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USING OMEGA TO MODEL RISKS OF ESCAPED FISH ASSOCIATED WITH OFFSHORE FINFISH CULTURE IN SOUTHERN CALIFORNIA: AN EVALUATION OF PROPOSED PACIFIC OCEAN AQUAFARMS OPERATIONS

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Using OMEGA to model risks of escaped fish associated with offshore finfish culture in Southern California: an evaluation of proposed Pacific Ocean AquaFarms operations.

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Executive Summary

Pacific Ocean Aquaculture (POA) proposes to begin operation of a new aquaculture facility to cultivate California yellowtail (*Seriola dorsalis*) within a moored net pen system in Southern California. Two location alternatives are being considered: 1) four nautical miles off the coast of San Diego, and 2) four nautical miles off the coast of Huntington Beach. The purpose of this report is to evaluate ways fish may escape from the net pen system, the magnitude and age distributions of escaped fish under different production and escape scenarios, and the potential consequences of escapes surviving in the wild. The analysis in this report focused on potential magnitude of escape levels and consequences related to within-population genetic diversity and reproductive fitness of wild conspecifics.

Modeling of escapes was conducted using the Offshore Mariculture Escape Genetic Assessment (OMEGA) model. The purpose of OMEGA is to simulate escapes from a farm system to a wild system and the potential effect of escapes surviving to encounter wild conspecifics. The model is intended to provide an assessment of risk associated with aquaculture operations and aid in the development of strategies to reduce adverse effects from escapes. The analysis focused on a series of ‘scenarios to describe the full measure of effects that could theoretically occur based on data collected from other programs described in literature (Table E1). Scenario I was modeled to describe anticipated operational risk of escape events occurring due to individual or small groups of fish escaping from the net pen system (leakage) and fish escaping from episodic cage failures. Scenario I escape assumptions are at the higher end of reported leakage values of fish escapes from a review of global aquaculture operations and included a range of episodic cage failures. Scenario II was modeled to simulate a single large-scale loss of 100% of inventory from a major disaster impacting the net pen system such as a tsunami, severe storm, large vessel strike, or other major structural failure. Scenario III was developed that assumes management measures would be taken to minimize escape risk. This scenario assumed leakage would occur however episodic events would be at the lower end of the episodic frequency range modeled in Scenario I and the magnitude of loss following a cage failure would be lower (only a quarter to half of the fish would escape from a cage), Also, Scenario III assumed escaped fish would survive at half rate of wild California Yellowtail of the same size. Finally, Scenario IV was a modeled large scale escape event with the Scenario III lower survival assumption and 25% of the fish in the cages would be recovered or would be trapped in the collapsed cages and not escape to encounter wild California Yellowtail (i.e., the number of fish escaping would be 75% of inventory).

Table E1. Modeled California Yellowtail escape scenarios.

Scenario	Leakage[a]	Episodic[b]	Large Scale[c]	Other
Scenario I	0.32%	2,500 mt – 5%, 7.5%, & 12.5% 5,000 mt – 10%, 15%, & 25% Half to three-quarters of fish in cage escape	Not Modeled	Escaped fish survive as well as wild
Scenario II	Not Modeled	Not Modeled	One time escape of all fish in cages	
Scenario III	0.32%	2,500 mt – 5% 5,000 mt – 10% One quarter to half of fish in cage escape	Not Modeled	Escaped fish survive at half the rate of wild fish
Scenario IV	Not Modeled	Not Modeled	One time escape of 75% of fish in cages	

[a] Leakage is the percentage of fish escaping while held in a cage, leakage varied by size of fish – smallest size 0.20%, mid-size 0.04%, and largest size 0.08%. See Section 2.1.1, *Leakage Escape* for additional details.

[b] Episodic escapes are often the result from individual or multi-cage failures and the escape of half to all fish in cage. Shown are the annual likelihood of an episodic event (e.g., 10% -= 1 event every 10 years and 25% = 1 event every 4 years). See Section 2.1.2, *Episodic Escape* for additional details.

[c] Large-scale escapes are the one-time loss of all fish in cages from catastrophic events. This type of loss may result from extreme storm or weather events, or other disasters such as fires, collisions, or tsunamis that cause the failing of the mooring system and/or grid infrastructure. See Section 2.1.3, *Large-scale Events and Catastrophic Events* for additional details.

Production schedules and growth curves for *S. dorsalis* were provided by POA. The OMEGA team evaluated the POA program under a full-scale production level of 5,000 metric tons (about 11 million pounds) per year, and half-scale production of 2,500 metric tons (about 5.5 million pounds). Fish would be cultured for 65 to 74 weeks, to a harvest size of 7 to 8 pounds depending on time of year of initial stocking. Fish would be harvested year-round. All fingerlings would be grown from wild-caught broodstock captured locally in Southern California, and no intentional selection for traits would be done. At full production, fish would be harvested continuously 5 days a week for 17 weeks per year as the harvest cycle for one cohort ends and another begins.

S. dorsalis is native to Southern California with a range that extends to Baja California in Mexico. No significant genetic structure has been documented in the population, and studies support evaluating wild *S. dorsalis* in this area as a single population. Catch data from U.S. and Mexico over the last 20 years suggests a harvestable population of 17,000 to 34,000 metric tons, and a female spawning biomass of 8,000 to 18,000 metric tons.

