SUSTAINABILITY CONSIDERATIONS FOR THE EXPANSION OF US OPEN OCEAN AQUACULTURE

Managing Risks from Escaped Fish

Environmental Defense Fund

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Guided by science and economics, Environmental Defense Fund (EDF) tackles our most urgent environmental challenges with practical solutions. EDF is one of the world's largest environmental organizations, with more than 2.5 million members and a staff of 700 scientists, economists, policy experts, and other professionals around the world.

About the Project

EDF and partners are pursuing a science-based, inclusive approach to the development of aquaculture in the federal waters of the United States. EDF advocates for federally directed research to better understand potential offshore aquaculture impacts and steps needed to ensure aquaculture operations throughout the supply chain are sustainably designed and use best practices, which minimize risk. Well-regulated, responsible, and sustainable open-ocean aquaculture operations can drive new investment and jobs, support community resilience, increase U.S. food security, and address issues associated with climate crisis disruptions.

EDF is working to build support among ocean, coastal, and seafood stakeholders and policy makers to establish a rigorous, science-based environmental and social regulatory framework that provides a predictable environment for business investment, protects ocean health, and supports equitable outcomes for coastal communities and individuals working throughout the seafood industry.

To learn more about EDF's U.S. aquaculture portfolio, contact Maddie Voorhees, EDF's Climate Resilient Fisheries and Oceans program at *mvoorhees@edf.org* or visit *www.edf.org*.

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Environmental Defense Fund (EDF) enlisted Council Fire, PBLLC to collate research on the current landscape associated with the containment of native finfish species relevant to developing a U.S. open ocean aquaculture industry. This paper was developed in collaboration with EDF staff, who seek to identify ways to optimize opportunities and minimize risks to people and nature while supporting a sustainable seafood system domestically.

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Introduction

An estimated one-third of marine ecosystems are at risk from farmed fish escaping net pens (Atalah & Sanchez-Jerez, 2020). Fish farming operations are also at risk due to the socioeconomic impacts of these escaped fish (revenue, assets, staff time, and public perception or reputation of the aquaculture industry). Exposed fish interactions with wild populations may impact commercial and recreational fisheries. The causes and magnitude of escapes and the subsequent risks vary.

However, how risk is defined, measured, interpreted, and communicated varies greatly, leading to inconsistent and confusing narratives for industry and the public. It's easier to discuss the potential risks relating to fish escaping aquaculture pens than to measure the realized impacts of those escapees on marine ecosystems and capture fisheries. Many studies have been conducted on the survival and impacts of cultured fish in the wild, encompassing both intentional releases of cultured fish to support conservation or fisheries goals and accidental "escapes'' from fish farms, with sometimes conflicting conclusions about long-term survival and ecosystem impacts.

There is limited information regarding the impacts on wild fish populations of many native species likely to be cultured in U.S. open ocean aquaculture net pens in the future. Most of our knowledge regarding the impacts of accidental escapes comes from studies of the most prolific farming operations on salmonids (including outside their native range) and European seabass/sea bream in shallow coastal Mediterranean areas. Conclusions drawn from species reared in these operations may not be transferable to other finfish (see box inset below; Alvanou et al, 2023; Jorde et al, 2024).

Drawing Parallels from Salmon to Open Ocean Marine Finfish Aquaculture

The Atlantic salmon aquaculture industry is highly profitable and has been operating for 50 years in Norway, with significant early and sustained support and management from the Norwegian government. There is extensive information surrounding the cause, frequency and magnitude of escape events and subsequent survival of cultured fish from these operations. Measuring risk however, is difficult, even in this well-developed and highly documented industry. Substantial evidence indicates cultured salmonids have lower 'fitness' than wild fish, their interbreeding with wild salmon has resulted in genetic mixing across the North Atlantic, and subsequent altered life history characteristics in the "wild" population (Glover et al, 2017; Karlsson et al, 2016; Strand et al, 2023; Bolstad et al, 2021; Besnier et al, 2022). Regardless of adverse impacts documented from escaped salmon, including in the ocean environment, there remains debate on the impact cultured fish have generally, on wild populations (McMillan et al, 2023) and there is limited knowledge of the long-term ecological impact of escaped survivors in offshore waters (Bolstad et al, 2021).

While there are meaningful conclusions to be drawn from these abundant data, it is important to consider that salmon have differing life history traits from marine finfish and have been reared in unique habitats. Furthermore, areas with a high density of large salmon farms are also home to depleted wild populations, which lack resilience to stressors. Of marine species likely to be raised in a US open ocean industry, the wild counterparts produce more offspring than salmon, have larger population sizes, a lower level of genetic differentiation, and may be less susceptible to genetic risks (Waples et al, 2012). Despite these obvious differences between salmon and other species, there are cautious lessons to be learned from the science and management of large-scale salmon operations and it would be wise to consider opportunities in technology, genetics, and fish health that have been utilized in this sector to prevent escapes and mitigate their impacts.

This paper draws conclusions primarily from the escapes of marine finfish farmed in their current natural range or their native ocean basin that would be relevant to marine species and operations expected to be reared in U.S. offshore waters (e.g., Seriola spp., red drum, cobia, etc; Engle et al, 2022), although the survival and subsequent impacts of non-native aquatic species escapes/introductions in the U.S., China, and other nations have been well- documented (BC Salmon Farmers Association; Ju et al, 2019). As stressors mount and ocean systems shift due to climate change, our understanding of the natural range of species and the resilience of surrounding wild populations may change, thus complicating risk assessment (NOAA Fisheries, 2023). While this paper is focused on managing risks from farming native marine finfish, concerns about risks from seaweed and shellfish also abound (see box inset below).

What about Seaweed and Bivalve Containment?
Cultivated seaweed and shellfish in open production systems also pose potential risks to local ecosystems, through broadcast spawning. Gene flow from farmed to wild organisms is poorly quantified and remains low for seaweeds (Graf et al, 2021), but impacts have been documented (e.g., hybridized mussels in Fla.) and are dependent on species and management techniques. Variables affecting impacts and best practices are similar for seaweeds and shellfish (e.g., farm size and siting affect dispersal of reproductive products, adherence to genetic protocols reduces risk).

