions of the American Fisheries Society*, 147: 525-540.

Abstract: Dams and their impoundments disrupt river habitat connectivity to the detriment of migratory fishes. Removal of dams improves riverine connectivity and lotic habitat, which benefits not only these fishes but also resident fluvial specialist species. Restoration efforts on the Penobscot River, Maine, are among the largest recently completed in the United States and include the removal of the two lowermost dams and improvements to fish passage at several remaining barriers. We assessed fish assemblages in the main-stem river and several major tributaries before (2010–2012) and after (2014–2016) dam removal using boat electrofishing surveys and a stratified random sampling design. In total, we sampled 303 km of shoreline and captured 107,335 individual fish representing 39 species. Similarity indices and rarefaction curves indicated that significant changes in fish assemblage composition occurred in reaches that underwent both habitat and connectivity changes (i.e., directly above removed dams). The newly connected reaches became more similar in fish assemblage composition, as demonstrated by an average increase of 31% in similarity scores. The changes in similarity score in these reaches were driven by increasing access for anadromous fishes and decreasing abundances of slow-water specialist species. For example, we observed a marked reduction in lacustrine species in former impoundments. These assemblage shifts were further illustrated by nonmetric multidimensional scaling in which sites directly above former dams exhibited the largest ordinal shifts immediately following dam removal. We also found all anadromous species in greatest abundance below the lowermost dam during each respective sampling period, though we did find some anadromous species above the lowermost dam during postremoval sampling. Our results demonstrate the potential for large dam removal projects to restore both fluvial and anadromous fish assemblages.

Background / Additional Reading

Bosch, W. J. 2004. The promise of hatchery-reared fish and hatchery methodologies as tools for rebuilding Columbia Basin salmon runs: Yakima Basin overview. *American Fisheries Society Symposium* 44:151-160.

Synopsis: Overview of Yakima Basin Projects and why supplementation is necessary.

Brannon, E. L., D. F. Amend, M. A. Cronin, J. E. Lannon, S. LaPatra, W. J. McNeil, R. E. Noble, C. E. Smith, A. J. Talbot, G. A. Wedemeyer, and H. Westers. 2004. The controversy about salmon hatcheries. *Fisheries* 29(9): 12-30.

Synopsis: Reviews literature that has been often cited to show the negative effects of hatcheries and explains how poor experimental designs or the use of inappropriate (e.g., non-local origin, multiple generations in hatcheries) hatchery stocks contributed to the negative results reported in these papers. Documents many examples where fish from traditional hatcheries have spawned successfully and done well under natural conditions.

Canfield Jr., D.E. 2017. Comment: Do Something or Do Nothing—the Fisheries Management Conundrum. *North American Journal of Fisheries Management* 37:809-815.

Columbia River Inter-Tribal Fish Commission. 1995. WY-KAN-USH-MI WA-KISH-WIT Spirit of the Salmon. The Columbia River Anadromous Fish Restoration Plan, Vol. I and II. Portland, Oregon.

Columbia River Inter-Tribal Fish Commission. 2000. WY-KAN-USH-MI WA-KISH-WIT Spirit of the Salmon. The Columbia River Anadromous Fish Restoration Plan Update, Vol. I and II. Portland, Oregon.

Dompier, D. W. 2005. *The Fight of the Salmon People: Blending Tribal Tradition with Modern Science to Save Sacred Fish*. Xlibris Corporation, www.Xlibris.com.

Gallinat, M. P., and L. A. Ross. 2008. Tucannon River Spring Chinook Salmon Hatchery Evaluation Program, [2007 Annual Report](#). WDFW, Olympia, WA.

Narum, S.R., T.L. Schultz, D.M. Van Doornik, and D. Teel. 2008. Localized genetic structure persists in wild populations of Chinook salmon in the John Day River despite gene flow from outside sources. *Transactions of the American Fisheries Society* 137:1650-1656.

Abstract: Samples of Chinook salmon *Oncorhynchus tshawytscha* collected from four spawning areas in the John Day River, Oregon (n = 330), were genotyped with 13 microsatellite loci to test for bottlenecks and temporal stability within sites as well as genetic differentiation among sites, and to estimate gene flow from outside populations. Since the John Day River has never been stocked with hatchery-reared fish, this study provided the opportunity to evaluate the genetic integrity and structure of Chinook salmon in a wilderness area amid many hatchery-supported populations in the Columbia River. No tests for bottlenecks (Wilcoxon tests for heterozygosity excess) were significant,

and the temporal variation was slight and not significant within any spawning reach except for the collections from the Middle Fork John Day River. Overall, the genetic distance estimates suggest that there are three distinct subpopulations in the John Day River, namely, those in (1) the North Fork John Day River (including Granite Creek), (2) the Middle Fork John Day River, and (3) the upper main-stem John Day River. These genetic relationships were supported by results from a neighbor-joining dendrogram. Assignment tests indicate that out-of-basin straying occurs throughout the John Day River, the largest percentage of strays going to the North Fork John Day River. Immigration may have acted to avert genetic bottlenecks and maintain genetic diversity in populations with fluctuating census size. Yet the genetic substructure of the Chinook salmon in the John Day River indicates natural reproduction from philopatric individuals, possibly with higher reproductive success than immigrants. The evidence presented here elucidates the balance of philopatry and dispersal acting to maintain genetic diversity and localized structure among the Chinook salmon of the John Day River.

Perrier, C., G. Evanno, J. Belliard, R. Guyomard, and J-L. Baglinière. 2010. Natural recolonization of the Seine River by Atlantic salmon (*Salmo salar*) of multiple origins. *Canadian Journal of Fisheries and Aquatic Sciences*, 67(1): 1-4.

Abstract: The restoration of previously extinct salmon populations is usually achieved with stocking programmes, but natural recolonization can also occur through the straying of individuals from nearby populations. Here we investigated the origin of Atlantic salmon (*Salmo salar*) that recently recolonized the Seine River (France). The degradation of this river had led to the extinction of the population, but since the 1990s, the water quality has greatly improved. Although no stocking was performed, 162 individual salmon were recently observed by video-counting. Seven fish were sampled for morphological and genetic analyses. These individuals were genotyped at 17 microsatellites markers and their probable source populations were identified using baseline samples from regional and distant populations. Four of the sampled individuals were grilse and three were multi-sea-winter fish. Genetic analyses revealed that the fish partly originated from a nearby stock but also from distant populations, suggesting long-distance straying. This natural recolonization of a large river by strayers from several origins is discussed in terms of population sustainability and management.

References

RASP (Regional Assessment of Supplementation Planning). 1992. Supplementation in the Columbia River Basin, Parts 1-5. Report DOE/[BP 01830-11](#), Bonneville Power Administration.

RIST (Recovery Implementation Science Team). 2009. Hatchery Reform Science. A review of some applications of science to hatchery reform issues. More information on the RIST, as well as an electronic copy of this report, can be found at <http://www.nwfsc.noaa.gov/trt/index.cfm>.

CRITFC Comments on Mitchell Act DEIS, Review of Fitness Studies

Review of Studies Providing Measures of Relative Fitness and Relative Reproductive Success

Analyses and the proposed alternatives presented in draft environmental impact statement (DEIS) for the Mitchell Act (MA) rely heavily on use of the proportionate natural influence (PNI) and the proportion of hatchery-origin spawners (pHOS) standards proposed by the Hatchery Scientific Review Group (HSRG 2009). Strict application of these standards can put severe restrictions on the scale of hatchery programs, and on the numbers of hatchery-origin fish that are permitted to augment abundance of a natural spawning population. Hence, all of the proposed alternatives in the MA DEIS, other than Status Quo, require moderate to substantial reductions in current and proposed hatchery programs in the basin.