Leakage and Episodic Cage Failure: Scenario I

OMEGA was parameterized to simulate a range of possible escape scenarios under both full and half production alternatives. During operation of the net pen system under full or half production, 0.32% of fish across the program were assumed to be lost due to program leakage for a variety of reasons, including seeding of fingerlings, size-grading, handling, and maintenance. The episodic failure of an individual cage is also assumed to occur on a periodic basis, at a rate of once every four to ten years, resulting in an escape loss of a half to a full cage of fish. This type of episodic event may occur due to a structural failure, net tears by a predator, or net replacement operations.

To report model results, net pen operations were simulated in OMEGA over a 90-year period, assuming variability in episodic escape events over a range of values for natural population abundance, as recorded in catch data for the U.S. and Mexico. According to OMEGA results, at full production under Scenario I conditions, wild fitness would reduce by less than 0.20% from wild optimum conditions. This reduction is likely due to unintentional selection of local broodstock resulting in traits maladapted to spawning in nature, however the minimal loss in fitness is due to the use of wild-caught broodstock in the program. Therefore, while escaped fish from leakage and episodic events would likely survive to reproduce, resulting in a mixed cultured-wild fish in the wild, a loss in fitness of this magnitude would result in a minimal effect on reproductive fitness of wild conspecifics within a short-term (5, 10, 25 years) and long-term (90 years or more) time horizon.

Genetic diversity of wild populations is important because populations with high genetic diversity have greater adaptive capacity to changes in the environment. When genetic diversity is low, populations become smaller and more isolated, and these smaller less-diverse populations have lower potential for long-term survival. The common measure of genetic diversity is effective population size, or N_e. The value of N_e may be evaluated as the number of breeding adults; however, the true value is influenced by the range of fecundities among broodstock in the captive and wild environments. There are no studies that estimate N_e for *S. dorsalis*, and there is no stock assessment data available for the Southern California population. As such N_e is difficult to predict in the marine wild environment. This analysis examines outcomes for the full range of N_e values for wild *S. dorsalis* and considers possible values for N_e of the wild population based on other species with similar levels of abundance. For the culture program, the value of N_e is based on the number of broodstock and with adjustments made as necessary for the potential range in fecundities in the system, considering that broodstock would spawn naturally in captivity.

Based on simulations from leakage and cage failures at both full- and half-scale production, the effective size of the mixed population was sufficiently large enough to avoid deleterious effects of small effective population of culture-origin fish. However, if under full production episodic losses were to occur with a likelihood of 25% in any given year, the wild population could potentially experience loss of genetic diversity associated with the Ryman-Laikre effect.

Ecological effects are not examined in this study, however, escape magnitudes reported by OMEGA may be used to inform future analysis. Ecological consequences from program escapes include impacts from escaped fish as prey, predators, and competitors in the wild. According to modeling, a range of 2,500 to 103,000 fish may escape in any given year, with higher numbers of escapes occurring from episodic events that are modeled to occur every 4 to 10 years.

Large-scale Program Level Escape Event: Scenario II

Another set of model simulations examined the effects of the loss of an entire net pen system under full and half production alternatives. While such events are very rare, history has shown that unexpected events happen, and as such the potential consequences of large-scale losses are evaluated.

According to OMEGA modeling a large-scale loss event under full or half production would result in negligible loss in reproductive fitness, largely due to the use of locally sourced broodstock with no intentional selection for specific traits during captive breeding.

A large-scale loss under full or half production would likely result in a high effect on genetic diversity of the wild population. Under full production up to 2.7 million fish may escape, and the effect of few parents producing high numbers of offspring with high survival in the captive program would be amplified, increasing the likelihood that fewer genetically distinct individuals reproduce successfully with wild fish. For several years immediately following the escape under full production, the proportion of cultured fish in the population exceeds 10% and the effective population size may not be large enough to avoid deleterious Ryman-Laikre effects and the subsequent loss of genetic diversity. Therefore, a large-scale loss may contribute to a reduced adaptive potential for wild conspecifics. The ability to retain genetic diversity depends on the value of N_e for the wild population, and considering the size and range of the single population of California Yellowtail there may be sufficient diversity within the population to restore heterozygosity within a relatively low number of generations. However, given the many opposing factors involved in effects to genetic diversity of a population, there is a high level of uncertainty in prediction of N_e for the wild population.

Scenarios III and IV

Scenarios in this report also examined assumptions that considered management measures that would be implemented at the beginning of operations to reduce potential for adverse effects from escapes. Under the Scenario III and IV, fitness effects would be minimal like for Scenarios I and II and there would be a lower likelihood of effects to genetic diversity compared to Scenarios I and II.