The Nature of Escape Events

The three main ways finfish escape net pen aquaculture are 1) discrete large-scale "catastrophic" escape events due to equipment breakdown and loss of containment, 2) ongoing low-level "leakage" of fish through small holes in nets or during transport/handling, and 3) release of eggs and/or fertilized gametes into surrounding waters. Scientists have estimated that 2-5% of farmed fish may escape open net pens (0-2% per event, which occurs multiple times per year), representing several million fish each year globally (Lorenzen et al, 2012; Alvanou et al, 2023; Fry et al, 2018). Despite increased production, there has been an overall decline in the reported number of escapees in recent years. This decline has been attributed to the adoption of technical standards in Norway and subsequent investment in technologies and infrastructure and the adoption of plans, policies, and practices that reduce catastrophic escapes from net pen failures to *de minimus* levels (N. Sims, pers. comm., Føre & Thorvaldsen, 2021; Strand et al, 2023).

Most large-scale escape events are caused by progressive breakdown and/or system failure of technical equipment (e.g., damaged nets, failure of one component in a complex mooring) due to stressors including abrasion, biological fouling, attack by large predators, and severe storms or earthquakes, and sabotage. These causes are easily identified by industry employees and are often documented, allowing for [internal] quantitative analysis. Ongoing "leakage" events, however, are more difficult to estimate. Leakages are not frequently reported but may be significant over time, especially in areas with high concentrations of net pens (0.5 -1% salmon leakage; Thompson, 2008). A common cause of leakage, fish "nibbling," accounts for as much as 50% of cod escapes due to leakage through smaller holes in the net (Jackson et al, 2015). Furthermore, some fish must be kept in captivity in order to reach desirable market size, and those individuals that reach maturity before harvest release eggs and/or fertilized gametes into surrounding waters through the net mesh. The magnitude of these "escapes" is not tracked, nor can it be quantified easily (Jorde et al, 2024).

More recently and as a result of the trend towards larger farms and consolidation in the industry, human and organizational errors during stocking or harvest operations (e.g., mishandling of equipment) have been identified (Føre & Thorvaldsen, 2021; Alvanou et al, 2023). Regardless of the reason for escape, once fish escape net pens, recapture success is variable but most often low (8%; Dempster et al, 2016), varying with fish size, number, behavior, weather/safety conditions, predation, local fishing pressure, and incentives for recapture (Alvanou et al, 2023; Chittenden et al, 2011; Toledo-Guedes et al, 2014).

Transparency is critical to evaluating escapes, their causes, and their impacts, and a global database does not exist, although many operations record and report this information to local authorities and, if applicable, certification organizations. It remains clear that large-scale escapes continue to challenge the industry. Leakage is difficult to estimate, and it will be increasingly critical to consistently and accurately estimate escape losses as aquaculture production increases. The known lack of precision in escapes reporting and transparency performed in other countries has undermined the trust required to secure a social license to expand the U.S. industry in the open ocean (Berglihn & Gezelius, 2024).

Considering Intentional Releases of Cultured Fish

Much can be learned by studying the impacts of *intentional* releases of cultured fish for conservation or recreation purposes. U.S. Federal hatchery managers and their partners have introduced native and non-native cultured fish into the wild for over a century to support sportfishing opportunities, meet fish population rebuilding goals, or provide important subsistence food resources in coastal areas (Pister, 2001). High-trophic species, similar to those chosen for net pen operations for seafood, are often selected for their aggressive behavior, which is attractive to sport fishermen. The number of cultured fish released is immense–In 2022, 98 million finfish were released from Federal hatcheries, and 1.9 billion salmon were released from Alaskan hatcheries (US Fish and Wildlife Service; Wilson, 2022). However, survival rates of marine species such as white bass are considered extraordinarily low due to predation, lack of food-finding skills of cultured fish, etc. While some stock enhancement programs contribute to conservation or fisheries goals, others may be ineffective, risky, or have not been evaluated (World Fisheries Congress).

Stock "Enhancement"?
Approximately 100,000 white sea bass, reared in hatcheries and coastal net pens for stock enhancement to increase sportfishing opportunities, have been released per year in CA marine waters. By 2013, 2 million cultured fish had been released. To date, 199 adult fish have been recaptured (0.01%). Scientists have concluded that the released cultured fish experience high mortality, despite the large size of individuals at release (CA Sea Grant, 2017). Regardless of its failure to meet stated goals, this program is widely supported by stakeholders.

Potential Risks to Wild Populations and Current Knowledge

If fish that escape from aquaculture operations survive in the wild, compete for food sources, and reproduce with wild individuals, they could pose an important threat to wild fish populations (Alvanou et al, 2023). That risk varies depending on multiple factors, including species (i.e., native vs non-native and fish behavior), escape rates, genetic management (selective breeding for certain traits), site of introduction, farm and hatchery management practices/protocols, fish health management, and environmental conditions in the wild. Subsequent risks rise with the number of escapes when fish are farmed in their native range, when wild populations are outnumbered, and when fish carry pathogens (Naylor et al, 2005; Lorenzen et al, 2012). The relative abundance of the "neighboring" wild population is a major factor in the significance of potential risk; most negative impacts are greatest when cultured fish are abundant and wild populations are depleted or declining (Florida Sea Grant, 2019). Robust native populations tend to be more resilient to the risks introduced by cultured fish in the wild. In addition to localized risks, the cumulative effects of multiple stressors of escapes are unknown. Over the long term, if risks are not minimized, impacts on ecosystems could be irreversible (Atalah & Sanchez-Jerez, 2020).

Competition for Food/Habitat/Mates

To pose a risk to wild fish, escaped cultured fish must survive and thrive by learning to procure food, avoid predation, and find mates. Many escaped fish die shortly after being released into the wild because they are eaten by predators or lack the skills to find food, but for some species, a modest survival rate and dispersal throughout an ecosystem could result in negative ecological consequences due to the magnitude of some escape events (Arechavala-Lopez et al, 2017). Over time, surviving cultured fish could compete for prey and habitat with their wild counterparts, which is problematic in areas with limited availability of those resources, thus limiting the growth of the wild population. This is especially true if the cultured fish exhibit plasticity in certain traits in the short term to become more “feral” (e.g., becoming better “hunters”), as hypothesized for European sea bass (Valero-Rodriguez et al, 2015; Toledo-Guedes et al, 2021). “Leakage” of fish from net pens (in contrast to one-off large-scale escape events) provides a continuous source of cultured fish to the surrounding waters, allowing for competitive interactions to occur in the near term, regardless of whether those fish survive or reproduce in the longer-term (Arechavala-Lopez et al, 2017).