Justification for the PNI and pHOS standards are based on the presumption that hatchery rearing will affect a substantial negative effect on fitness of a natural population that is receiving hatchery-origin adults, and that this effect is genetically-based. This presumption is derived from assessment of results of studies that provide quantified measures of relative fitness (RF) or relative reproductive success (RRS) of the hatchery-origin (HO) versus natural-origin (NO) fish. In particular, two recent studies of Hood River steelhead (Araki et al. 2007b and 2009) are widely cited as “proof” that hatchery programs have dramatically large deleterious effects on natural population productivity, and that even over a small number of generations, these effects will rapidly accumulate so as to render natural fitness of the affected population significantly reduced.

We feel that this conclusion is exaggerated and misrepresents the scientific data that exists across the breadth of studies that have examined the issue. Further, focus on this single aspect to drive hatchery management policy in the Columbia basin ignores benefits that hatcheries may have on other viable salmonid population (VSP) parameters – abundance, spatial structure and diversity (McElhany et al. 2000), and completely disregards the associated legal, social and political issues related to fisheries and mitigation responsibilities for operation of the hydrosystem. It is for these reasons, as summarized in the cover letter to our comments, that the tribes recommend that NOAA not proceed on developing a preferred alternative and a final environmental impact statement based on the proposed document.

In this document, however, we concentrate solely on the rationale behind our conclusion that the presumption that use of hatcheries to supplement natural salmonid populations will significantly depress population fitness is exaggerated and misrepresents the available data. We provide synopses of all (to our knowledge) currently available information from studies of anadromous salmonids that have derived quantified measures of RF and RRS, then have summarized these data in a table and series of figures. The data were compiled from published manuscripts, technical reports and oral presentations made at scientific meetings. Results for several of these reports were previously presented within Table 1 of Araki et al. (2008) and/or in Figure 4 of the report Hatchery Reform Science by the Recovery Implementation Science Team (RIST 2009),

copied below. Information from additional studies, many of them recently described for ongoing programs, are also presented.

Of note, substantial caution is required in interpreting these results, especially when illustrated together within a graph such as RIST (2009) Figure 4, whose format was followed in the summary graphs. The data are not necessarily directly comparable. The methodologies used to obtain the RF and RRS measures differ greatly among studies, and the management schemes followed by the hatchery programs vary dramatically in terms species, source of the broodstock, broodstock management, and hatchery rearing and juvenile release practices. These issues and how they affect the resulting RF/RRS data are described in more detail below, followed by the synopses, and table and graphs. a) Some of the measures are of RF, representing differential survival between various life stages of HO and NO fish, while other studies are of RRS, involving differential natural spawning success plus survival to various life stages. b) Results for six different species are represented among these studies. However, the substantial differences in life histories among species will undoubtedly have varying impact on how hatchery rearing may affect reproductive fitness and survival. For example, except for one study each of Atlantic and Chinook salmon, the studies (limited to those using local broodstock sources) that provided the lowest measures of RF/RRS were of steelhead (Figures 2a and 2b). c) Some of the studies compare performance of hatchery stocks from non-local sources – often following several generations of deliberate selection for altered run/spawn timing, growth and/or behaviors relative to the natural population to which they were compared. When the objective is to assess effects of Supplementation hatchery programs (e.g., as described by Cuenco et al. 1993) for the purposes of rebuilding depressed populations, results from these studies using non-local hatchery stocks must necessarily be excluded (as was done in Figures 3 and 4). d) Some of the studies involve hatchery programs which followed segregated broodstock management (only HO adults were incorporated into the broodstock), while others integrated NO fish into the broodstock (from small proportions to 100%, depending on the program) each generation. The two approaches will have obvious impacts on the extent to which genetically-based impacts on fitness may accumulate over generations. e) The majority of the studies are indicated as “Confounded” within the “Effect on RF/RRS” column in the summary table. That is, results of the comparison between performance of HO and NO fish does not solely represent a genetically-based effect on fitness, but instead represents possible genetic effects plus confounding non-heritable environmental effects associated with the different spawning and juvenile life histories experienced by the fish being compared. If it possible to parse out the environmental effects from the overall RF/RRS measure, the resulting estimate for heritable RF/RRS would be closer to 1.0, and the data points for measures <1.0 would shift upwards. To illustrate this, the RF and RRS data from studies indicated as Confounded and < 1.0 were recalculated on the presumption that 50% of this difference was due to non-genetic effects. Graphing of the modified data (Figures 4a and 4b) provides a much more moderated impression of the magnitude might be of a deleterious effect of hatchery rearing that could accumulate (due to its heritable/genetic nature) over generations. Of note, even in those studies whose “Effect on RF/RRS” in the summary table is indicated

as “Genetic” (studies whose “common garden” designs permitted comparison of RF or RRS of fish with similar immediate rearing histories, but with differential natural versus hatchery genetic backgrounds), there are invariably additional confounding environmental effects that may have influenced results of the studies, typically to the detriment of the HO fish.

f) In Figures 3 and 4, results from the Araki et al. (2007a and b, 2009) for Hood River (HR) steelhead are differentiated from those of other studies using local source broodstock. These results from Araki et al 2007b and 2009 (although not those from 2007a, as they indicate non-significant effects on natural fitness following a generation of hatchery rearing), as indicated above, have been widely referenced to support the view that hatchery effects on natural population fitness are substantially negative and threaten their viability, and that hatchery programs must therefore be reduced in scope and duration. However, examining the compiled results for all of the studies presented here, it is evident that the RRS measures for HR steelhead are at the extreme low end of the range for reported data. In light of the “outlier” nature of these HR steelhead data, normal scientific caution requires that they be noted as cause for concern, but that to the extent that one is permitted to make generalized statements, it would be that the magnitude of heritable effects of a properly managed hatchery supplementation program will likely of a much reduced magnitude relative to that indicated by the HR steelhead studies.

g) Again, a reminder is appropriate that recommendations on how salmonid hatchery programs are scaled and managed – in particular for supplementation of depressed natural stocks - must not be based solely on possible deleterious fitness effects, but must also consider counteracting positive effects on the other VSP parameters - population abundance, diversity and spatial structure. Additionally, decisions of how best to manage hatchery programs within the Columbia basin must not be made in isolation from the social, political and legal issues associated with fisheries mitigation and alternative actions (restoration of freshwater habitat, changes in hydrosystem management to reduce mortality, and harvest management) that might be effective in rebuilding the basin’s salmon stocks.

In view of the substantial variation among study designs and the great dispersion of the resulting RF/RRS data, one cannot justifiably draw a general conclusion as to the magnitude of the effect that hatchery rearing may have on productivity of a natural population. The data do imply, however, that appropriate management of a hatchery program can diminish negative effects on reproductive fitness, both of an environmental and a genetic basis. Instead of imposing a single set of management standards (PNI and pHOS), hatchery programs need to be designed on a species and river-specific basis. The management plans must also be adaptive in nature so as to respond to environmental variation and to changes in population VSP parameters.

Abbreviations: H - hatchery
W - wild HO - hatchery-
origin NO - natural-origin

References

Hatchery Scientific Review Group (HSRG). 2009. Columbia River hatchery reform system-wide report. (http://www.hatcheryreform.us/hrp/reports/system/welcome_show.action)

McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-42, 156 p.

(<http://www.nwfsc.noaa.gov/publications/techmemos/tm42/tm42.pdf>)

Recovery Implementation Science Team (RIST). 2009 RIST (Recovery Implementation Science Team). 2009. Hatchery Reform Science. National Marine Fisheries Service (NMFS) Northwest Regional Office, Salmon Recovery Division, Portland OR.