1.0 Introduction

Rapid worldwide development of marine finfish cage farming has raised awareness over the effects escaped fish may have on wild populations and on the natural ecosystem. Marine fish can escape from farms for a variety of reasons, for example, due to normal wear and tear of cages, maneuvers transferring fish from one cage to another while grading or harvesting, high wind and high sea conditions during severe storms, net cage breeches by predators, or holes in nets from cultured fish biting at threads (Jensen et al. 2010; Jackson et al. 2015; Føre and Thorvaldsen 2021). It is nearly impossible to guarantee through technology or management measures that farmed fish will not escape from offshore net cages. However, types of escape occurrences vary widely between one or a few fish escaping intermittently over the course of a production period to potentially millions of fish escaping at once from a catastrophic failure of the pen structures, and the impact on wild populations and ecosystems will similarly vary with those escape scenarios. Potential genetic effects of aquaculture escape include the introduction of maladaptive genes and reduced fitness to the wild populations, the loss of within population genetic diversity, and the loss of between population genetic diversity (Waples et al. 2016). Potential non-genetic effects of escapes include the potential for increased competition on the part of wild populations for food and space (Flemming et al. 2000), increased predation on native stocks (Green et al. 2012), and the transfer of disease (or novel pathogens).

The knowledge of risks from escaped aquaculture fish has led to improved aquaculture standards implemented in various regions around the world to greatly reduce the number of fish escaping from aquaculture operations (e.g., Norwegian standard NS 9415: Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation, and operation).

With increased interest in implementation of marine aquaculture in the United States, NOAA Fisheries, and other federal and state regulators charged with stewardship of marine ecosystems, need tools to understand and mitigate risks from aquaculture operations and to inform management and regulatory decisions (NSTC 2022). The Offshore Mariculture Escapes Genetic Assessment (OMEGA) model that evaluates risks from escaped farmed fish is a key example of one of the tools developed to advance marine aquaculture. OMEGA was developed jointly by ICF and National Marine Fisheries Service (NMFS) in 2012 to evaluate the genetic risks to a wild population of conspecifics from escaped cultured fish.

This report begins with a general overview of the risks and consequences of marine aquaculture escapes and is followed by an assessment of potential impacts of escaped California Yellowtail (*Seriola dorsalis*) from a proposed commercial aquaculture operation off the coast of Southern California. The discussion of risk examines information from worldwide finfish aquaculture operations as large-scale finfish operations are rare in U.S. coastal waters. The discussion of the consequences of fish escaping is a combination of lessons learned from use of cultured marine fish for stock enhancement, the wealth of information studying the consequences of Atlantic Salmon escapes from Norway, and the use of theoretical concepts to evaluate potential consequences of escapes. The remainder of this report (Sections 4.0 through 8.0) focuses on an assessment of the Pacific Ocean AquaFarms proposed aquaculture operation.

2.0 Escape Risks and Consequences

In considering risk, Kaplan and Garrick (1981) suggest defining and addressing three questions: (1) what can go wrong? (2) what is the likelihood of that happening? and (3) what are the consequences? The following sections describe how fish may escape and the likelihood that fish may escape (Section 2.1, *Escape Background and* Categories), and the consequences of fish escaping (Section 2.2, *Consequences of Fish Escaping*).

2.1 Escape Background and Categories

In terms of considering fitness and genetic risk on wild conspecific populations from aquaculture and in thinking about what can go wrong, fish escaping from culture is the primary consideration. Fish escapes are inevitable in aquaculture and have been reported in almost every country where aquaculture occurs (Jackson et al. 2015, Glover et al. 2017, McIntosh et al. 2022). These escape events occur at all levels, ranging from the escape of a single fish to large-scale escapes where most or all fish on-station escape (Naylor et al., 2005, Leggatt et al. 2010, Atalah and Sanchez-Jerez 2020). The likelihood (or frequency) and magnitude of different escape pathways determines, in part, the level of risk an operation or a particular aquaculture scenario poses to conspecific wild populations and to the broader ecosystem.

Figure 2.1 shows the four categories of ways fish escape from cages as conceptualized in the OMEGA model. Type one and two represent leakage and the escape of 10s to 100s of fish at a time. Type three represents episodic escapes resulting in intermediate escape numbers of 1,000s to 10,000s, and Type four represents the rare complete failure of multiple cages or a catastrophic equipment failure and loss of 100,000s to millions of fish. Each escape type is discussed in detail in the following sections, plus an even more difficult to quantify fifth category representing gametes released from mature fish held in cages is described.