Competition between cultured native and wild fish has not been documented in the U.S. Researchers elsewhere have documented poor performance of several escaped species in the wild; cultured fish are not adapted to the wild environment and may be susceptible to disease or increased predation (Alvanou et al, 2023; Rodriguez-Estrada, 2017; Sims, 2013; Strand et al, 2023). Studies indicate survival rates of fish released as part of stock enhancement programs can be extraordinarily low (CA Sea Grant, 2017; see box inset below). Still, some cultured fish, farmed and intentionally released, can disperse and survive (Arechevala et al, 2018; Castellanos-Galindo et al, 2018; "Tracking Red Drum from Hatchery to Adulthood"). In the open ocean environment where fish are more often dispersed (cobia, in this instance), the risk of competition for resources by escaped native fish is not considered significant (Monterey Bay Aquarium Seafood Watch, 2022).

Reproduction in the Wild and Weakening of Wild Populations

Interbreeding between native farmed escapees and wild fish and subsequent genetic mixing in the population (gene flow) is of the greatest ecological concern because farmed fish are bred for a range of traits they do not share with wild fish. Those traits may not be advantageous over time in the wild (Glover et al, 2017). The *extent* of genetic impacts of escaped fish depends on the size of the wild stock in proportion to the frequency and numbers of escapes, wild stock genetic structure, degree of selective breeding of escaped fish, and the source of broodstock used to produce the farmed fish (Arechavala-Lopez et al, 2017). The *speed* of intermixing of those genes likely depends on the genetics (parentage) of the released fish, the number of fish released and the rate of stocking, the duration of release, and the fitness (survivability) of hatchery fish (Kitada, 2018). Models indicate that higher quantities of escapees and greater genetic differentiation from the wild population increase genetic impacts (Darden et al, 2017). Despite their low numbers, because survivors of low-level leakage continuously increase the proportional genetic contribution of poorly adapted cultured fish to the total population, it is essential to **address and reduce low-level leakage AND large-scale, one-time events when seeking to mitigate potential genetic risks** (Baskett et al, 2013).

There is a lack of information about interbreeding as a long-term result of fish or egg escapes for many species and regions where aquaculture is practiced, and ongoing monitoring is largely absent (Arechavala-Lopez et al, 2017; Jorde et al, 2024). Cultured sea bream, sea bass, cobia, and salmon have been found to reproduce in the wild (Jorstad et al, 2014). No long-term genetic impacts have been documented to date due to escapees' interbreeding with sea bream, cod, or cobia populations (Alvanou et al, 2023; Jorde et al, 2024; Benetti et al, 2010). Regarding egg "escapes," although cod eggs originating from farmed fish have been identified outside of net pens, their survival rate is unknown.

Concerning intentionally released cultured fish, only a few marine fish stocking programs have been evaluated to assess genetic mixing in wild populations. Gene flow from hatchery fish to wild populations has been documented in those programs that have been evaluated. However, reductions in the "fitness" of wild populations from interbreeding between intentionally released fish and their wild counterparts have not been demonstrated (Kitada, 2018). The genetic impact of marine stock enhancement diminished with the increased size of the wild population of the same species, suggesting that fisheries management and habitat protection are more important to sustaining ecosystem health (Kitada et al, 2019). The genetic risk from escaped farmed species in open ocean environments is dependent on many variables and remains unclear, and there remains a lack of knowledge, even of basic impacts, of the global extent of the issue for species other than salmon (Jorde et al, 2024).

Disease Transmission

All finfish species are vulnerable to parasitic, viral, and bacterial diseases. The proximity of cultured and wild fish where net pens are placed can create novel transmission dynamics (even without escapes), including an amplified abundance of pathogens (Krkosek, 2017). Pathogenic transmission risk among marine species in open ocean environments remains unclear and dependent on many variables, including survival and behavior of escapees, their levels of infection, and pathogen characteristics. Still, **stock enhancement program monitoring and risk assessment modeling suggest that there are solutions to mitigate the risks** (Atalah & Sanchez-Jerez, 2020; Aseffa & Abunna, 2018; Alves et al, 2020; Bartley et al, 2006). These prevention and control measures include maintenance of fallow (fishless) nets to eliminate disease cycles, biological and chemical disease control strategies, and biosecurity measures such as careful siting, transportation from other facilities, monitoring for disease outbreaks, etc.

Best Practices to Minimize Risks

The most responsible aquaculture operations adhere to widely accepted practices and protocols (genetic, fish health, and management) that are designed to minimize risks from escapes (NOAA Fisheries, 2020; Lorenzen et al, 2010; ASC International, U.S. Army Corps of Engineers, 2016; Norway, 2022). Proposed aquaculture operations should be evaluated individually, based on known risk-influencing factors and safety indicators; internal audits, development of preventative measures, and staff training have proven useful (Holmen et al, 2021).

Risk Assessment/Planning Operations

At the outset, responsible aquaculture risk assessment of proposed operations assumes escapes are inevitable in offshore net pens. The assessment should consider multiple factors, including the effects of storms, predation, petroleum spills, hurricanes, harmful algal blooms, fish health, and biosecurity mitigation, to minimize risks (Rhodes et al, 2023). Powerful planning and assessment tools utilized by multiple regulatory agencies during aquaculture permitting processes in the U.S. evaluate interactions between cultured and wild fish and predict impacts, such as resource competition, genetic mixing, and disease transmission (e.g., Lorenzen, 2005, NOAA Fisheries, 2022; see box inset below).

Offshore Mariculture Escapes Genetic Assessment (OMEGA)

While multiple state and Federal agencies weigh in on permitting considerations for US aquaculture depending on proposed location of a farm, it is NOAA staff that have developed a mathematical model (OMEGA) as a promising tool to evaluate genetic risks associated with escapes of farmed fish from open ocean aquaculture operations. While a risk assessment model is not a solution to manage escape risks, it provides rigorous evaluation and appropriate caution during the permitting process. NOAA continues to collaborate to evaluate model parameters based on current and planned aquaculture operations that influence model predictions (NOAA Fisheries, 2022).