(<http://www.nwfsc.noaa.gov/trt/index.cfm>)

Table 1 - Araki et al. 2008 Evolutionary Applications 1(2): 342-355

Table 1. Conditions, methodologies and estimated relative fitness (RF) in studies that compared the relative fitness hatchery and wild salmonids. Genetic effects are presumed where hatchery and natural adults were artificially spawned and the fitness of the resulting offspring was compared (assumes environmentally-mediated maternal effects of rearing from egg to smolt have no effect on offspring fitness). All paternal effects are also assumed to be genetic (assuming no grandparental maternal effects). Genetic and environmental effects are considered confounded where hatchery-born and wild-born fish are directly compared because they experienced very different juvenile environments. The duration of the hatchery fish in captivity is expressed in the number of generations in captivity (NGC), which was approximated as years of hatchery operation divided by modal age at sexual maturity. In integrated programs, where either wild fish are spawned in the hatchery or hatchery-origin fish spawn in the natural environment, the ancestry of hatchery and wild fish may differ by only a single generation, even if the duration of the hatchery program is much longer.

I. Completed Study	Species	Life History segment	Method	Effect on RF	NGC	RF*
Broodstock of nonlocal origin						
Chilcote et al. (1986)	Steelhead (<i>Oncorhynchus mykiss</i>)	Lifetime	Group genetic mark	Confounded	6	0.13
Leider et al. (1990)						
Fleming and Gross (1993)	Coho (<i>O. kisutch</i>)	Adult-to-fry	Individual behavior	Confounded	5	(m) 0.62 (f) 0.82
McLean et al. (2003)	Steelhead	Lifetime	Mixed stock analysis	Confounded	10+	0.02–0.11
McLean et al. (2004)	Steelhead	Adult-to-smolt	Mixed stock analysis	Confounded	10+	0.04–0.07
Araki et al. (2007a)	Steelhead (winter-run)	Lifetime	Pedigree	Confounded	10+	(m) 0.06 (f) 0.11
Araki et al. (2007a)	Steelhead (summer run)	Lifetime	Pedigree	Confounded	10+	(m) 0.35 (f) 0.37
Scenario 2: Local origin						
Reisenbichler and McIntyre (1977)	Steelhead	Egg-to-parr	Group genetic mark	Genetic	2	0.8
Reisenbichler and Rubin (1999)	Steelhead	Fry to age-1	Group genetic mark	Genetic	6	0.8
Fleming et al. (1997)	Atlantic salmon (<i>Salmo salar</i>)	Adult to fry	Individual behavior	Environment	1	(m) 0.48 (f) ~1.0
Dannowitz et al. (2004)	Brown trout (<i>S. trutta</i>)	Egg-to-parr	Pedigree	Genetic	7	1.27
McGinnity et al. (2004)	Atlantic salmon	Egg-to-adult	Pedigree	Genetic	5	~1.0
Dahl et al. (2006)	Brown trout	Parr to parr (1 year in stream channel)	Nose tag	Genetic	7	~1.0
Ford et al. (2006)	Coho	Adult-to-smolt	Pedigree	Confounded	25	(m) 1.01 (f) 0.74
Araki et al. (2007a,b)	Steelhead (winter-run, integrated)	Lifetime	Pedigree	Confounded	1	(m) 0.70 (f) 0.88
					2	(m) 0.32 (f) 0.30
				Genetic	1 vs 2†	(m) 0.55 (f) 0.55

*m, male, f, female, when the relative fitness (RF) was estimated separately for each sex of parent.

†Hatchery fish having one wild parent and one first-generation hatchery parent (NGC-2) compared to hatchery fish having two wild parents (NGC-1).

RIST Figure 4

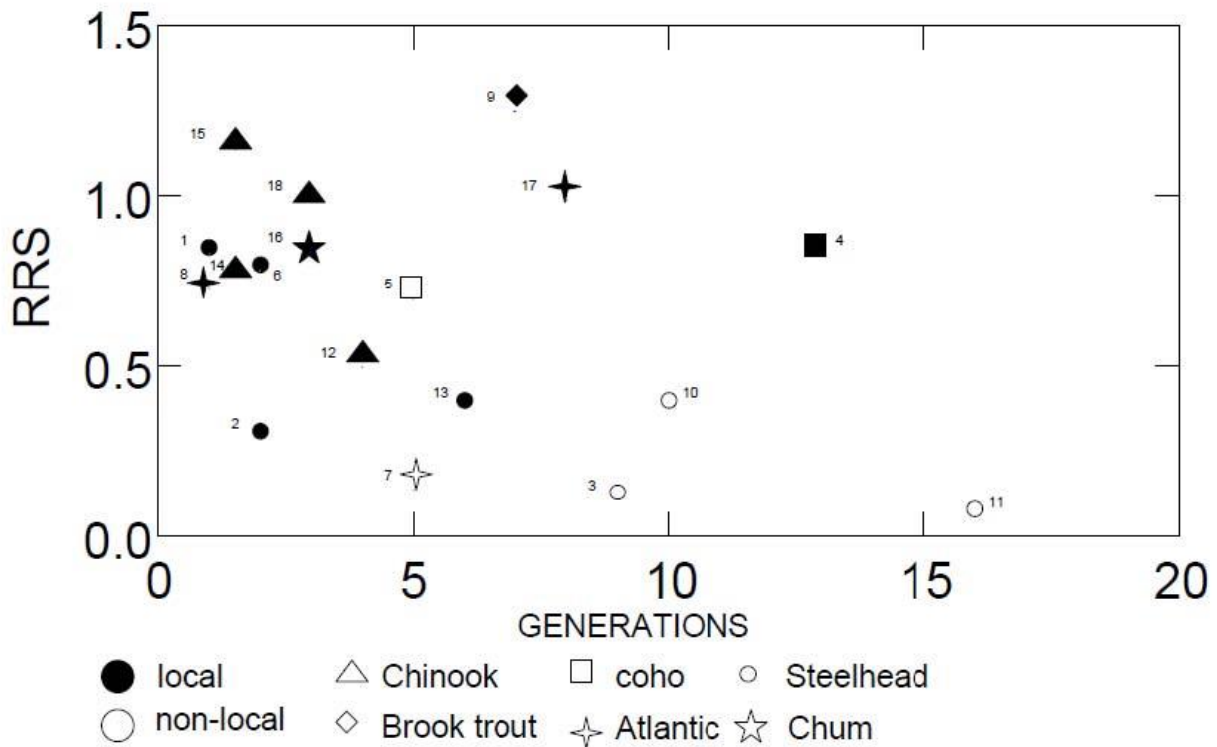


Figure 4 – Summary of relative fitness estimates by species, broodstock origin, and generations in the hatchery (compiled by Berejikian, NWFSC). 1 - Araki et al. (2007b)), 2 - Araki et al. (2007b), 3 - Leider et al. (1990), 4 - Ford et al. (2006), 5 - Fleming and Gross (1993), 6 - Reisenbichler and McIntyre (1977), 7 - Fleming et al. (2000), 8 - Fleming et al. (1997), 9 - Dannewitz et al. (2003), 10 - Araki et al. (2007a), 11 - Araki et al. (2007a), 12 - Murdoch et al. (2008), 13 - Moran and Waples (2007), 14 - P. Moran (NWFSC, personal communication), 15 - P. Moran (NWFSC, personal communication), 16 – Berejikian et al. (2008), 17 - McGinnity et al. (1997.), 18 – Leth (2005).

Hatchery broodstock of Non-Local origin

Leider, S. A., P. L. Hulett, J. J. Loch, and M. W. Chilcote. 1990. Electrophoretic comparison of the reproductive success of naturally spawning transplanted and wild steelhead trout through the returning adult stage. *Aquaculture* 88:239-252.

(preceded by: Chilcote, M.W., S.A. Leider, and J.L. Loch. 1986. Differential reproductive success of hatchery and wild summer-run steelhead under natural conditions. *Transactions of the American Fisheries Society* 115:726-735.)