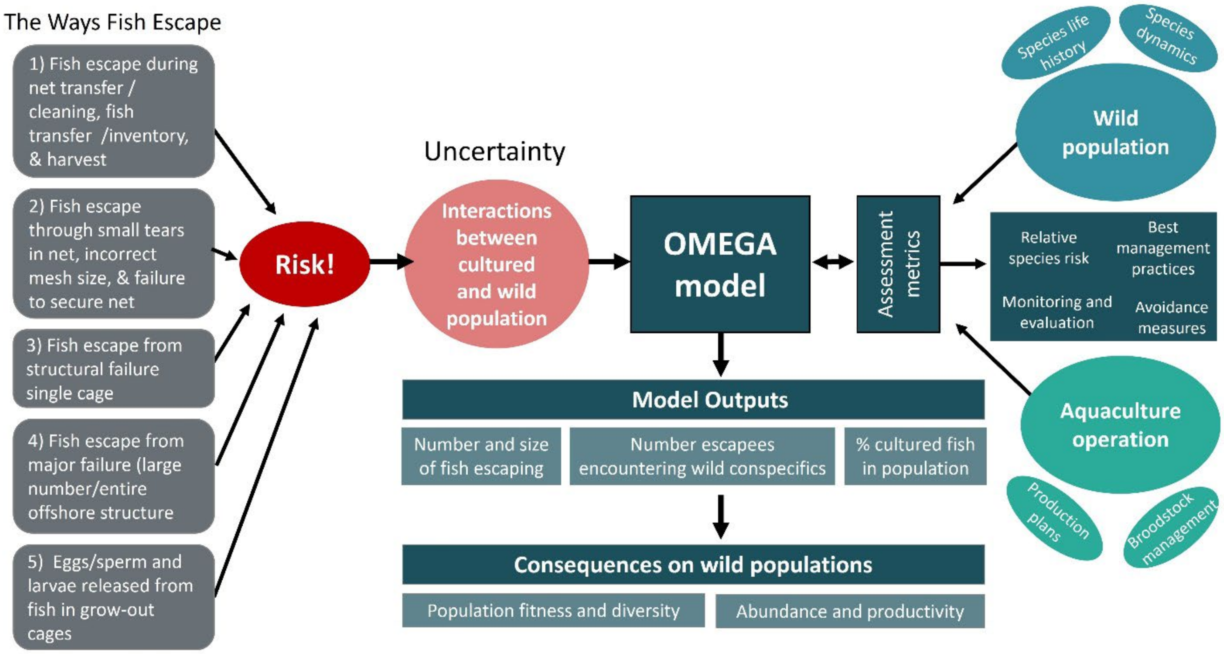

Figure 2.1. The ways fish escape, and OMEGA model conceptual design.

2.1.1 Leakage Escape

The leakage type of escape scenario refers to the loss of one to possibly 100s of fish at a time. This type of escape results from processes associated with daily operations such as feeding, maintenance, handling/transferring maneuvers, and other such occurrences (Glover et al. 2017, Føre and Thorvaldsen 2021, Yang et al. 2022). While this type of loss is inevitable in aquaculture, determining the cause(s), or detecting the losses is very difficult given the few fish involved at any one time (Naylor et al. 2005). However, this type of escape is the most frequent in terms of the number of occurrences (Skilbrei et al. 2015, Glover et al. 2017). In Yang et al. (2022), out of the 300 escape events that included a detectable loss of fish, approximately 59% of those events (or 176 events) would have been considered leakage-level events, but this accounting is likely incomplete. Even though any one event results in few fish escaping, the rate of occurrence and cumulative effect of fish escaping over time could have a considerable impact on a conspecific wild population (Baskett et al. 2013). This has been demonstrated in previous sensitivity analyses using OMEGA (ICF 2018).

Because leakage occurrences are often not recorded, quantifying escapes from leakage is more difficult than for any other type of escape (Leggatt et al. 2010). It is difficult to detect small numbers of fish escaping from a system, and as such, there is a considerable level of under-reporting, leading up to possibly 50% of reportable incidents not being reported (Yang et al. 2022). An analysis conducted on salmon in Norway found that the actual number of escaped fish was two- to four-fold higher than the numbers reported by the industry (Skilbrei et al. 2015), and this 2-4x multiplier has now been used in recent modeling of salmon escapes in Canada and Iceland (Bradbury et al. 2020, MFRI 2020) to account for this under-reporting.

2.1.2 Episodic Escape

Episodic escapes often result from individual or multi-cage failures, or other malfunctions where all or a portion of fish escape from a cage(s) (Naylor et al. 2005). Advances in farm technology have reduced the incidence of escape overall, and particularly for catastrophic failures (Føre and Thorvaldsen 2021), but these episodic events may still happen at sites using some of the most advanced technology (e.g., Ocean Farm 1 in Norway lost 16,000 salmon in 2018 when water entered an inspection hatch that was accidentally left open) (Fujita et al. 2023, https://www.fishfarmingexpert.com/escape-ocean-farm-1-salmar/ocean-farm-1-escape-total-worked-out-at-16000/1323127). This type of escape often occurs during vulnerable maneuvers such as inventorying of fish, nursery net replacement, detaching and towing harvest pens, initial seeding of pens, and size-grading of fish using crowders, well-boat operations, net cleaning and repair, use of equipment to remove dead fish from pens, vessel mooring, bottom weight handling, and float line handling (Jensen et al. 2010, Atalah and Sanchez-Jerez 2020, Føre and Thorvaldsen 2021, Holmen et al. 2021). These events may occur due to human error during these activities, although unfavorable and unexpected weather and wave conditions (e.g., rogue wave) are also contributing factors (Føre and Thorvaldsen 2021). Analyses of Norwegian fish farm escapes found that net holes accounted for many escape events (e.g., 47% of escape events and 76% of escaped fish; Holmen et al. 2021); submerged nets due to operational and structural failures were another large contributor of escape events (Holmen et al. 2021, Yang et al. 2022). In addition to the factors above leading to escapes and possible holes in the net, the species in culture also has a significant impact on escape risk. Cod, for example, are more likely to bite at nets than salmon, and as a result, have a higher rate of escape (Moe et al. 2009, Jensen et al. 2010). Similarly, Gilthead Sea Bream are also more prone to biting at the net, while European Sea Bass do not bite the net, but are more opportunistic than sea bream in escaping from sea cages (Sanchez-Jerez et al. 2008, Arechavala et al. 2018). Predators may also contribute to episodic events through net breakage, enlargement of pre-existing holes, and/or distress of fish in the pens (Arechavala et al. 2018).

