Agenda item 6.1
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Approaches to minimising unintended negative consequences to wild Atlantic salmon populations from hatchery and stocking activities

(Kyle A Young, University of Zurich)

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SUMMARY

This paper outlines a talk of same title presented at the Theme-based Special Session on '*Understanding the risks and benefits of hatchery and stocking activities to wild Atlantic salmon'* held at the NASCO Annual Meeting in Varberg, Sweden, 6-9 June, 2017. I draw freely on relevant theory and empirical data from species other than Atlantic salmon. I do not comprehensively review the vast relevant literature, but offer key references as entries into that literature. Unless otherwise qualified, I assume that the integrity (*i.e.* evolutionary and ecological *naturalness*) of wild salmon is a management priority. I begin by summarising the science underpinning the evidence-based consensus that stocking hatchery-reared fish into wild populations should be avoided. I then offer a few explanations for why we continue stocking despite this consensus and suggest that understanding, challenging, and accommodating these sociopolitical drivers is essential for minimising the negative consequences of hatcheries and stocking to wild salmon. I next describe three types of existing guidance on hatcheries and stocking. I then present a new 'where, when and how' approach to stocking that accommodates the reality that we will likely continue stocking where and when we should not. The approach is built around simple rules informed by first principles, theory, empirical evidence, and the recommendations of existing guidance. It departs from current guidance and practice by proposing that capturing and transplanting wild fry within and between populations offers a cost-effective alternative to stocking hatchery-reared fish that accommodates sociopolitical drivers while minimising risks to the integrity of wild salmon.

BACKGROUND

We have been stocking Atlantic salmon since the time of Darwin. The apparent benefit is obvious; stocking can increase the number of adults, but not always, not always by a lot, and perhaps not for very long. The risks are nearly as obvious, and the contemporary scientific consensus that stocking hatchery fish threatens wild populations could have been predicted from the theory and empirical evidence that spurred the Evolutionary Synthesis of the mid-20th century (Huxley 1942). That prediction came in 1977, when Reisenbichler and McIntyre (1977) combined simple genetic techniques with one of evolutionary ecology's most informative experimental designs to provide the first compelling evidence that stocking hatchery fish threatens wild salmonids. They bred genetically identifiable Hatchery and Wild steelhead (*Oncorhynchus mykiss*) to create pure HH, pure WW, and crossed HW offspring. Using a 'reciprocal transplant' experiment, they stocked these offspring together in a hatchery pond and four sections of stream. Pure HH fish survived best in the hatchery pond, and pure WW fish survived best in natural streams. This empirical evidence that hatchery-imposed selection leads to the evolution of phenotypes that are maladapted to the wild led the authors to warn, "…that the short-term effect of hatchery adults spawning in the wild is the production of fewer smolts and ultimately, fewer returning adults than are produced from the same number of only wild spawners".

Stocking science over the last 40 years has used a range of approaches to confirm, clarify and refine this prescient warning. Much of this research is from the Pacific Northwest (PNW) of the United States, where large and valuable salmon runs, severe and wide scale habitat destruction, hundreds of industrial-scale hatcheries, and the Endangered Species Act have provided the sociopolitical mandate, empirical data, and resources required to advance the field. Empiricists compiled examples of (non)adaptive phenotypic divergence between hatchery and wild populations (Swain and Riddell 1990, Fleming and Gross 1993, Heath *et al.* 2003). Theorists clarified the neutral and (non)adaptive evolutionary genetic consequences of hatcheries and stocking (Waples 1991, Ford 2002, Araki *et al.* 2008). Applied ecologists studied the wider impacts of hatcheries and stocking on wild salmonids and their ecosystems (Rand *et al.* 2012).