- Electrophoretically identifiable Skamania (out-of-basin, segregated) stock Steelhead smolts stocked into the Kalama River in 4 successive broodyears
- Returning adults, beginning 2 years later, identified, and smolt production (Chilcote et al 1986) then adult production (Leider et al 1990) estimated for naturally spawning Skamania stock versus wild Kalama stock
- Relative productivity of Skamania stock was 75-79% for adult-to-smolt production (originally reported as 28% by Chilcote?), and 11-13% for adult-to-adult production
- Note: Poorer performance of Skamania stock was to have been expected – this hatchery stock differed from the Kalama River steelhead in life history, including altered timing for adult return, spawning timing, timing of seaward migration, and number of years spent at sea. These changes were the result of generations of intentional artificial selection and stock mixing. Additionally, there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.

Fleming, I. A., and M. R. Gross. 1993. Breeding success of hatchery and wild coho salmon (*Oncorhynchus kisutch*) in competition. *Ecological Applications* 3:230-245.

- Adult Quinsam Hatchery coho (segregated for 4-5 generations) stocked into an artificial stream with 2 groups of wild returning adults from nearby rivers in 1988 and in 1989
- Time of capture and pre-stocking handling similar between stocks within years; fish were size-matched between stocks
- Compared spawning behaviors and estimated egg production per individual as a measure of breeding success
- Breeding success of hatchery females = 82%, and of hatchery males = 62% relative to wild
- Hatchery-reared females did experience greater delays in the onset of breeding, suffered more injuries, and nest site locations were significantly different from wild-reared females, but had a longer life span in the multiple density experiments. The delays in the onset of breeding and the longer life span may be due to their inability to directly compete with wild females for optimal territory, or could be a tactic to reduce the likelihood of nest superimposition
- Hatchery males in the multiple density experiments were more submissive, less aggressive, and incurred more injuries than did wild fish
- Note: RRS was evaluated in competition, therefore cannot determine if difference was attributable to competition and/or to inherent differences in productivity between stocks; is unclear if traits in hatchery stock had undergone directed selection during segregated

breeding. Additionally, there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish

McGinnity, P., Stone, C., Taggart, J.B., Cooke, D., Cotter, D., Hynes, R., McCamley, C., Cross, T. and A. Ferguson. 1997. Genetic impact of escaped farmed Atlantic salmon (*Salmo salar* L.) on native populations: use of DNA profiling to assess freshwater performance of wild, farmed and hybrid progeny in a natural river environment. *J. Marine Sci.* 54: 998-1008.

- Study designed to control for confounding environmental factors, to compare eyed-egg to parr/smolt survival of progeny from wild versus farmed stock adults in a natural river
- Wild = native Burrishoole stock (Ireland), and Farmed = Norwegian Mowi strain (6 to 8 generations intense segregated selective breeding for net-pen culture)
- In 2 years (1993 and 1994), between 6 to 15 adults per stock (wild versus farmed) and per sex were factorially mated, and the eggs reared to the eyed-stage
- Known numbers of viable eye-eggs per cross were pooled, then placed in egg boxes and planted into a stream devoid of other salmon
- Parr sampled by electroshocking and smolts collected in traps
- Relative total number of juveniles collected: $W \times W > W \times H > H \times W > H \times H$; however, even the maximum difference ($H \times H = 83\%$ and 81% of $W \times W$) was not statistically different
- Note: By making the crosses artificially and out-planting viable eyed-eggs, the study design avoids confounding environmental effects of differential homing and spawning success and differential survival to the eyed-stage. The Farmed stock was of out-of-basin source and had been in segregated intensive selective breeding for 6 to 8 generations for net-pen rearing.

Fleming, I. A., K. Hindar, I. B. Mjølnerod, B. Jonsson, T. Balstad, and A. Lamberg. 2000. Lifetime success and interactions of farm salmon invading a native population. *Proceedings of the Royal Society, Series B Biology* 267:1517-1523.

- 22 out-of-basin Norway National Breeding Program farm stock adult Atlantic salmon and 17 native wild salmon placed upstream of weir in small (1 km) river for natural spawning in Nov 1993; fish were homozygous for alternative MEP-2 alleles;
- 0+ parr sampled by electrofishing fall 1994, and out-migrating smolts captured in trap in 1995 and 1996; and juveniles genotyped for MEP-2
- The proportions of WW, WH and HH were similar for parr versus smolt (therefore no observation of progressive decrease in productivity beyond parr); essentially all hybrid fish had W mothers
- Relative fitness: $WW = 68\%$, $WH = 26\%$, $HH = 6\%$, approximately; therefore $RRS \approx 18\%$ [= $(6 \times 2 + 26)/22 / (68 \times 2 + 26)/17 = 38/22 / 162/17$], although the manuscript indicates lifetime RRS was 16%
- Observations of spawning behavior indicated that farm males had 24% the “spawning success” relative to wild males - courted fewer females and participated in fewer spawnings

- Farm females constructed fewer nests and had significantly smaller eggs, and showed only 32% “spawning success” relative to wild females
- Note: Oddly, the # of males and females within each group of adults was not provided, so RRS could not be estimated within sexes. The total number of adult progeny for the 39 broodfish on which this assessment was based only 26 fish. However, RRS ≈ 0.16 was similar when measured at the age 0 stage (122 fish) and at out-migration (352 fish), giving greater credence to the determination for the adult RRS measure in spite of it being based on such a small sample size. While results of this study might be applicable to assessing productivity of farmed fish following escape from net-pens, it is not appropriate for inferring effects of hatchery supplementation. The farmed stock being tested had undergone intense selective breeding over 5 generations, for improved growth in net-pen rearing and fecundity (likely related to the smaller egg size of farm females?), making it predictable that there might be a reduction in natural reproductive performance. Reduced egg size is associated with selection for high fecundity, which typically occurs in a selective breeding program for farmed stock, and small egg size (and smaller size of fry) is known to correlate positively with small fry size, and small fry size with reduced fry survival in nature. The design is severely confounded in that natural reproductive performance of NO fish was being compared to adult fish coming straight out of farm net-pens – held 1 month in round tanks, then “dumped” into the river.

McLean, J. E., P. Bentzen and T. P. Quinn. 2004. Differential reproductive success of sympatric, naturally spawning hatchery and wild steelhead, *Oncorhynchus mykiss*. *Environmental Biology of Fishes* 69: 359–369.

- Forks Creek hatchery stock created with Bogacheil Hatchery stock derived from Bogacheil R + Chambers Creek hatchery stock) – 10 generations of segregated hatchery rearing
- Smolts released and adults allowed to spawn naturally in Forks Creek for two years (1996 and 1997); thereafter, HO fish culled at the weir
- Hatchery stock is genetically distinct, and has been deliberately selected for early return and spawn timing
- Age 1+ juveniles sampled and mixed stock analysis used to assign them to hatchery or wild parents; presumed little or no hybrid crosses due to large (2+ month) differences in average return timing (and presumably spawn timing) between hatchery and wild
- 1996 smolts per female: W=18.8, H = 1.07, H/W = 0.57
- 1997 smolts per female: W=24.5, H = 1.33, H/W = 0.54
- But, W females generally larger/more fecund than H females; after adjusting for size/fecundity, 1996 H/W = 0.043 (... how was this lower than before adjustment??), and 1997 H/W = 0.071
- Note: Poor performance of the hatchery fish is entirely to be expected, given the manner in which they were deliberately selected for return/spawn timing that is altered from that of wild stock. Additionally, there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.

McLean, J. E., P. Bentzen and T. P. Quinn. 2003. Differential reproductive success of sympatric, naturally spawning hatchery and wild steelhead trout (*Oncorhynchus mykiss*) through the adult stage. Canadian Journal of Fisheries and Aquatic Sciences 60: 433-440.