The design of individual aquaculture operations will have implications for the expected frequencies and magnitudes of episodic escape events. If it is assumed that the likelihood of an episodic escape occurrence is similar for large and small cages, then sites with more cages (regardless of size) will have a higher risk of an episodic escape event. However, a site with fewer, but larger cages, may have a lower overall frequency of episodic escapes, but a greater impact in terms of magnitude if an escape occurs (McIntosh et al. 2022). To evaluate the risk-consequence trade-off, McIntosh et al. (2022) plotted the average number of cages per farm in a region against the mean cage surface area. The analysis revealed that Chile and Japan had the highest risk of escape events due to high average number of cages, while Norway had the fewest cages per farm. However, Australia, Norway, Faroe Islands, and Iceland had the largest average cages and accordingly, high consequences from escape events, compared to Scotland and Japan that had the smallest cages and therefore smallest consequences of escape (McIntosh et al. 2022). In the Yang et al. (2022) analysis, out of the 300 events that included loss of fish, approximately 41% of those events (or 124 events) would have been considered episodic-scale events. The magnitude of episodic escapes is much less than large-scale or catastrophic failures, but large enough that pulses of fish escaping into the environment in this way should be modeled in addition to impacts from chronic leakage. Accounting for both the frequency and magnitude of episodic escape events helps evaluate the risk of escape from an operation.

2.1.3 Large-scale Escape and Catastrophic Events

Large-scale losses from catastrophic events are the headline grabbing occurrences that the public unfortunately associates with offshore aquaculture. This type of loss may result from extreme storm or weather events, or other disasters such as fires, collisions, or tsunamis that cause the failing of the mooring system and/or grid infrastructure (Yang et al. 2022, Føre and Thorvaldsen 2021, Jackson et al. 2015). While these large-scale escape occurrences are rare events, they have historically occurred and may lead to the release of hundreds of thousands (e.g., 500,000 Atlantic Salmon in Norway in 2005, ~155,000 in Scotland in 2014, ~250,000 in Washington State, U.S. in 2017, 120,000-130,000 in Tasmania in 2020) to even millions (e.g., 1.5 million with 90% of those sea bass and 10% sea bream in the Canary Islands at end of 2009/beginning of 2010) of cultured fish into the environment at one time or over a very short escape period (Jensen et al. 2010, Toledo-Guedes et al. 2014, Jackson et al. 2015, Atalah and Sanchez-Jerez 2020, Lyle 2021, Yang et al. 2022, http://aquaculture.scotland.gov.uk/data/fish_escapes_record.aspx?escape_id=64). Improvements in engineering, equipment technology (e.g., submersible cages, copper-alloy mesh pens), and industry standards (e.g., Norwegian Standard NS 9415) have reduced the frequency of these events (Føre and Thorvaldsen, 2021, McIntosh et al. 2022). However, the sudden presence of such large fish biomasses in the natural environment represents a unique environmental risk compared to other types of escape (Arechavala-Lopez et al. 2018), and the ability of a wild population to buffer a high level of escape biomass will vary and warrants evaluating the impact independently from other forms of escape.

2.1.4 Gamete-based Escape

Gamete-based escape involves the release of viable, and fertilized eggs from sexually mature cultured fish inside of grow-out cages (Arechavala-Lopez et al. 2018), in an open setting within the natural environment (Leggatt et al. 2010). This phenomenon is known to occur in Atlantic cod, where genetically tagged, cultured-origin larvae were reported to make up to 20 to 25% (Jorstad et al. 2008) and 4.3 to 19.7% (van der Meeren et al. 2012) of the total cod larvae sampled in the Norwegian fjord where the net pens were located. Modeling simulations indicated that from a standard pen, holding 60,000 cod, between 1.4 and 21 tons of 3-year-old ‘escaped’ farm-origin cod may be produced through spawning in the net pens (Uglem et al. 2012). Similarly, a report by Somarkis et al. (2013) estimated that cultured Gilthead Sea Bream release between 3.5×10^{11} and 7.0×10^{11} eggs from pens in the Mediterranean based on assumptions of 5 to 10% mature fish and 130,000 tons of annual production. Sexual maturation is usually detrimental to the growth and fillet quality of the cultured fish, and if possible, it is avoided in most farming operations (Taranger et al. 2010), however precocious maturity can be an issue for some cultured fish species (e.g., salmonids and cod) (McClure et al. 2007, Karlsen et al. 2006).

While preventing the physical escape of eggs and larvae would be nearly impossible, the risk from gamete-based escape is negligible if fish are harvested before reaching sexual maturity.

2.1.5 Recapture Rates

Leakage of 10 to 100s of fish are generally not recorded until final inventory of fish in cages during harvest and then recorded as a negative difference between the number of fish stocked and the number at harvest. Some of this difference may be accounted for from counts of mortalities during grow-out, but a significant proportion may be unnoticed escapes during grow-out. Thus, tracking escapes from leakage may be incomplete and recapture of escaped fish from leakage is generally not possible. Some recovery may be possible if operators notice farmed fish in the immediate vacuity of the cages and escapees remain long enough to allow recapture.