In the last decade, two types of evidence have firmly established the critical links between hatchery breeding/rearing and reduced individual fitness in the wild, and between stocking and declines in population productivity. Two studies tell the story. Christie et al. (2014) quantitatively synthesised the results of studies that used genetic parentage analysis to estimate the fitness of first generation hatchery-born adults (*i.e.* the offspring of wild broodstock) and wild-born adults spawning in the wild. They compiled 51 estimates of mean reproductive success for these two types of fish from six studies on four species (including Atlantic salmon). In 46 cases, adults born in a hatchery to wild parents had lower fitness than wild-born adults. These and other studies demonstrate that a single generation of hatchery rearing can drive the evolution of phenotypes maladapted to the wild (Christie *et al.* 2012). Chilcote et al. (2011) used the vast data available from the PNW to estimate the population productivity (*i.e.* the slope at the origin of the adult-to-adult stock-recruitment curve) for 94 populations of three Pacific salmonid species. They found that productivity declined with the proportion of hatchery-born adults in the spawning population. Across species, using stocking to double adult population size reduced productivity by half, meaning there is no demographic benefit to balance the damage caused by stocking. Consistent with the evidence summarised by Christie et al., they found that hatchery fish from wild-broodstock schemes reduced population productivity by the same amount as those from traditional multi-generation hatchery populations.

Forty years of research supports a simple, long-standing, evidence-based scientific consensus: if the integrity of wild salmon is a management priority, stocking hatchery fish should be avoided (Hilborn 1992, Blanchet *et al.* 2008, Araki and Schmid 2010, Palme *et al.* 2012). Understanding exactly how a single generation of hatchery rearing reduces fitness in the wild remains one of several interesting research challenges (Christie *et al.* 2016), but the management challenge lodged in 1977 is unequivocally resolved.

THE PATHOLOGY OF STOCKING

And yet we keep doing it.

Minimising the negative consequences of stocking requires understanding why, in the face of overwhelming scientific evidence, we continue stocking hatchery fish into wild populations. For a few notable exceptions (Meffe 1992, van Poorten *et al.* 2011), the stocking literature lacks explicit sociopolitical perspective. The glaring disconnect between scientific evidence and management practice suggests this is a mistake. We need to understand, challenge and accommodate the pathologies that compel and perpetuate irrational management interventions (Holling and Meffe 1996, Rist *et al.* 2013). I offer a few reasons I suspect we continue stocking. The relative importance of these sociopolitical drivers depends on the degree to which management decisions are influenced by government agencies, scientists, anglers, NGOs and other stakeholders. Embracing alliteration, my "Seven Hs" elaborate on one of the "Four Hs" threatening wild salmon more generally: Habitat, Harvest, Hydropower, *Hatcheries*.

Habit. We stock mostly because we stock. It is far easier to build a hatchery than close a hatchery. We have invested countless millions building and operating hatcheries. Hatcheries attract volunteers and fatten agency budgets. From anglers running a small wild-broodstock scheme to occupy their spring, to agencies releasing millions of hatchery fish to 'mitigate' a dam, old habits, no matter how wasteful and harmful, are hard to break.

High. People love fish. Playing with them gives us a bit of a high. Anglers love collecting, handling and spawning adults, then dumping buckets of fry into their favourite stream. Schoolchildren love visiting hatcheries and watching fry grow in their classrooms. Hatcheries and fish engage, inform and inspire.

Hubris. Meffe's (1992) original critique of hatcheries as manifestations of "techno-arrogance" targeted the large hatcheries of the PNW. A similar arrogance contributes to stocking for any purpose by any name. We are wedded to the idea that we can use technological interventions to overcome the fundamental rules of population and evolutionary ecology.

Honour. Individuals and institutions have staked their reputations and resources on hatcheries and stocking. Intransigent pride can compel otherwise rational actors to behave irrationally. We must be sympathetic and sensitive to those who have, with best intentions, dedicated their careers to supporting and delivering management interventions that are more harmful than helpful.

Hope. No matter how much evidence accumulates demonstrating stocking hatchery fish compromises the integrity of wild populations, people will hope. They will hope that their broodstock collection, breeding designs, rearing environment and stocking strategy are different, that their river and fish are different, that what they do will help rather than harm. Blind faith sees no evidence.