- Examination of adult returns from the 1996 and 1997 broodyears described above in McLean et al. (2004)
- Broodyear of adult progeny assigned according to scale age
- Hatchery stock is genetically distinct, and has been deliberately selected for early return and spawn timing (see above)
- Adult progeny assigned to hatchery or wild parents using mixed stock analysis; presumed no hybrid crosses due to large (2+ month) differences in average return timing (and presumably spawn timing) between hatchery and wild
- 1996 average adult progeny per female: W=3.73, H = 0.41, H/W = 0.110
- 1997 average adult progeny per female: W=6.70, H = 0.16, H/W = 0.024
- Note: As stated above (McLean et al 2004), poor performance of the hatchery fish is entirely to be expected, given the manner in which they were deliberately selected for return/spawn timing that is altered from that of wild stock. Additionally, there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.

Araki, H., W. R. Ardren, E. Olsen, B. Cooper, and M. S. Blouin. 2007a. Reproductive success of captive-bred steelhead trout in the wild: evaluation of three hatchery programs in the Hood River. Conservation Biology 21 (1), 181-190.

- See below: Hatchery broodstock on Local origin – Integrated broodstock management

Hatchery broodstock of Local origin – Segregated broodstock management

Reisenbichler, R. R., and J. D. McIntyre. 1977. Genetic differences in growth and survival of juvenile hatchery and wild steelhead trout, *Salmo gairdneri*. Journal of the Fisheries Research Board of Canada 34:123-128.

- Deschutes River HO and NO adult steelhead were captured and artificially spawned such that their progeny were electrophoretically identifiable
- Equal numbers of HH, HW and WW eyed-eggs or unfed fry were then stocked into sections of 4 natural streams or a hatchery pond
- periodic samples of surviving fry collected by electrofishing or in traps
- in 5 of 12 samples collected in the four natural streams: (2 of 4, 1 of 3, 0 of 3, and 2 of 2), WW fry survived significantly better than HH, and HW was intermediate; in the other 7 of 12 samples there was no statistical difference
- in the hatchery pond, in contrast, HH fish survived significantly better than WW, with HW intermediate
- Note: The HO population had gone through 2 generations of apparently non-random segregated hatchery breeding (there was already noted a difference in spawn timing

between HO and NO steelhead – although spawning for this study was conducted on the same day) which potentially biases results against the HO fish. Additionally, the study was conducted in competition, without comparisons of performance under separate rearing. The conclusion that the HH fish were “genetically different” overstates the weight of the data, but if the HH fish are genetically different, isn’t it likely due to broodstock management and not to an unavoidable effect of hatchery rearing?

Reisenbichler, R. R., and S. P. Rubin. 1999. Genetic changes from artificial propagation of Pacific salmon affect the productivity and viability of supplemented populations. *IC ES Journal of Marine Science* 56:459-466.

- This manuscript reviews several published reports on relative fitness of HO and NO, but also provides data on an study, indicated as “in progress”, that the authors are conducting on Clearwater River (Idaho) summer steelhead (although no subsequent publication was found in the literature ...?)
- For the latter, very few details of the study design were provided
- In two broodyears, adults of hatchery-origin (North Fork Clearwater origin, 6 generations in segregated rearing) and wild-origin (Middle Fork Clearwater) were apparently artificially spawned, and their eggs reared to the eyed-stage prior to “release” (in a natural stream environment ...?)
- Age 1+ parr apparently captured and identified as H vs. W by some means (?)
- Survival of the eyed-eggs to age 1+ parr for hatchery compared to wild – RF was approx. 0.8 (average for the 2 broodyears? - indicated simply as a data point in Figure 1)
- Note: The lack of details and data on study design, and the inability to find a subsequent published report/manuscript cast doubt on the reliability of these data. The hatchery stock, while derived from a nearby wild population, had apparently been in segregated rearing for 6 generations.

McGinnity, P., P. Prodohl, N. O. Maoileidigh, R. Hynes, D. Cooper, N. Baker, B. O’Hea and A. Ferguson.. 2004. Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. *Journal of Fish Biology* 65(Suppl. A):173–187.

- compare relative survival: A) eyed-egg to smolt survival, and B) eyed-egg to adult - of wild (W) versus native ranched stock (R) versus wild non-native (nN) Owenmore River stock released in a natural river
- Wild = native Burrishoole stock (Ireland), and sea-ranched = native Burrishoole stock after 18 generations of segregated rearing, non-native = wild Owenmore River stock (80 km north)
- A) eyed-egg to smolt: known number of eyed eggs for each cross type planted in artificial redds, and progeny sampled as parr and smolts by electrofishing and in out-migrant trap
- A) Relative survival eyed-egg to smolt: R = 98% and nN = 81%; the R stock did, however, show greater early out-migration as 1+ pre-smolts and a higher proportion that were mature

- B) smolt to adult: smolts for each cross type were reared in the hatchery, microtagged, and released; survival to adult stage measured by sampling in fishery and in in-migrant trap
- B) Relative survival smolt to adult (after accounting for estimated capture rate in coastal fishery): R = 104% (11.8% / 11.3%) and nN = 27% (3.1% / 11.3%); also, R showed a sex-ratio of returning adults significantly skewed in favor of females while W was 1:1, and time of freshwater entry for R was significantly delayed relative to W
- The low nN survival to adult did not appear to be due to straying
- Note: Common garden rearing eliminates primary confounding environmental effects. Despite 18 generations of segregated hatchery spawning/juvenile rearing, the sea-ranched stock (derived from wild Burrishoole stock) showed no differences in survival. In contrast, the wild non-native stock showed significant reduction in survival, despite the fact that its native coastal stream was only 80 km distant

Dannewitz, J., E. Petersson, T. Prestegard, and T. Järvi. 2003. Effects of sea-ranching and family background on fitness traits in brown trout *Salmo trutta* reared under near-natural conditions. *Journal of Applied Ecology* 40:241-250.

- Comparisons of eyed-egg to parr survival of eyed-eggs planted in egg boxes within an artificial stream (110 m, 345m²)
- factorial matings (in 1997 and 1999) of wild stock (W), versus sea-ranched stock (S) (local origin, 7 generations segregated), versus reciprocal hybrids (WxS and SxW); 10 females and 10 males each per stock
- Stream drained and 0+ parr collected and assigned parentage via microsatellite analyses
- In both years, survival to parr was numerically greater for SxS versus WxW, and in one year survival of hybrids was lower than for intra-stock crosses, and was greater for hybrids with S female parent
- After accounting for family effects (wide variation in survival between families) no significant difference in survival between crosses
- Note: HO fish were from a segregated hatchery stock; NO and HO fish both created by artificial spawning and planting of eggs in egg boxes – therefore eliminating confounding environmental effect of comparing fish with differing juvenile life histories

Dannewitz, J., E. Petersson, J. Dahl, T. Prestegard, A. Lofs and T. Järvi. 2004. Reproductive success of hatchery-produced and wild-born brown trout in an experimental stream. *Journal of Applied Ecology* 41: 355-364.

- In 2000, 6 females and 6 males each from a wild stock (W) and a sea-ranched stock (S) (local origin, 7 generations segregated) stocked into an artificial stream (110 m, 345m²) for natural spawning
- Stream drained and 0+ parr collected and assigned parentage
- Parr production was greater for the hatchery stocks, although difference was not significant; of note, there was great disparity in individual parentage, with a single WxS mating producing the majority of parr
- No assortative mating observed

- Reproductive success was not significantly different between stocks; RRS reported as 1.27 in Table 1 (Araki et al. 2008), although am unsure how this was calculated ...?
 - Note: The sea-ranched stock was segregated for 7 generations, and there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – both conditions should bias results against sea-ranched stock
 - (Experiment was repeated in 2001 with S (7th generation) and new first generation -created from wild parents - hatchery stock; first generation hatchery males fathered more progeny than seventh generation males, although no difference observed between females)

Dahl, J., E. Petersson, J. Dannewitz, T. Jarvi, and A. C. Lof. 2006. No difference in survival, growth and morphology between offspring of wild-born, hatchery and hybrid brown trout (*Salmo trutta*). Ecology of Freshwater Fish 15:388–397.