Equipment/Infrastructure Systems

Innovative net/cage technology, including innovative materials and design of pens, mooring systems, and submergence systems, have been developed to sustain high-energy environments/storms and predator damage (e.g., Stronger America Through Seafood & Innovasea, 2024). Understanding cultured fish and predator behavior has led to even better designs. When coupled with continued attention to maintenance (e.g., removing biofouling on netting, which can affect net pen sturdiness) and commitments to anti-predator measures such as additional physical barriers, stronger net materials, or acoustic deterrents, fish farmers can further minimize the ecological and economic impacts of escapes (Berillis et al, 2017).

Operational Strategies

Monitoring of Gear and Fish and Staff Training

Monitoring of infrastructure and numbers of fish can prevent escape events resulting from fish "nibbling" or, on a larger scale, equipment failure (e.g., due to biofouling, predation, etc.). Fish monitoring systems can also result in a more accurate assessment of the number of escapes (e.g., Cooke Aquaculture Pacific, 2021) and how the number of escapees varies across life cycle stages, which is needed to support risk assessment (see above, e.g. State of Maine; Baskett et al, 2013). When cost-effective and where adopted, advanced technology and data analytics such as artificial intelligence (AI), sensors, and camera systems monitor fish behavior to decrease risks of escapes and increase recapture success (Stronger America Through Seafood & Innovasea, 2024). Consistent and thorough training of farm employees in operational standards such as transporting and handling cultured fish and monitoring and reporting can also improve outcomes in preventing escapes.

Genetic Protocols and Sterility

Genetic protocols are established practices that may include selecting appropriate, non-transgenic, and genetically similar broodstock compatible with wild populations. Genetic isolation is the most effective way to minimize genetic impacts from escaped farmed fish onto wild populations. It is accomplished by rearing sterile (infertile) individuals, including gene-edited species strains that cannot breed with wild fish or are not likely to survive outside the farm (Xu et al, 2022). Selective breeding programs also have been effective at delaying maturity in farmed fish and may prevent the release of cultured fish eggs from individuals in captivity (Taranger et al, 2010). U.S. Fish and Wildlife Service and the U.S. Department of Agriculture

(USDA) maintain the capacity to evaluate and/or minimize the genetic impacts of escaped fish through genomic sequencing and, with colleagues at the National Oceanic and Atmospheric Administration (NOAA), maintain the expertise to develop standards related to genetic risks and solutions for open ocean aquaculture (e.g., USDA)

Biosecurity Strategies

Biosecurity strategies are widely adopted measures that protect the health of farmed fish and the surrounding wild populations. They include selecting appropriate species, controlled transport/harvest, health surveillance/certification of fish placed in net pens; decreased stocking densities, siting, minimized stress, vaccination, disposal of mortalities, and disinfection and decontamination (Rhodes et al, 2023). Health management recordkeeping is essential for tracking and responding to issues that arise (Florida DACS, 2023).

Reporting and Contingency Plans Post-Escape

Different states have different permitting requirements (summary of states) however, generally, U.S. aquaculture operations are subject to fish escape reporting (fish production, fish health, and escape numbers) and response plan requirements, which include emergency reporting to state and tribal agencies, enacting fish recapture plans, limiting continued escapements, and providing an annual fish release report (e.g., State of Maine, US NPDES; Cooke Aquaculture Pacific, 2021; Florida DACS, 2023). Making information publicly available helps track trends in escapes and builds trust. Training and adopting service vessel operating procedures can decrease human errors leading to escapes and are already required by several U.S. states (e.g., Florida Department of Agriculture and Consumer Services (DACS)) that open ocean operators would have to transnavigate to reach their farms.

Ongoing Monitoring, Documentation, Research of Impacts, Solutions

Monitoring operations and escape events and performing research evaluating subsequent impacts of escaped fish must be swift and widespread. Funding, partnerships, and, critically, pilot studies with fish farmers would enable researchers to respond to events and fill critical knowledge gaps, including individual or multi-species-specific genetic and siting criteria that would minimize genetic impacts and disease transmission and technology performance/minimum standards for aquaculture infrastructure by region. This type of research and monitoring would also support the evaluation of cumulative risks of open ocean aquaculture.

Strengthening Wild Populations of Fish

The extent of impacts from escapees on wild populations depends, in part, on the health of the surrounding fish assemblages and, by association, their habitats. Maintaining healthy habitats, water quality, and sustainable fishing levels (both on wild populations of farmed species and predatory fish around net pens) is likely to reduce the negative impacts of escapees through increased resilience of wild populations (Arechevala-Lopez et al, 2018; Dempster et al, 2016). Healthy ecosystems benefit fish farmers and fishermen; these stakeholders co-exist in many locations. Their coexistence is supported by the adoption of best practices in both aquaculture and fisheries management (Nimmo et al, 2022; National Aquarium Association, 2021).

Conclusions

The following conclusions represent outstanding concerns and recommendations affecting sustainable open ocean aquaculture industry growth.

Without Standards, A Growing Industry = Growing Risks

Best practices require treating escape events, both large and small, as an inevitability. As a result of an expanding aquaculture industry, risks to marine ecosystems are likely to become more prevalent without environmental protection standards in place. **Adopting currently recognized best practices could suffice in the near term to minimize risks if widely adopted. Still, additional approaches and emerging technologies should be supported to heighten U.S. aquaculture's sustainability.** Genetic, fish health, and fishery management protocols and technical and operational standards developed for preventing escapes provide a framework for optimizing ecological, economic, and social goals. To ensure these protocols are used, the open ocean industry in the U.S. must be guided by a comprehensive regulatory framework that protects ecosystems and enables sustainable industry growth. The U.S. lacks a federal regulatory framework and strong standards needed to support sustainable and profitable open ocean farming. This regulatory absence has left domestic aquaculture growth vulnerable to regional and state-driven regulatory inconsistencies, resulting in lawsuits and stymied investment.

An Ounce of Prevention is Worth a Pound of Cure

Escapes may be a cost of doing business for some fish farmers, but the cost to wild fish populations is hard to measure. In the absence of definitive and specific research findings on the long-term impacts of marine finfish escapees on wild populations in open ocean settings, **risk assessments should guide the mandatory adoption of proven prevention and mitigation safeguards,** including infrastructure standards and genetic and fish health protocols, that address risks before fish have a chance to escape.