Escapes from episodic and large-scale escape events may be mitigated by attempts to recapture escaped fish. However, Dempster et al. (2018) found that the overall recapture rate across various species was low, 8% of fish that escaped, and this value exhibited large variance based on the species, the number of fish, and the size of fish escaping. Experimental cod recapture rates have varied widely among studies, for adult cod, rates between 28 and 52% were reported by Uglem et al. (2008, 2011), 11% by Zimmerman et al. (2013), and much lower rates (up to 4.5% recaptured) for juvenile cod (Serra-Llinares et al. 2013). As reviewed in Dempster et al. (2018), Atlantic salmon recapture rates have varied as high as 69% for experimental releases of fewer than 100 large fish, whereas recapture rates following large-scale escape events of smaller salmon was much lower (1.5 to 10%), which may be partially due to higher predation at that smaller size. In the Mediterranean, single events have resulted in higher levels of recapture, for example, 64.7% of Gilthead Sea Bream were recaptured following a large-scale escape (Izquierdo-Gomez and Sanchez-Jerez 2016), and 20% of the sea bream and sea bass following a different large-scale escape event (Toledo-Guedes et al. 2014). However, Arechavala-Lopez et al. (2018) reported lower recapture rates overall for European sea bass (5.4%), sea bream (7.1%), meagre (8.7%) in the Mediterranean.

Generally, recapture rates improved with increasing size of escapees (Dempster et al. 2018), but it is difficult to determine whether this was due to more effective fishing or recapture methods for larger fish, or if this was due to higher mortality for smaller escaped fish, but both factors are likely important. Dempster et al. (2018) also found a negative correlation between escapee size and the number of escaped fish, meaning generally that a greater number of smaller fish escape than larger fish. Across the studies, recapture efforts that started as soon as possible, and ideally within 24 hours, were more successful (Uglem et al. 2011, Dempster et al. 2018).

2.1.6 Summary

While escape events will continue to occur in aquaculture, the magnitude and frequency has improved with advancing technologies and adaptive regulations. Detailed reporting infrastructure is critical to assessing improvements and developing mitigation measures. For example, in Norway, fish escape incidents must be reported with information regarding the number of fish lost, type of fish farm, operational and technical contributing causes, and sea and weather conditions; these are reported with the goal of helping to further develop industry recommendations for best practices (Holmen et al. 2021, Yang et al. 2022).

2.2 Consequences of Fish Escaping

The previous section described the first and second aspects of risk assessment: 1) things that can go wrong (different ways fish escape), and 2) the probabilities of each of these types of events. The third component of assessing risk from escaped fish revolves around the potential consequences from those escapes. The potential consequences of escaped cultured fish is dependent on their interactions with their wild counterparts. In considering the consequence of escaped fish, we focus on three possible impacts: 1) the fitness effects on the wild population(s); 2) the genetic diversity effects on the wild population(s) (both within and between population diversity); and 3) the ecological effects on multiple species, including the conspecific species. Each of these potential impacts is discussed below, but generally, the extent of the impact varies depending on the number of cultured fish escaping (size and frequency of escape events), cultured population husbandry and genetic management, and the size and health of the wild conspecific population (Lorenzen et al. 2012, Atalah and Sanchez-Jerez 2020).

2.2.1 Interactions

The potential consequences of escaped cultured fish is dependent on their interactions with their wild counterparts. These include their ability to survive to reproductive age, the probability they will encounter their breeding wild counterparts, and their ability to effectively mate with their wild counterparts.

2.2.1.1 Survival of Escaped Fish

Survival of escaped fish may be lower than similarly sized wild counterparts (Lorenzen et al. 2000, Arechavala-Lopez et al. 2012, Arechavala-Lopez et al. 2014), and this may occur for a few reasons. First, farmed fish are raised on pelleted food and thus they are unaccustomed to finding live food once in the natural environment (Glover et al. 2017). Olsen and Skilbrei (2010) and Abrantes et al. (2011) reported high mortality in escaped salmonids due to starvation from failing to acclimate to wild food sources. In a 2003 report by the South Australian Research and Development Institute, a sampling effort on escaped Yellowtail kingfish (*S. lalandi*) similarly determined that stomachs of these fish were either empty or contained atypical contents (e.g., plant material) compared to diets of wild conspecifics (Fowler et al. 2003). This acclimation challenge would likely apply to all sizes of escaped fish with subsequent starvation-induced mortality. However, acclimation success to wild food sources varies by species, with escaped Sea Bream (*Sparus aurata*) beginning to feed on natural prey after only one week in the wild (Arechavala-Lopez et al. 2012).

Second, predation pressure on escapees may be quite high from the large and diverse fish assemblages often found near pens, leading to high mortality of any escaped fish (Dempster et al. 2009). Interestingly, this “wall of predatory mouths” has been suggested as an escape mitigation approach to limit fishing on piscivorous fish in the vicinity of the pens (Dempster et al. 2018) and was similarly suggested as an escapee survival reduction method by Arechavala et al. (2018). Mortality associated with predation is likely to be associated with escapee size with smaller escapees being more vulnerable to predators and having ae higher predation mortality. Predation from marine mammals may be significant on larger escapees.