Heresy. If well-intentioned hope is understandable, the cynical dismissal of evidence-based scientific consensus is inexcusable. Science denial afflicts society more generally, making it acceptable, even admirable, to dismiss scientific consensus as mere opinion. It does not help that fisheries managers long supported, even promoted, stocking into wild populations as a responsible and effective management intervention.

h-index. Scientists are judged in part by the impact of their papers. Increasing one's GoogleScholar *h-index* (the number of papers *h* with at least *h* citations) requires publishing more, and more interesting, papers. We are trained to amplify uncertainty, state our conclusions cautiously, and seize any funding opportunity. At best, we tacitly support stocking to advance our careers. It is a short and slippery slope from 'we may as well collect data if we're stocking' to 'we need to keep stocking because we're collecting data'. At worst, we prevent informed precautionary management by amplifying managerially irrelevant scientific uncertainty in the name of apolitical righteousness. Stocking science is political. Scientists who benefit from this fact have a responsibility to be so too.

EXISTING GUIDANCE

Nearly every agency and NGO involved in salmonid management offers guidance on stocking, much of which is focused on minimising negative consequences to wild salmonids. This guidance can be crudely grouped into three types.

The first addresses the challenge of minimising the impacts of traditional hatcheries with populations of proper 'hatchery fish'. This work has been led by the US National Oceanic and Atmospheric Administration's Northwest Fisheries Science Center, which guides the Hatchery Scientific Review Group (HSRG) in the PNW. While work began earlier, since 1999 HSRG members have been reviewing hatchery programs, providing advice, and publishing reports and peer reviewed papers (HSRG 2017). Minimising demographic and genetic interactions between hatchery and wild populations figures prominently. Large populations of hatchery fish are not going away. The idea is to keep hatchery fish away from wild fish using physical (*e.g.* weirs and traps) and behavioural (*e.g.* release and spawning times/places) methods, mark them with adipose fin clips, and kill them when they are captured.

The second type focuses on smaller stocking schemes whose principal purpose, regardless of linguistic qualifier (*e.g.* mitigation, enhancement, restoration), is to provide more fish to catch. While the HSRG contributes, this type of guidance is often provided by fishery agencies and NGOs (*e.g.* NASCO 2006, RAFTS 2014). Beyond timid discouragement, the principal goal is to reduce the negative impacts of wild-broodstock schemes that, contrary to the above, *purposely* mix wild and hatchery fish. Advice is offered on, among other topics, selecting broodstock, breeding protocols, rearing conditions, and stocking locations and densities.

The final, and least developed, type of guidance is motivated by the observation that anadromous salmonids display some elements of meta-population structure (Levins 1969, Hanski and Gilpin 1991, Hanski 1998); discrete populations are demographically and genetically connected to varying degrees by straying adults (Schtickzelle and Quinn 2007). The idea is that some habitable patches are (functionally) vacant and stocking can be used to artificially increase inter-population migration rates, thus increasing the total number of adult fish, and the size and resilience of wild salmon meta-populations (Young 1999, Schindler *et al.* 2010, Anderson *et al.* 2014).

A NEW APPROACH TO STOCKING

My suggested approach is based on four guiding principles, draws on existing guidance and the literature, and challenges and accommodates the 7-Hs. It begins with the evidence-based presumption that stocking hatchery fish is bad for wild salmon. We should thus do it as little as possible, and in the least damaging way possible, where and when wild salmon matter.

The approach combines simple rules for *where* and *when* (not) to stock with an operational step-change in *how* we stock. Accepting that we will continue stocking where and when we should not, it attempts to minimise the damage we inflict on wild salmon when doing so too.