Data For All—Accessible Escape Event and Response Information

Required reporting and contingency plans allow for tracking and evaluating escape events. When mitigating actions are successfully carried out swiftly, they can minimize negative interactions through subsequent containment or recapture (e.g., Cooke Aquaculture Pacific, 2020). **Requiring transparent monitoring and reporting across the industry, supported by an accessible, interoperable national data system,** would improve the completeness, quality, timeliness, and accessibility of marine aquaculture data and support increased sustainability in the industry (e.g., a state-federal collaborative program similar to the existing U.S Fisheries Information System program; NOAA Fisheries, 2024).

Knowing What You Don't Know and Then Filling/Funding the Gaps

Fish farmers are financially incentivized to develop and adopt solutions for reducing escapes; they not only lose profit in the short term when their fish swim off, but their reputation suffers as well, affecting long-term profitability. **Cooperative research could be useful to identify, pilot, and potentially invest in cost-effective technologies and practices that improve environmental performance,** including those used in terrestrial food systems (e.g., containment and monitoring technology, siting criteria; Fujita et al, 2023). Broader topics of global risks to food security and fishing communities also require attention. Finally, it is necessary to provide accurate information about the sustainability of marine open ocean aquaculture with heightened dissemination of science-based conclusions.

Tradeoffs in the Context of Other Food Systems

Achieving a goal of zero escapes from net pens may be possible, but the best technology may have cost, operational, and maintenance limitations. While there are several emerging technologies and approaches to minimize risks of escapes, widespread adoption of currently recognized best practices may suffice. All food systems, not just seafood, require tradeoffs, and **aquaculture is already far more sustainable than many other food systems** in terms of greenhouse gas emissions, nutrient runoff, water and land use, and climate resilience (Troell et al, 2023). Many of the risks identified in this paper are accepted in livestock and crop management programs as tradeoffs for attaining food security, conservation, or other goals (Liu et al, 2021; Wu et al, 2018).

> *"The same general questions, it should be noted, are relevant to assessing the consequences of other anthropogenic actions that affect marine populations (such as fishing or habitat modification), as well as the consequences of propagation programs that release large numbers of individuals of other taxa into the wild (e.g., birds, insects, trees)"*
>
> -Waples et al., 2012

Paradox of Public Opinion About Farmed Fish: Improved Communication Needed

Not only are many food systems impacts regularly accepted in terrestrial agriculture that are paradoxically lambasted in aquaculture, but the specific risks of cultured finfish outlined above are widely accepted for intentional fish releases for stock enhancement programs. This popular support, including for programs that do not achieve their stated conservation or socio-economic goals (CA Sea Grant Results, 2017), is in direct contrast to the outrage expressed in the media regarding the unintentional escape of fish farmed in net pens for food. (note: Some popular stock enhancement fish are even raised in coastal net pens.) Despite numerous escape events and billions of cultured fish released intentionally in multiple marine regions around the U.S., there are few examples of long-term impacts from either type of operation that are directly relevant to U.S. open ocean aquaculture. Operators will continue to adopt best practices for aquaculture seafood operations that result in equally valuable outcomes of greater food security and social and economic support of coastal communities. **To secure social license to operate in public waters in the U.S., it is incumbent on fish farmers to widely adopt best practices, publicly communicate their commitment to reducing escapes and mitigating escape risks, and transparently report on their progress and outcomes, allowing for public recognition of their successes and dispelling myths commonly perceived by the public.**

Consumers derive health benefits from eating aquatic species, including cultured finfish. Many of these species are relatively low-priced and available year-round and generally have a lower climate impact than terrestrial livestock systems. Changing common misperceptions will be more likely if a governance framework is in place to prevent escapes and minimize unavoidable risks, thus supporting the development of sustainable open ocean aquaculture operations. An industry committed to minimizing environmental impacts will benefit seafood consumers and enable the continued growth of a sustainable food system.

Appendix 1. Improvements to the Regulatory Framework

Effective and enforceable regulatory regimes to address genetics, siting, and containment management by net pen operations exist in several countries/provinces/states, including the U.S. and Canada (NOAA & Fisheries and Oceans Canada, 2018; NOAA Fisheries et al, 2022). They are soon to be supported generally by FAO's Draft Guidelines for Sustainable Aquaculture. Requirements related to escapes couple technical standards with operational processes, codes of practice, and staff training (ASC FARM STANDARD; The Scottish Government; Iceland; European Federation of Aquaculture Producers). Permit requirements that include escape management policies could reduce the number of unintentionally released fish and mitigate risks to biodiversity, ecological systems, and habitat (Ju et al, 2019; Arechavala et al, 2017; Alvanou et al, 2023).

To minimize escapes and mitigate possible ecological, genetic, and pathogenic risks, the U.S. regulatory framework should contain specific provisions:

- Assigning a federal agency in charge and identifying responsibilities for permitting and ongoing management
- Convening an Advisory Committee composed of a broad range of stakeholders (FAO, 2023)
- Developing environmental risk assessments that include evaluating site characteristics, operational parameters, species choice, heritage, etc.
- Adopting technical equipment and operations standards specific to siting/species (OECD; ISO work, Prevent Escape in EU) and monitoring
- Improving staff training
- Adherence to genetic, biosecurity, fish health practices (e.g., NOAA Best Practices), and post-escape fishery monitoring protocols (e.g., marking fish for post-escape ID)
- Adopting interoperable modern data system for tracking escape events: number of fish escaped, causes, mitigation efforts and success and subsequent impacts of escapees that is accessible to researchers and the public

Post-Escape Provisions

- Developing Reporting/Monitoring programs: collecting information and learning from reported incidents; providing publicly accessible data

- Developing contingency plans, including engaging recapture efforts; levying fines
- Conducting a technical evaluation of specific escape incidents
- Funding research to address uncertainties in the impacts of unintentional releases
- Rapid knowledge sharing of research findings to aquaculture practitioners and the public

References

"2019 Pioneering Offshore Aquaculture Workshop." Florida Sea Grant, 5 June 2023, www.flseagrant.org/2019-pioneering-offshore-aquaculture-workshop/.

"Aqua Policy Dashboard." Tableau | Public, Aqua Policy Admin, public.tableau.com/app/profile/aquapolicyadmin/viz/AquaPolicyDashboard/Home. Accessed 13 June 2024.

"Aquaculture-Aided Fisheries Enhancement, Conservation, and Restoration: Towards Responsible Development and Effective Reform." World Fisheries Congress, wfc2024.fisheries.org/2023/02/07/aquaculture-aided-fisheries-enhancement-conservation-and-restoration-towards-responsible-development-and-effective-reform/. Accessed Apr. 2024.