- Comparison of juvenile FW survival (age1 to age 2 parr)
- 10 matings each made in fall 1998 of wild stock (W), sea-ranched stock (S) (local origin, 7 generations segregated), and reciprocal hybrids (WxS and SxW); 10 females and 10 males each per stock
- After 1 year rearing under hatchery conditions (size was similar among cross types) the parr were nose tagged and stocked into an artificial stream (110 m, 345m²) for an additional 1 year FW rearing under natural conditions
- At harvest, no differences among cross types – neither for survival (approx. 40%) nor for growth
- Note: As for the 2 Dannewitz studies of this same stock, segregated rearing of this sea-ranched (hatchery) stock affected no difference in survival

Hatchery broodstock of Local origin – Integrated broodstock management

Araki, H., W. R. Ardren, E. Olsen, B. Cooper, and M. S. Blouin. 2007a. Reproductive success of captive-bred steelhead trout in the wild: evaluation of three hatchery programs in the Hood River. Conservation Biology 21 (1), 181-190.

- A study comparing RRS of traditional (out-of-basin segregated) summer run (Skamania – 1995 & 1996) and winter run (Big Creek - 1991) hatchery stocks used to supplement the depressed wild Hood River steelhead.
- Also, compared RRS of new integrated winter run hatchery fish (1995 to 1997) to wild Hood River steelhead
- Microsatellite and parentage analysis performed on DNA extracted from archived scales collected since 1991 on all natural origin fish arriving at Powerdale Dam (and passed upstream for natural spawning), and all hatchery origin fish that were passed upstream
- RRS Big Creek (1991) females = 0.11, males = 0.06
- RRS Skamania (1995 & 1996 – average of values with and without consideration of estimated angling upstream of Powerdale Dam) females = 0.37 and males = 0.35
- RRS of first generation hatchery reared fish produced from wild origin broodfish (1995 to 1997 – average of values with and without consideration of estimated angling upstream of Powerdale Dam) females = 1.08 and males = 0.98

- Quote from Abstract: “These are the first data to show that a supplementation program with native broodstock can provide a single-generation to the boost to the size of a natural steelhead population without obvious short-term fitness costs.”
- However, they also caution: “On the other hand, crosses between hatchery fish of either type (traditional or supplementation) were less fit than expected, suggesting a possible interaction effect.”
- Note: see below

Araki, H., B. Cooper, and M. S. Blouin. 2007b. Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science* 318:100-103.

- As described above, a supplementation hatchery (captive, C) program for winter-run steelhead in the Hood River began in 1991, using only wild (W) fish as parents. Substantial numbers of returning adult progeny (C) began in 1995.
- Beginning in 1995, the supplementation hatchery program used some of these HO returning adults as broodstock (in each case crossing them to wild fish to produce second generation of HO fish - C(CxW), as well as additional crosses with only wild x wild broodstock - C(WxW); and wild crosses – W(WxW) - also occurred each BY
- In 1998, 1999 and 2000, these second and first generation HO fish, and the wild fish, were allowed to spawn naturally. Their adult progeny were detected in run years beginning in 2001, and RRS calculated relative to wild fish, and relative to each other - C(CxW) vs. C(WxW).
- RRS of C(WxW) vs. wild (involves a difference associated with 1 generation of hatchery rearing): females = 0.77 and males = 0.49 (average for the 3 BYs). This comparison is confounded by environmental effect of the two groups of fish having experienced different spawning and juvenile rearing experiences.
- RRS of C(CxW) vs. wild (involves a difference associated with 1.5 generations of hatchery rearing): females = 0.30 and males = 0.32 (average for the 3 BYs). This comparison is confounded by environmental effect of the two groups of fish having experienced different spawning and juvenile rearing experiences.
- RRS of C(CxW) vs. C(WxW) (involves a difference associated with 0.5 generations of hatchery rearing): females = 0.55, and for males = 0.55 (average for the 3 BYs). This design is not confounded by environmental effects, as both groups were spawned and reared in the common hatchery environment. Therefore, the observed reduction in fitness is apparently due entirely to a genetic influence derived from a single generation of hatchery rearing in one of the grandparents.
- Note: see below

Araki, H., B. Cooper, and M. S. Blouin. 2009. Carry-over effect of captive breeding reduces reproductive fitness of wild-born descendants in the wild. *Biology Letters* doi: 10.1098/rsbl.2009.0315 (<http://rsbl.royalsocietypublishing.org/content/5/5/621.full.pdf+html>)

- the Hood River began in 1991, using only wild fish as parents for the winter run steelhead supplementation program. Substantial numbers of returning adult progeny (C) began in 1995.

- Beginning in 1995, some of these returning HO adults spawned naturally with each other - W(CxC) or with a wild fish -W(CxW), as well as additional wild x wild crosses - (WxW) - occurred
- In 1998, 1999 and 2000, these fish were allowed to spawn naturally, and their adult progeny were detected in run years beginning in 2001, and RRS calculated relative to wild fish, and relative to each other - W(CxC) vs. W(CxW) vs. W(WxW)
- RRS for W(CxW) vs. W(WxW), involving 0.5 generation difference in hatchery rearing, was: females = 0.84, and males = 0.92
- RRS for W(CxC) vs. W(WxW), involving 1 generation difference in hatchery rearing, was: females = 0.42, and males = 0.31
- This design, because the fish were all spawned and reared in the common natural environment, effectively limits observed differences in productivity to genetic causes
- Note: see below

Notes regarding Araki et al studies of Hood River steelhead:

- The authors report a series of RRS estimations following analysis of data from different subsets of BYs, involving a) comparisons of hatchery origin fish to wild fish which are confounded by environmental effects due to the fish having experienced differing spawning and juvenile rearing backgrounds, or b) comparisons of fish with NO vs. HO differences in grand-parentage, but similar parentage (common parental spawning and rearing environments), such that observed productivity differences can be attributed solely to genetic effects.
- The differences attributable to genetic effects in the latter studies are dramatic, and generally increase in magnitude with increase in the number of generations of hatchery rearing in the background of the fish. And, it is these results in particular which have been highly publicized and are cited by the HSRG and in the Mitchell Act draft EIS, as providing the rationale for (greatly) reducing the scale of current hatchery supplementation programs, and for impeding initiation of new programs.
- On the other hand, RRS measures reported in these studies for the comparisons that are confounded by environmental effects tend to be of a (much) lower magnitude. There is an apparent contradiction between these results, which the authors have not adequately addressed.
- Concerning these RRS comparisons which are confounded by environmental effects, in Araki et al. (2007a) the authors state: “Wild and hatchery fish experience very different freshwater environments. Thus, any fitness differences we observed could have a genetic or environmental origin, and a lack of difference (*RRS in their 2007a study was not significantly different from 1.0*) could conceivably include environmental deviations that are the opposite of genetic effects.” The authors anticipate that genetic effects associated with hatchery rearing will be negative, therefore the environmental effects must be positive??? By what mechanism(s) do the authors suspect that spawning and juvenile rearing in a hatchery improves natural spawning success and productivity of these hatchery-origin fish when they reach the adult stage? Common sense, and data from other studies, would indicate that these environmental effects will also likely be negative, and would be additive to negative genetic effects. Therefore, if one observes a measure of RRS that is not significantly different from 1.0 in a study where the genetic and

environmental influences on productivity are confounded, one must conclude that the portion attributable solely to genetic effects was even smaller, and certainly insignificant. Likewise, for a measure of RRS that is lower than 1.0, if the proportion of the reduction attributable to environmental effects could be subtracted from the overall reduction, the RRS value would increase, and the RRS measure is graphed such as in RIST Figure 4, the data point would shift upwards towards 1.0, such as illustrated in Figures 3a and 3b.