Third, the cultured fish may be more susceptible to capture by fishing gear than wild counterparts (Lorenzen et al. 2012). Mezzera and Largiader (2001) report angling efforts disproportionately caught higher numbers of cultured Brown Trout (*Salmo trutta*) compared with electrofishing. Behavioral differences in cultured fish compared to wild fish may increase their vulnerability to fishing efforts. Härkönen et al. (2014) reported that higher 'moving activity' among cultured fish predicted vulnerability to angling in brown trout, but the study could not determine the role of hunger in this increased activity. Greater vulnerability of cultured fish to angling has also been reported in the Common Carp (*Cyprinus carpio L.*); Klefoth et al. (2013) concluded that differences were due both to genetic factors and behavioral differences increasing boldness in the cultured fish.

2.2.1.2 Probability of Escaped Fish Encountering Wild Populations

The probability of escaped cultured fish encountering wild conspecifics is strongly influenced by the location of the pens in relation to suitable habitat for the species, the range of the species at different life stages, size of fish at escape in terms of proximity to similar sizes of wild conspecifics, and timing of the escape occurrence (Dempster et al. 2018). Much work has been conducted with dispersal of cultured Atlantic salmon in the Northeast Atlantic (e.g., Hansen and Jacobsen 2003), the Northwest Atlantic (e.g., Whoriskey et al. 2006), North Pacific (e.g., McKinnell and Thomson 1997) and the coastal waters of Chile (Soto et al. 2001). Whoriskey et al. (2006) reported the rapid dispersal of tagged Atlantic salmon released from aquaculture sites where most fish had left the vicinity of the pens within a day. They found that the dominant tidal circulation was important in fish dispersal direction. Jensen et al. (2013) found that at least a portion of Atlantic salmon that escaped during the post-smolt period migrated and dispersed in the sea like wild Atlantic salmon. A study following the escape of farmed cod discovered that they rapidly disperse over large areas with a distribution that overlaps with wild cod populations (Uglem et al. 2008). Moreover, the escaped cod were later found at local cod spawning locations during the spawning season (Uglem et al. 2008). Similarly, Zimmerman et al. (2013) suggested there is potential for interactions between cultured and wild cod based on their study which found rapid and long-distance dispersal of escaped cod (e.g., 157 km in this study).

Multiple studies have found that in the Mediterranean, escaped (or simulated escaped) Gilthead Sea Bream and European Sea Bass may disperse long distances over time (Arechavala-Lopez et al., 2012, 2014, 2018). Studies of post-escape behavior of Gilthead Sea Bream and the European Sea Bass have shown that fish move towards coastal areas at varying dispersal distances based on the species and location of escape (Arechavala-Lopez et al. 2018). Toledo-Gudes et al. (2009) found escaped European Sea Bass dispersed up to 11 km along the coast, while Toledo-Guedes et al. (2014) found Gilthead Sea Bream moved as much as 50 km from the point of escape. Other studies have reported slightly shorter dispersion distances for Gilthead Sea Bream (Izquierdo-Gomez and Sanchez-Jerez 2016, Segvić-Bubić et al. 2018). Izquierdo-Gomez and Sanchez-Jerez (2016) reported the farthest recapture was 30 km from the pens and most recaptures were within 3 km. Segvić-Bubić et al. (2018) found Gilthead Sea Bream in the eastern Adriatic Sea displayed short-term farm fidelity, with 70% of tagged individuals remaining near the escape site after two weeks. The Meagre (*Argyrosomus regius*), another farmed species in the Mediterranean, was found to rapidly disperse from the farm location within a short 24- to 48-hour window following the escape event, showing little-to-no farm fidelity (Arechavala-Lopez et al. 2017).

In summary, most studies found evidence that either a portion of escaped cultured fish find their way into wild conspecific populations or are capable of dispersing at distances where encountering wild conspecific populations is possible. The weight of evidence indicates it is appropriate to account for this likelihood unless specific information exists to refute this possibility (e.g., location of the farm-site or biology of the wild population).

2.2.1.3 Relative Reproductive Success

Relative reproductive success (RRS) describes the reproductive fitness of escapees, i.e., their fitness as it relates to spawning success. RRS generally is a value between 0 (reproductively sterile escapees) to 1.0 (same spawning contribution as wild fish). It is possible that escapees may have a RRS that exceeds 1.0 if evidence supports a higher contribution to the next generation per individual compared to wild fish. RRS can be both a function of environmental effects (i.e., non-genetic factors such as culture methods or sterilization of farmed fish) and genetic factors resulting from domestication selection (e.g., time of spawning or fecundity). It has been suggested that this RRS improves with the length of time at liberty in the wild following the escape event, i.e., younger escapees surviving to maturity may have higher RRS (Jonsson 1997, Glover et al. 2017).

Evidence for RRS in marine species is scarce with only one study examining RSS in a marine species (Leggatt et al. 2010). That study was a laboratory experiment and found that cultured cod had lower reproductive success than wild cod. Almost all direct evidence for reduced RRS in cultured fish comes from experimental work in salmonids. In a particularly compelling study, fifth generation farmed Atlantic salmon had greatly reduced relative reproductive success compared to their wild conspecifics; cultured females were only one third as reproductively successful as wild females, and farmed males only exhibited 1 to 3% of the reproductive success that wild males achieved (Fleming et al. 1996). A later study by Fleming et al. (2000), found that farmed Atlantic salmon had less than one third of the reproductive success of wild fish, with males again performing more poorly. Jonsson (1997) and Weir et al. (2004) found the relative reproductive success of cultured male Atlantic Salmon in general was lower than in corresponding cultured females. Specific mechanisms resulting in the lower relative reproductive success in cultured Atlantic salmon compared to wild counterparts was reviewed in Weir and Grant (2005). In experiments with Chinook salmon (*Oncorhynchus tshawytscha*), cultured males had significantly lower reproductive success relative to wild males in egg-to-fry survival due to competitions with wild offspring (Lehnert et al. 2013).