"Assessing Vulnerability of Fish and Invertebrates to Climate Change in the Southeast." NOAA Fisheries, 6 Nov. 2023, www.fisheries.noaa.gov/feature-story/assessing-vulnerability-fish-and-invertebrates-climate-change-southeast.

"Cobia - Panama Marine Net Pens" Monterey Bay Aquarium Seafood Watch. March 7, 2022.

"National Genomics Center for Wildlife and Fish Conservation." U.S. Forest Service Research and Development, www.fs.usda.gov/research/rmrs/projects/ngc. Accessed 13 June 2024.

"National Pollutant Discharge Elimination System (NPDES)." U.S Environmental Protection Agency, www.epa.gov/npdes. Accessed Apr. 2024.

"The New ASC Farm Standard." ASC International, asc-aqua.org/the-new-asc-farm-standard/. Accessed April 2024.

"Tracking Red Drum from Hatchery to Adulthood." Marine Stocking Research Program, South Carolina Department of Natural Resources, www.dnr.sc.gov/marine/stocking/research/reddrumtracking.html. Accessed Apr. 2024.

Alvanou, Maria V., et al. "Mediterranean Aquaculture and Genetic Pollution: A Review Combined with Data from a Fish Farm Evaluating the Ecological Risks of Finfish Escapes." Journal of Marine Science and Engineering, vol. 11, no. 7, 2023, p. 1405. DOI: 10.3390/jmse11071405.

Arechavala-Lopez, P., et al. "Implications of Sea Bream and Sea Bass Escapes for Sustainable Aquaculture Management: A Review of Interactions, Risks and Consequences." Reviews in Fisheries Science & Aquaculture, vol. 26, no. 2, 2018, pp. 214–234. DOI: 10.1080/23308249.2017.1384789.

Atalah, Javier, and Pablo Sanchez-Jerez. "Global Assessment of Ecological Risks Associated with Farmed Fish Escapes." Global Ecology and Conservation, vol. 21, 2020, https://doi.org/10.1016/j.gecco.2019.e00842.

Ayalew Assefa, Fufa Abunna, "Maintenance of Fish Health in Aquaculture: Review of Epidemiological Approaches for Prevention and Control of Infectious Disease of Fish", Veterinary Medicine International, vol. 2018, Article ID 5432497, 10 pages, 2018. https://doi.org/10.1155/2018/5432497

Bartley, Devin M., Melba G. Bondad-Reantaso, and Rohana P. Subasinghe. "A Risk Analysis Framework for Aquatic Animal Health Management in Marine Stock Enhancement Programmes." Fisheries Research, vol. 80, no. 1, 2006, pp. 28-36. ScienceDirect, https://doi.org/10.1016/j.fishres.2006.03.011.

Baskett, Marissa L., et al. "Assessing Strategies to Minimize Unintended Fitness Consequences of Aquaculture on Wild Populations." Evolutionary Applications, vol. 6, no. 7, Nov. 2013, pp. 1090-1108. DOI: 10.1111/eva.12089.

BC Salmon Farmers Association. Modern Salmon Farming in BC: A Review. BC Salmon Farmers Association, Campbell River, British Columbia, 2024, 518 pages. Available at www.bcsalmonfarmers.ca.

Benetti, Daniel D., et al. "Growth Rates of Cobia (Rachycentron canadum) Cultured in Open Ocean Submerged Cages in the Caribbean." Aquaculture, vol. 302, no. 3–4, 2010, pp. 195-201. ScienceDirect, https://doi.org/10.1016/j.aquaculture.2010.02.021.

Berglihn, H., & Gezelius, H. "Norwegian Salmon Farmers Under Fire for Misreporting Number of Fish Escapes." Interfish, 9 January 2024.

Berillis, P., Mente, E., & Kormas, K.A. "The Use of Copper Alloy in Aquaculture Fish Net Pens: Mechanical, Economic and Environmental Advantages." Journal of Fisheries, vol. 11, 2017, pp. 1–3.

Besnier, Francois, et al. "Introgression of Domesticated Salmon Changes Life History and Phenology of a Wild Salmon Population." Evolutionary Applications, vol. 15, no. 5, May 2022, pp. 853-864. DOI: 10.1111/eva.13375.

Bolstad, Gunnar H., et al. "Introgression from Farmed Escapees Affects the Full Life Cycle of Wild Atlantic Salmon." Science Advances, vol. 7, no. 52, 24 Dec. 2021, article eabj3397. DOI: 10.1126/sciadv.abj3397.

California Sea Grant. Evaluation of the Ocean Resources Enhancement and Hatchery Program. Report submitted to California Department of Fish and Wildlife, Project no. P1470005, 12 December 2017, Publication no. CASG-17-010.

California Sea Grant. Results of the 2018 Town Hall Meetings for the Ocean Resources Enhancement and Hatchery Program. Report submitted to California Department of Fish and Wildlife, Project no. P1770013, 19 December 2018, Publication No. CASG-18-027.

Castellanos-Galindo, Gustavo A., Ximena Moreno, and D. Ross Robertson. "Risks to Eastern Pacific Marine Ecosystems from Sea-cage Mariculture of Alien Cobia." Management of Biological Invasions, vol. 9, no. 3, 2018, pp. 323–327.

Chittenden, C. M., et al. "An Effective Method for the Recapture of Escaped Farmed Salmon." Vol. 1, 2011, pp. 215–224. DOI: 10.3354/aei00021.

Cooke Aquaculture Pacific. "Cooke Aquaculture Pacific- 2020 Annual Accidental Fish Release Report and Annual Biomass,

Feed Use and Disease Control Summary Reports". January 28, 2021.

Darden, T. L., et al. "Forecasting the Genetic Impacts of Net Pen Failures on Gulf of Mexico Cobia Populations Using Individual-based Model Simulations." Journal of the World Aquaculture Society, vol. 48, no. 1, 2017, pp. 20–34.

Dempster, T., Arechavala-Lopez, P., Barrett, L.T., Fleming, I.A., Sanchez-Jerez, P., & Uglem, I. (2018). Recapturing escaped fish from marine aquaculture is largely unsuccessful: alternatives to reduce the number of escapees in the wild. Reviews in Aquaculture, 10, 153-167. https://doi.org/10.1111/raq.12153

Engle, Carole R., et al. "Characterization of Supply of Marine Finfish Species with Potential for Commercial Growth in the United States." Journal of the World Aquaculture Society, vol. 54, no. 1, 2023, pp. 54-72.