- And, not only are the RRS measures from the genetic-effect only designs of a larger magnitude than expected relative to their RRS measures for their confounded designs, they are also at the extreme low end for the array of RF and RRS measures observed in other studies (not including those studies which made comparisons involving non-local stocks, which would be invalid if the intent is to assess impacts of a hatchery supplementation program, *sensu* Cuenco et al 1993).
- While there is no denying the “elegance” of the designs in Araki et al. 2007b and Araki et al. 2009 that restrict observed productivity differences to genetic effects, taken in context with results across the breadth of published studies, scientific caution dictates that one be much more reticent presuming the generalized predictions of dramatic and rapid fitness loss associated with supplementation that have resulted from the manner by which the authors’ results have been publically presented and vaunted.
- One additional potentially confounding factor to these Araki et al. studies relates to the manner by which broodstock for the winter run steelhead program were chosen. These fish were sampled from among the winter run adults upon their return to the fish trap at Powerdale Dam. However, the Hood River also has a run of summer run steelhead, and there is overlap in return timing between stocks, and managers are certain that some level of misidentification has occurred in the past. The summer and winter runs have differing spawning and juvenile rearing life histories, such that hybridization between stocks will likely result in fish maladapted for one life history or the other. This situation was discussed by Matala et al (2009), and a relatively reliable molecular genetics test to distinguish between ecotype was described. To assure the readers that the differences that they are not, at least in part, attributable to the artifact of use of misidentified or hybridized individuals among the winter-run broodstock, Araki et al need to test and report that such was or was not the case.

Matala, A. P., R. French, E. Olsen and W. R. Ardren. 2009. Ecotype distinctions among steelhead in Hood River, Oregon, allow real-time genetic assignment of conservation broodstocks. *Transactions of the American Fisheries Society* 138: 1490-1509.

Fleming, I. A., A. Lamberg, and B. Jonsson. 1997. Effects of early experience on the reproductive performance of Atlantic salmon. *Behavioral Ecology* 8:470-480.

- Study to assess the environmental effects of juvenile rearing on spawning success - differences between wild reared adults and adults that were hatchery reared
- Salmon from a “common genetic background” (achieved by mixing wild-origin and sea-ranch hatchery-origin fish both in the river for natural spawning and in the hatchery broodstock ... am unclear as to how equivalent the genetic background would be ...?) were produced by natural spawning and rearing, and by artificial spawning and hatchery rearing

- Upon smolting, the sea-ranched smolts were released into the river with the wild smolts
- Adults were captured after 1 year (90%) or 2 years (10%) in the ocean, then stocked into experimental spawning arenas at varying densities and sex-ratios
- Observations made on spawning behaviors, and on number of eyed-eggs produced
- Sea ranched and wild males differed in competitive and reproductive performance, with wild males having significantly higher reproductive success
- There were few differences in competitive and reproductive performance between sea ranched and wild females
- Body size was shown to play a key role in competition in both sexes, with larger individuals being more aggressive
- A few of the large males in each arena dominated spawning, and attained considerably higher reproductive success than all other males
- For females, larger body size principally provided higher fecundity, but also influenced competitive behavior and early egg survival, likely through the effects on nest quality. In males, body size was highly correlated with aggressive behavior
- RRS for males averaged approx. 0.48; RRS for females was approx. 1.0
- Therefore, because the fish were from a common genetic background, “our results suggest that the differences in reproductive performance may be ascribed to early juvenile experience and related to the development of specialized skills important for not only early life, but also later river life”. This study indicates that environmental conditions may account for some (a large?) portion of the observed differences in reproductive success of HO versus NO – at least among males, rather than hatchery-dependent genetic changes.

Leth, B. D. 2005. Reproductive success of hatchery and natural origin Chinook salmon (*Oncorhynchus tshawytscha*) in a stream with a history of supplementation management. Master’s thesis. University of Idaho, Moscow, Idaho.

- RRS comparison of juvenile recruits per spawner for BY 2002 Pahsimeroi River spring/summer Chinook for BY 2002 NO and HO (first generation - produced from wild parents) adults
- Chi square analysis, within sexes, of observed and expected numbers of progeny
- For both males and females, no significant differences –

RRS 95% assignment 80% assignment average
 Females 0.89 1.11 1.00
 Males 1.21 1.23 1.22

- Acclimation site downstream, but not dramatically, of the primary spawning area
- Spawning area surveys showed similar distribution and spawn-timing of HO and NO adults
- There was no evidence of assortative mating
- Note: HO fish from an only partially integrated stock – they were 3rd generation, with 1st generation being 50% segregated HO fish, crossed to NO fish in the 2nd generation; additionally, there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish

Ford, M., H. Fuss, B. Boelts, E. LaHood, J. Hard, and J. Miller. 2006. Changes in run timing and natural smolt production in a naturally spawning coho salmon (*Oncorhynchus kisutch*) population after 60 years of intensive hatchery supplementation. *Canadian Journal of Fisheries and Aquatic Sciences* 63:2343-2355.

- Minter Creek coho salmon have undergone approx. 25 generations of supplementation following a segregated (?) hatchery program that used a broodstock of local origin, but with no restrictions (culling) of HO spawners (so the wild population was integrated)
- In 2000 and 2001, similar numbers of NO and HO adults were passed upstream of hatchery weir for natural spawning
- Size and run-timing similar between HO and NO, but run-timing much earlier than historic timing
- RRS not significantly different from 1.0 for both sexes: males = 1.01, females = 0.74
- Note: The wild population was integrated and so the NO fish tested had an unknown proportion of hatchery ancestry (as inferred by the altered run timing). The authors speculate that the lack of difference in RRS is most likely due to fitness of the NO stock having already been substantially reduced due to effects of their hatchery ancestry, such that the additional generation of hatchery rearing in the HO resulted in a reduction in fitness that was too small to be detected within the power of the study design and analysis. There is also the additional confounding environmental factor in the design of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.

Berejikian, B. A., D. M. Van Doornik, J. A. Scheurer, R. Bush. 2009. Reproductive behavior and relative reproductive success of natural - and - hatchery - origin Hood Canal summer chum salmon (*Oncorhynchus keta*). *Canadian Journal of Fisheries and Aquatic Sciences*, 66:781-789.

- In both 2004 and 2005, NO and HO (3 generations, integrated) Quilcene River (Puget Sound WA) adult chum salmon were collected and stocked into an artificial stream – 12 fish per sex for both stocks
- Spawning behavior observed, and fry collected and genotyped for parentage assignment
- Similar spawning behaviors between stocks
- RRS not significantly different from 1.0 (males = 1.03; females = 0.72)
- Note: there is the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish

Schroder, S. L., C. M. Knudsen, T. N. Pearsons, T. W. Kessler, S. F. Young, C. A. Busack, and D. E. Fast. 2008. Breeding Success of Wild and First-Generation Hatchery Female Spring Chinook Salmon Spawning in an Artificial Stream. *Transactions of the American Fisheries Society*, 137:1475-1489.

- Report of 7 trials in which ripe wild-origin and first generation hatchery-origin females

and males were stocked into an artificial stream for spawning

- Observations were made on spawning behaviors and redd characteristics, and fry were collected to assess relative adult-to-fry reproductive success via microsatellite DNA parentage analysis
- No differences detected in the egg deposition rate; subtle differences between hatchery and wild females in redd abandonment, egg burial, and redd location choice
- Average RRS for females = 0.94
- Geomean RRS calculated as the straightforward ratio of progeny identified with a H or W female parent divided by the total number of H or W female parents =0.86 (from Table 8 in Schroder et al. 2010)
- Note: Artificial stream design eliminates confounding influences attributable to differential homing and spawning distribution of HO and NO fish. In 6 of the 7 trials the W females were larger than the H females, although “body weight had no effect on egg deposition, egg-to-fry survival, or on the capacity to convert absolute fecundity to fry”.