Four guiding principles

All populations face inevitable extirpation. If ecological conditions render a population's growth rate perpetually negative, extirpation will be deterministic, unless such 'sink' populations are demographically rescued by immigrants from larger 'source' populations (Pulliam 1988). Extirpation can also occur because of environmental stochasticity (e.g. a volcano), demographic stochasticity (all individuals fail to replace themselves by chance), and genetic stochasticity (the chance accumulation of 'bad' or loss of 'good' genes through drift and inbreeding). Except for environmental stochasticity, these risks only threaten very small populations, which are likely to suffer extirpation by demographic stochasticity before genetic factors are important (Lande 1993).

Adding individuals to a population will (almost always) decrease its growth rate. This decrease may be negligible and difficult to detect in small populations free of strong density-dependent effects. Adding individuals can conceivably increase a small population's growth rate if it suffers from depensation, or 'Allee effects', whereby its deterministic growth rate *declines* as population size drops below some critical level (Courchamp *et al.* 1999, Liermann and Hilborn 2001).

Adding maladapted individuals to a population will decrease its growth rate *more*. Regardless of a population's size or growth rate, adding individuals with phenotypes mismatched to environmental conditions will decrease the population growth more than adding individuals whose phenotypes have evolved under similar selection regimes.

Adding (any) individuals may rescue small populations from extirpation by demographic stochasticity. For such populations, it is possible that the benefit of larger population size will outweigh the risk of a lower deterministic growth rate. A population's future may be brighter with 1000 maladapted individuals than with 13 well-adapted individuals.

Where and when (not) to stock

Evolutionary theory and empirical evidence suggest the following scenario approximates reality. The threat to wild populations from stocking is the product (semi-literally) of three quantities: the ratio of hatchery to wild adults in the spawning population; the degree to which hatchery fish are maladapted to the wild; and the probability of hatchery fish breeding and interbreeding with wild fish. All else being equal, the higher the ratio of hatchery to wild fish, the greater the risk is to the wild population. The more maladapted a hatchery population, the greater the risk is to the wild population. But as a hatchery population becomes more maladapted, the probability of hatchery fish successfully breeding declines. For a given ratio of hatchery to wild spawners, the threat from hatchery fish will be lowest when they are phenotypically extremely similar or divergent to wild fish. In the first case, hatchery fish will 'nudge' the wild population off its adaptive peak through interbreeding. In the second case, the wild population would be 'shoved' off its adaptive peak through interbreeding, but the probability of that happening is low. The greatest threat to wild populations likely comes when hatchery fish are maladapted, but still able to successfully reproduce. With a threat scaled to the ratio of hatchery to wild spawners, perpetually stocking hatchery fish parented by wild-broodstock will incessantly nudge the wild population off its adaptive peak, making it less and less wild, leading to a 'semi-wild' broodstock scheme. Though intuitively appealing, socially engaging, and increasing popular, subjecting viable wild populations to wild-broodstock stocking schemes is ecologically and evolutionarily irrational.

Where and when TO stock

Where and *when* there are no wild salmon, or *where* and *when* the integrity of wild salmon is not a management priority.

or (possibly and rarely)

Where there is a wild salmon population and *when*: it is at immediate risk of extirpation; there is no targeted harvest; it does not receive immigrants from other wild populations; ecological restoration is, and will continue to be, funded and delivered. Importantly, extirpation risk should be determined using Population Viability Analysis (PVA) and our knowledge of salmon population dynamics. It should not be determined using status assessments such as: 'there are fewer fish than before', 'there are not enough fish to catch', 'a dam removed half the habitat', 'it's below its conservation limit', or 'its 10-year growth rate is negative'. In the absence of formal PVA, a reasonable rule might be: if there are enough adults to support a stocking programme, then don't stock.

Where and when NOT TO stock

Where and *when* there is a wild salmon population that does not meet the conditions above.

These simple 'where' and 'when' criteria allow us to continue stocking hatchery fish to support fisheries in some areas, while protecting wild populations from stocking in other areas. Angling regulations can be adapted to support these management objectives. This stocking-angling 'portfolio' approach has been recently implemented on the Oregon coast of the PNW (ODFW 2014). Doing so will be more challenging where rivers and fisheries are not managed by government agencies as shared and freely accessible public resources.