FAO. 2023. Guidelines on assessing and minimizing the possible impacts from the use of non-indigenous species in aquaculture. General

Fisheries Commission for the Mediterranean. Rome. https://doi.org/10.4060/cc3207en

Florida Department of Agriculture and Consumer Services (DACS). Division of Aquaculture. "Aquaculture Best Management Practices Manual." November 2023. Accessed 29 Apr. 2024, https://ccmedia.fdacs.gov/content/download/64045/file/BMP-Manual-Final-11-2023.pdf.

Føre, H. M., & Thorvaldsen, T. "Causal Analysis of Escape of Atlantic Salmon and Rainbow Trout from Norwegian Fish Farms During 2010–2018." Aquaculture, vol. 532, 2021, article 736002. ISSN: 0044-8486, DOI: 10.1016/j.aquaculture.2020.736002.

Fry, J., Love, D., & Innes, G. "Ecosystem and Public Health Risks from Nearshore and Offshore Finfish Aquaculture." Johns Hopkins University, 2018. clf.jhsph.edu/sites/default/files/2019-09/ecosystem-and-public-health-risks-from-nearshore-and-offshore-finfish-aquaculture.pdf.

Fujita, Rod, et al. "Toward an Environmentally Responsible Offshore Aquaculture Industry in the United States: Ecological Risks, Remedies, and Knowledge Gaps." Marine Policy, vol. 147, 2023, article 105351. ISSN: 0308-597X, DOI: 10.1016/j.marpol.2022.105351.

Glover, K. A., et al. "Half a Century of Genetic Interaction Between Farmed and Wild Atlantic Salmon: Status of Knowledge and Unanswered Questions." Fish and Fisheries, vol. 18, no. 5, 2017, pp. 890-927. DOI: 10.1111/faf.12214.

Holmen, Ingunn Marie, et al. "Identification of Safety Indicators in Aquaculture Operations Based on Fish Escape Report Data." Aquaculture, vol. 544, 2021, article 737143. ISSN: 0044-8486, DOI: 10.1016/j.aquaculture.2021.737143.

Jackson, Dave, et al. "A Pan-European Valuation of the Extent, Causes and Cost of Escape Events from Sea Cage Fish Farming." Aquaculture, vol. 436, 2015, pp. 21-26. DOI: 10.1016/j.aquaculture.2014.10.040.

Jorde, P. E., et al. "Genetic Analyses Verify Sexually Mature Escaped Farmed Atlantic Cod and Farmed Cod Eggs in the Natural Environment." Evolutionary Applications, vol. 17, no. 4, 2024, article e13688. DOI: 10.1111/eva.13688.

Jorstad, K. E., et al. "Genetic Marking of Farmed Atlantic Cod (Gadus morhua L.) and Detection of Escapes from a Commercial Cod Farm." ICES Journal of Marine Science, vol. 71, no. 3, March/April 2014, pp. 574–584. DOI: 10.1093/icesjms/fst171.

Ju, Rui-Ting, et al. "Emerging Risks of Non-Native Species Escapes from Aquaculture: Call for Policy Improvements in China and Other Developing Countries." Journal of Applied Ecology, vol. 57, no. 1, 2019, pp. 85-90. DOI: 10.1111/1365-2664.13521.

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Karlsson, S., et al. "Widespread Genetic Introgression of Escaped Farmed Atlantic Salmon in Wild Salmon Populations." ICES Journal of Marine Science, vol. 73, no. 10, November 2016, pp. 2488–2498. DOI: 10.1093/icesjms/fsw121.

Kitada, S. "Economic, Ecological and Genetic Impacts of Marine Stock Enhancement and Sea Ranching: A Systematic Review." Fish and Fisheries, vol. 19, no. 3, 2018, pp. 511-532. DOI: 10.1111/faf.12271.

Kitada, S., Nakajima, K., Hamasaki, K. et al. Rigorous monitoring of a large-scale marine stock enhancement program demonstrates the need for comprehensive management of fisheries and nursery habitat. Sci Rep 9, 5290 (2019). https://doi.org/10.1038/s41598-019-39050-3

Krkošek, M. "Population Biology of Infectious Diseases Shared by Wild and Farmed Fish." Canadian Journal of Fisheries and Aquatic Sciences, vol. 74, no. 4, 2017, pp. 620-628. DOI: 10.1139/cjfas-2016-0379.

Liu, Xinfeng, et al. "Selection and Introgression Facilitated the Adaptation of Chinese Native Endangered Cattle in Extreme Environments." Evolutionary Applications, vol. 14, no. 3, 2021, pp. 860-873. DOI: 10.1111/eva.13168.

Lorenzen, K., et al. "Cultured Fish: Integrative Biology and Management of Domestication and Interactions with Wild Fish." Biological Reviews, vol. 87, no. 3, 2012, pp. 639-660. DOI: 10.1111/j.1469-185X.2011.00215.x.

Lorenzen, K., et al. "Responsible Approach to Marine Stock Enhancement: An Update." Reviews in Fisheries Science, vol. 18, no. 2, 2010, pp. 189–210. DOI: 10.1080/10641262.2010.491564.

Lorenzen, Kai. "Population Dynamics and Potential of Fisheries Stock Enhancement: Practical Theory for Assessment and Policy Analysis." Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 360, 2005, pp. 171–189. doi.org/10.1098/rstb.2004.1570

McMillan, John R., et al. "A Global Synthesis of Peer-reviewed Research on the Effects of Hatchery Salmonids on Wild Salmonids." Fisheries Management and Ecology, vol. 30, no. 5, 2023, pp. 446-463.

National Aquaculture Association. “Refuting Marine Aquaculture Myths: Unfounded Criticisms and Assumptions in the United States.” Aquaculture Magazine , 2021, pp. 19–25.

Naylor, Rosamond, et al. "Fugitive Salmon: Assessing the Risks of Escaped Fish from Net-Pen Aquaculture." BioScience, vol. 55, no. 5, May 2005, pp. 427–437. https://doi.org/10.1641/0006-3568(2005)055[0427:FSATRO]2.0.CO;2.