Schroder, S. L., C. M. Knudsen, T. N. Pearsons, T. W. Kassler, S. F. Young, E.P. Beall, and D. E. Fast. 2010. Behavior and Breeding Success of Wild and First-Generation Hatchery Male Spring Chinook Salmon Spawning in an Artificial Stream. Transactions of the American Fisheries Society, 139:989-1003.

- Report of 7 trials in which ripe wild-origin and first generation hatchery-origin females and males were stocked into an artificial stream for spawning
- Observations were made on spawning behaviors, and fry were collected to assess relative adult-to-fry reproductive success via microsatellite DNA parentage analysis
- Male breeding success increased with weight, and wild males were on average slightly larger than hatchery origin males
- RRS calculated as the straightforward ratio of progeny identified with a H or W male parent divided by the total number of H or W males parents (adult + jack + precocious parr); geomean for RRS was 0.95
- Note: Artificial stream design eliminates confounding influences for differential homing and spawning distribution. RRS was not significantly different from 1.0, even without removing confounding effects

Williamson, K. S. A. R. Murdoch, T. N. Pearsons, E. J. Ward, and M. J. Ford. 2010. Factors influencing the relative fitness of hatchery and wild spring Chinook salmon (*Oncorhynchus tshawytscha*) in the Wenatchee River, Washington, USA. Canadian Journal of Fisheries and Aquatic Sciences 67: 1840-1851.

(Replaces: Murdoch, A., T. Pearsons, T. Maitland, M., and K. Williamson. 2008. Monitoring the reproductive success of naturally spawning hatchery and natural spring Chinook salmon in the Wenatchee River. BPA Project No. 2003-039-00. Bonneville Power Administration, Portland, Oregon. <http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=P106770>. Department of Energy, Bonneville Power Administration.)

- Report of RRS results for two BYs (2004 and 2005) of wild and hatchery origin Wenatchee/Chiwawa River spring Chinook, based on juvenile (out-migrating age 1 smolts) per spawner

- Integrated hatchery supplementation program in 4th generation (began 1989)
- Average RRS for females = 0.52, and for males = 0.32
- However, analyses showed significant confounding environmental effects:
 - ○ females – very large effect for spawning location (concentration in lower river due to homing to acclimation site – higher spawner density and poorer habitat) and lesser effects for age/size (in part attributable to accelerated growth in hatchery) and for run-timing
 - ○ males – very large effects for spawning location (concentration in lower river due to homing to acclimation site – higher spawner density and poorer habitat) and for age/size (tendency to return higher % of jacks, attributable to accelerated growth in hatchery), and lesser for run-timing
 - Note: because these confounding effects are in large part environmental (non-heritable effects associate with hatchery rearing practices), RRS attributable to genetic effects is much closer to 1.0 (when using spawning location as a predictor in two alternative statistical models, the effect of origin diminished in both, becoming non-significant in one of them) Additional non-genetic confounding factors associated with the different juvenile life history experience – hatchery rearing versus natural rearing –could bias results against HO fish

Sharpe, C. S, P. L. Hulett, C. W. Wagemann, M. P. Small and A. R. Marshall 2010. Natural Reproductive Success of First-generation Hatchery Steelhead Spawning in the Kalama River: A Progress Report. Washington Department of Fish and Wildlife, Fish Program, Fish Science Division FPA 09-07.

- Progress report with nearly complete RRS data for 2003 broodyear of Kalama River summer run steelhead
- Hatchery stock initiated with wild adults from 1998 to 2000 run years; age 1 smolts (a portion acclimated) and released
- Adult returns (progeny) sampled in 2007, and assigned parentage to via microsatellite analyses
- RRS for progeny assigned with 2 BY 2003 parents = 1.0
- RRS for progeny assigned with only 1 BY 2003 parent = 0.55
- Note: This study is ongoing, and these data should be updated annually. Recruits per spawner were low of 873 HO and 897 NO parents, only 70 (two parents) + 66 (one parent) progeny were identified among the 2007 returns.

Baird, M. E. Berntson E., T. Hoffnagle, S. Boe, J. Harbeck, R. Carmichael and P. Moran. 2008. Relative Reproductive Success in Spring Chinook Lostine River, Grande Ronde Basin. Oral presentation at the Lower Snake River Compensation 2008 Annual Meeting. (<http://www.fws.gov/lsnakecomplan/Happings/2008AnnualMeeting.html>)

- Catherine Creek spring Chinook hatchery program
- RRS reported for 4 BYs (2002 to 2005) based on juvenile (parr) recruits per spawner
- Slide 9: Females – geomean (1.88, 1.16, 1.55, 0.94) = 1.34
- Slide 9: Males – geomean (1.11, 0.58, 0.81, 1.33) = 0.91

- Note: The study design has the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish. The PPT presentation also provides RRS information on Lostine River spring Chinook and Little Sheep Creek steelhead – however, more recent information for these two programs is provided in the presentations described below.

Bernston, E. 2009. Relative Reproductive Success in Spring Chinook Lostine River, Grande Ronde Basin. Oral presentation at the Nez Perce Tribe, Department of Fisheries Resources Management, 2009 Symposium on Salmon Supplementation.

(<http://www.nezperce.org/~dfm/Research/2009%20Symposium.html>)

- Lostine River spring Chinook hatchery program initiated as a captive broodstock program with captured wild parr in 1996, followed by integrated supplementation program with returning adults in 1997 – 1.5 generations
- RRS reported for BY 2001, 2002 and 2005, based on juvenile (parr) recruits per spawner
- Slide 8: Females - geomean (1.13, 2.12, 0.84) = 1.26
- Slide 8: Males - geomean (0.76, 0.90, 1.91) = 1.09
- Note: The study design has the confounding environmental factor of comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.

Bernston et al. Coastwide Salmon Genetics Meeting 2010 presentation (submitted: Bernston, E.A., R.W. Carmichael, M.W. Flesher, E.J. Ward and P. Moran *In Review*. Swimming against the current: diminished reproductive success of hatchery fish complicates the use of supplementation in Snake River steelhead recovery. Submitted to Transactions of the American Fisheries Society) (replaces: Moran, P., and R. S. Waples. 2007. Monitor and evaluate the genetic characteristics of supplemented salmon and steelhead. Project number 1989-096-00. Research Progress Report Oct 5, 2007. Report to Bonneville Power Administration.

<http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=P107430>)

- Reports RRS results for Little Sheep Creek steelhead – integrated supplementation program initiated in 1982 – 5 generations
- All adults passed above the weir were tissue sampled, and juveniles were collected annually
- Geomean RRS for adult-to-juvenile (2000 to 2005) = 0.39 for females, and 0.51 for males
- Geomean RRS for adult-to-adult (2000 to 2003) = 0.32 for hatchery females, and 0.50 for males
- RRS adult-to-juvenile and adult-to-adult very similar
- Note: Hatchery juveniles undergo accelerated rearing for release at age 1+, whereas naturally spawned and reared juveniles do not out-migrate until age 2+ or 3+, which no doubt affects differences in age and size of the adults. Data for location of juvenile

capture indicated that hatchery fish spawned primarily in the lower reaches (likely a homing response to acclimation location), while wild fish spawned more evenly throughout the river, including upper reaches where spawner densities were lower and habitat quality was higher. Is some (substantial?) proportion of lowered productivity of hatchery fish attributable to these effects? The study design has additional confounding environmental factors associated with comparing natural spawning performance of two groups of fish with different juvenile life history experience – hatchery rearing versus natural rearing – which should bias results against HO fish.