How to stock

Where and when wild salmon don't matter

In the first case, we accept, and aim to minimise, the risk posed to wild salmon by hatchery populations designed to support fisheries. The goal is to create maladapted hatchery fish and keep them away from wild fish. Physical isolation (distance and barriers) and release protocols should be used to minimise demographic straying and genetic introgression into wild populations. To allow monitoring, all hatchery fish should be adipose-clipped, and a sub-set can be code-wire tagged. All fin-clipped fish should be killed when captured.

Where and when wild salmon do matter

How to stock in the second case, where and when wild populations matter, is the more interesting challenge. The current vogue is to stock hatchery-reared offspring of wild-broodstock, but first principles and evidence suggest this approach can be demographically ineffective (Young 2013, Bacon *et al.* 2015) and evolutionarily damaging (Chilcote *et al.* 2011, Christie *et al.* 2014). Neither research into molecular minutia nor tweaking hatchery and stocking practices will change how the fundamental processes of population and evolutionary ecology operate.

We need a new approach to *how* we stock *where* and *when* wild salmon matter.

Three features of Atlantic salmon ecology (Aas *et al.* 2011) suggest capturing, transporting and stocking wild fry may be that *how*. First, adult spawners tend to be spatially clustered across river channel networks, which results in emergent fry being spatially clustered (Finstad *et al.* 2010, Foldvik *et al.* 2010). Second, most emergent fry belong to the 'doomed majority' that will die quickly, and the chance of dying increases with fry density (Einum and Nislow 2005). Third, emergent fry do not get far alive (Einum and Nislow 2005), so early density-dependent population regulation operates at fairly small spatial scales (10 to 100s, not 1000s of metres) (Einum *et al.* 2006, Einum *et al.* 2008). Together, these observations suggest we can remove thousands of emergent fry from high-density source areas, transport them, and stock them into target areas that would otherwise be stocked with hatchery-reared fish. By culling from the doomed majority at small spatial scales during the earliest post-emergence life stage, we are unlikely to reduce the adult-to-smolt productivity of source populations, even when they are relatively 'small'. Because stocked fish are wild, and exposed to un-natural environments for only hours to days instead of months to years, we will dramatically reduce the phenotypic and genetic 'footprint' of stocking.

Depending on the locations of source and target areas, wild fry stocking can be implemented at spatial scales ranging from reach (intra-deme), to river (intra-population), to basin (meta-population), to inter-basin (inter-stock). A reasonable first step for identifying source fry is to ask: "From where would fall fry and parr immigrate?" or "From where would adult colonists most likely come?" As a default, it is sensible to collect wild fry from as close to the target area (in river km) as possible. Still, while the population genetic structure of wild salmon conforms loosely to 'isolation by distance', the 'nearest neighbour' might not always be the 'nearest phenotype' (Fraser *et al.* 2011). The choice of source area should be informed by matching environmental variables (*e.g.* hydrology, migration distance, thermal regime, geology, water chemistry) and phenotypic traits (*e.g.* life history, body size, spawning time, parr maturation rates) to the target area. We can also use genetic distance indices like F_{st} to select source fry, but caution is required (Whitlock and McCauley 1999). The genetic effective migration rate between two populations depends on both the number of migrants exchanged *and* their reproductive success. Two populations may have a low F_{st} value (exchange lots of genese) because they exchange lots of migrants, but those migrants may have relatively mismatched phenotypes and low fitness. Given these general principles, in some cases it will be reasonable to hedge our bets by collecting fry from various source areas, even those that might offer phenotypic mismatches.