Nimmo, F, et al. Poseidon Aquatic Resource Management, 2022, Co-Existence of Capture Fisheries and Marine Aquaculture.

NOAA Fisheries, U.S. Department of Commerce and National Marine Fisheries Service. "Potential Risks of Aquaculture Escapes - Factsheet 2022." 2022.

NOAA Fisheries. "Best Management Practices, Standards, and Farming Manuals." Office of Aquaculture. March 26, 2020.

NOAA Fisheries. "Fisheries Information System Program." NOAA Fisheries, www.fisheries.noaa.gov/national/commercial-fishing/fisheries-information-system-program

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NOAA Fisheries. "Offshore Aquaculture Escapes Genetics Assessment (OMEGA) Model." Office of Aquaculture. February 2, 2022.

NOAA, Fisheries and Oceans Canada. "Regulatory Regimes for Environmental Management of Marine Net Pen Aquaculture in Canada and the United States." April 2018.

Norway. Ministry of Trade, Industry, and Fisheries. "Regulations on Technical Standards for Aquaculture Installations for Fish in the Sea, Lakes and Watercourses (NYTEK22)." 2022.

Pister, E. "Wilderness Fish Stocking: History and Perspective." Ecosystems, vol. 4, 2001, pp. 279–286. DOI: 10.1007/s10021-001-0010-7.

Rhodes, L. D., Parrish, K. L., & Willis, M. L. (2023). Review of Best Practices for Biosecurity and Disease Management for Marine Aquaculture in U.S. Waters. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-180. https://doi.org/10.25923/b4qp-9e65.

Rhodes, Linda D. et al. "Review of Best Practices for Biosecurity and Disease Management for Marine Aquaculture in U.S. Waters." 2023, https://doi.org/10.25923/b4qp-9e65

Rodriguez-Estrada, U. CABI Compendium. "Rachycentron canadum (Cobia)." CABI International, 2022. doi:10.1079/cabicompendium.66460.

Sims, N.A. "Kona Blue Water Farms Case Study: Permitting, Operations, Marketing, Environmental Impacts, and Impediments to Expansion of Global Open Ocean Mariculture." In A. Lovatelli, J. Aguilar-Manjarrez & D. Soto (Eds.), Expanding Mariculture Farther Offshore: Technical, Environmental, Spatial and Governance Challenges, FAO Technical Workshop, 22–25 March 2010, Orbetello, Italy. FAO Fisheries and Aquaculture Proceedings No. 24. Rome, FAO, 2013, pp. 263–296

State of Maine. "General Permit - Net Pen Aquaculture: Maine Pollutant Discharge Elimination System Permit Maine Waste Discharge License." Maine Department of Environmental Protection. April 10, 2014

Strand, N., et al. "Regional and Temporal Variation in Escape History of Norwegian Farmed Atlantic Salmon." ICES Journal of Marine Science, vol. 81, no. 1, January 2024, pp. 119–129. DOI: 10.1093/icesjms/fsad184.

Stronger America Through Seafood (SATS), and Tyler Sclodnick of Innovasea. “SATS Interviews Scientist on Latest Advancements in Science and Technology to Support Sustainable Aquaculture.” 15 Apr. 2024.

Taranger, Geir Lasse, et al. "Control of Puberty in Farmed Fish." General and Comparative Endocrinology, vol. 165, no. 3, 2010, pp. 483-515. ScienceDirect, https://doi.org/10.1016/j.ygcen.2009.05.004.

Teixeira Alves, M., and N.G.H. Taylor. "Models Suggest Pathogen Risks to Wild Fish Can Be Mitigated by Acquired Immunity in Freshwater Aquaculture Systems." Scientific Reports, vol. 10, 2020, p. 7513. DOI: 10.1038/s41598-020-64023-2.

Thompson, Jonathan. “Farmed Atlantic Salmon: Potential Invader in the Pacific Northwest?” Pacific Northwest Research Station/USDA Forest Service Science Findings, no. 100, Feb. 2008, p. 5.

Toledo-Guedes, K., et al. "Phenotypic Convergence in Sea Bass (Dicentrarchus labrax) Escaping From Fish Farms: The Onset of Feralization?" Frontiers in Marine Science, vol. 8, 2021, article 674635. DOI: 10.3389/fmars.2021.674635.

Toledo-Guedes, K., Sanchez-Jerez, P., & Brito, A. (2014). Influence of a massive aquaculture escape event on artisanal fisheries. Fisheries Management and Ecology, 21, 113-121. https://doi.org/10.1111/fme.12059

Troell, M., Costa-Pierce, B., Stead, S., Cottrell, R. S., Brugere, C., Farmery, A. K., ... Barg, U. (2023). Perspectives on aquaculture's contribution to the Sustainable Development Goals for improved human and planetary health. Journal of the World Aquaculture Society, 54(2), 251–342. https://doi.org/10.1111/jwas.12946

U.S. Army Corps of Engineers. "Minimum Standards for Acceptance of Aquatic Resources Delineation Reports." July 2016.

U.S. Fish and Wildlife Service. “2022 Distribution Reports.” 24 May 2023, www.fws.gov/story/2023-05/2022-distribution-reports.

Valero-Rodriguez, J.M., et al. "The Use of Trophic Resources by Argyrosomus regius (Asso, 1801) Escaped from Mediterranean Offshore Fish Farms." Journal of Applied Ichthyology, vol. 31, 2015, pp. 10-15. https://doi.org/10.1111/jai.12649.

Waples, Robin S., Kjetil Hindar, and Jeffrey John Hard. “Genetic risks associated with marine aquaculture.” NOAA Technical Memorandum NMFS-NWFSC-119. 2012. https://repository.library.noaa.gov/view/noaa/4247.

Wilson, L. "Alaska Salmon Fisheries Enhancement Annual Report 2022." Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report, No. 5J23-04, Juneau, 2023.

Wu, DD., et al. "Pervasive Introgression Facilitated Domestication and Adaptation in the Bos Species Complex." Nature Ecology & Evolution, vol. 2, 2018, pp. 1139–1145. DOI: 10.1038/s41559-018-0562-y.

Xu, L., Zhao, M., Ryu, J.H., et al. "Reproductive Sterility in Aquaculture: A Review of Induction Methods and an Emerging Approach with Application to Pacific Northwest Finfish Species." Reviews in Aquaculture, vol. 15, no. 1, 2023, pp. 220-241. doi:10.1111/raq.12712.

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