Operationally, stocking wild fry is cheaper and simpler than stocking hatchery fish. We are replacing a hatchery with perpetual staff and running costs with a few person-months of fieldwork. To ensure low capture efficiency, wild emergent fry can be collected using casual, low-power, single-pass electrofishing (or in some habitats pole seines). Fry can be collected from multiple sites throughout the emergence period to 'neutralise' capture-imposed selection on emergence location and time. During each morning capture session, fry can be held in live wells before being transferred to a tank filled with source water (and a block of ice or aerator if needed) for transport to the target area. Target water can be mixed into the tank during lunch, and the wild fry can be stocked in the afternoon. More elaborate holding and transport methods can be used as terrain and distances require.

Wild fry stocking is a natural extension of 'meta-population guidance' aimed at artificially increasing colonisation rates from occupied to vacant habitat patches (Young 1999, Anderson *et al.* 2014). To date, 'active colonisation' interventions have relied principally on transporting adults and stocking hatchery juveniles. In their recent review of Pacific salmonid reintroductions, Anderson et al. found "…no direct evidence that these approaches have established a demographically independent, self-sustaining population". The wide non-native distribution of many salmonid species suggests this conclusion should elicit reflection rather than dismay, though Atlantic salmon does seem to be a particularly poor colonist by salmonid standards.

In the current context, there are a number of reasons why it makes more sense to stock wild fry than transplant wild adults. First, fry emergence is more synchronized than adult spawning time, so it will take less time to sample across the phenological range of source-area fish. Second, stocked fry are much less likely than transplanted adults to swim out of the target area. Third, collecting fry will provide a better sample of the genetic and phenotypic diversity of the source area. Fourth, unless adults are collected on the spawning grounds, we have little idea of their destination (*i.e.* an area of low or high emergent fry density?). Fifth, when disaster strikes, it is better to lose a batch of fry than a truckload of adults. Sixth, wild fry stocking will support a much richer range of study designs to inform adaptive management.

Will wild fry stocking be better for wild salmon?

It can't be worse. While there is an overwhelmingly compelling body of evidence suggesting traditional and wild-broodstock approaches harm wild salmon, I know of none suggesting they have either saved a wild population from extirpation or increased wild population productivity or size.

Regardless of benefit, the risks to wild salmon are almost certainly lower. Instead of imposing fish to serial episodes of artificial selection through much of their life history (selecting broodstock, breeding, incubation, rearing, release), wild fry will spend a few hours (or at most days) in captivity. The target area will be stocked with what are wild fish by any but the strictest definition. For the source area, it seems unlikely that removing a small proportion of the doomed majority from areas of high emergent fry density will be tangibly more damaging than removing adults to support hatchery-based stocking. Obviously, initial wild fry stocking programmes should be well monitored, and ideally conducted in areas with spatiotemporally relevant data for one or more life-history stage.

Will wild fry stocking accommodate the 7 Hs?

We stock to satisfy people, not to benefit salmon. Wild fry stocking must compellingly challenge and accommodate relevant sociopolitical drivers.

Habit. We still get to stock fish, and even use hatchery staff and equipment. Wild fry stocking provides ample opportunities for stakeholder participation and education.

High. Electrofishing is way more fun than picking dead eggs or cleaning silt from intake screens. We still get to play with fish. Admittedly, we will miss catching, touching and stripping adult salmon.

Hubris. We still get to satisfy our techno-arrogance by improving nature with clever interventions.

Honour. We are still stocking, and could not be doing so without the knowledge and contributions of hatchery staff and stocking proponents.

Hope. We have a fresh target for our bottomless reservoir of hope.

Heresy. Winning over stocking science deniers is tough work. Wild fry stocking offers a new means to engage and educate.

h-index. Wild fry stocking can be used to address a wide range of pure and applied questions. If funding is available, researchers will do exciting science that will inform adaptive management and produce career-enhancing publications.

CONCLUSION

The persistent disconnect between scientific evidence and management practice suggests that stocking is in a conceptual and operational rut unlikely to protect or improve the integrity of wild salmon. I have offered an alternative approach that accommodates sociopolitical drivers, is unlikely to be worse, and likely to be better for wild salmon. I encourage those controlling research funding and stocking management to embrace this new approach in the spirit of adaptive management.

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