2.2.2 Fitness Effects

Because of the differences between the wild and cultured environments, fish, even if spawned directly from wild caught broodstock, will develop trait differences that are adapted to culture conditions (Glover et al. 2004, Liu et al. 2015, Bolstad et al. 2017). These differences, or phenotypes, may be caused by genetic changes in the captive population, or may be due to phenotypic plasticity where a single genotype may be expressed differently under varying environments (Wringe et al. 2015, and references therein). In addition, traits advantageous under culture conditions, or traits economically beneficial, can be intentionally targeted though selective breeding of captive broodstock or unintentionally selected during successive generations in the culture environment.

As heritable fish phenotypes become optimized towards culture conditions, then escaped cultured fish would experience lower fitness in the natural environment compared to their wild counterparts due to any number of morphological, behavioral, or physiological changes (Lorenzen et al. 2012, Wringe et al. 2015). When escaped cultured fish survive to encounter and reproduce with wild fish, then there is genetic introgression of cultured fish with the wild population. This then leads to a potential risk for cultured-wild hybrids to have intermediate traits, and thus also have lower fitness in nature (McGinnity et al. 2003, Naylor et al. 2005, Yang et al. 2019). Over successive generations, as there is continued escape of cultured fish that survive to maturity and interbreed with wild fish, the fitness of the natural population would be reduced through the continued introduction of maladapted traits and fixation of deleterious alleles (Basket et al. 2013, Boltstad et al. 2017, Glover et al. 2017, Yang et al. 2019, Bradbury et al 2020). Most evidence of genetic introgression of escaped cultured fish leading to reduced fitness, lowered population viability, and changes to the wild population demography are from salmonids (McGinnity et al. 2003, Bolstad et al. 2017, Sylvester et al. 2019), although it is reasonable to expect similar consequences for non-salmonid species interbreeding with escaped conspecifics.

The extent of the fitness consequences will vary based on the number of fish escaping to survive and breed with their wild counterparts, the degree of selection for traits during culture (e.g., domestication), and the size and resilience[1] of the wild population. Overall, the potential for loss of fitness is higher with greater number of escaped fish, a higher level of interbreeding of escaped fish, and more protracted level (years and generations) of genetic introgression into the wild population (Glover et al. 2017). However, there are differing opinions as to whether a constant low-level leakage of escapes of successive years (Baskett et al. 2013, Yang et al. 2019) or less-frequent larger-scale escape events (Hindar et al. 2006, Sylvester et al. 2019) have a greater impact on the wild population fitness. The varying results likely depend on whether the focus is the longer-term population equilibrium or short-term fitness outcomes (Glover et al. 2017). The constant influx of cultured fish from leakage leads to long-term consequences

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[1] Fish population resilience is the ability of a fish stock to remain viable and persist over time in the face of environmental variation and change.

whereas episodic escape events may result in short-term reductions in fitness with natural selection removing maladapted traits between escape events. In the latter case the frequency of events is important as well as the generation length of the species (escapees of long-lived species persisting longer in the breeding population).

The degree of selection, unintended selection or intended selection for traits favorable for culture (i.e., domestication) also directly impacts the fitness outcomes for the wild population. Cultured fish recently derived from wild broodstock have the greatest potential to interbreed with the wild counterparts because theoretically they would be more alike their wild counterparts (Lorenzen et al. 2012), however, because selection in the culture environment has not occurred over multiple generations, the genetic differences between the cultured and wild fish are likely to be minor and thus have a lower effect on the fitness of the wild population (Glover et al. 2017). When cultured fish have undergone multiple generations of breeding within the culture environment, selection (intended or unintended) results in traits that are likely highly maladapted to the natural environment, however in this case, the long history of domestication is also thought to reduce their ability to successfully survive and reproduce with the wild population (Baskett et al. 2013). It is theorized that domestication intermediate to those two points actually poses the greatest risk to the population, where escaped cultured fish are likely to have accumulated heritable traits maladapted to the natural environment, but also still retain the ability to survive and reproduce with their wild counterparts (Baskett and Waples 2013, Lorenzen et al. 2012, Baskett et al. 2013, Glover et al. 2017).

The size and resilience of the wild conspecific fish population is also significant when considering the extent of fitness impacts from escaped cultured fish. The larger the wild population size, the lower the proportions of escaped farmed fish will be in that population (Diserud et al. 2022), so population size in terms of absolute numbers is an important factor. Escapees are most damaging when wild populations have low abundance or a depleted population size due to excessive fishing pressure or environmental factors affecting recruitment (Lorenzen et al. 2012, Baskett et al. 2013). The population genetic structure of the wild population is another consideration for evaluating fitness impacts (Lorenzen et al. 2012). For species exhibiting significant spatial structuring, escaped fish may alter (e.g., homogenize) genetically distinct locally adapted populations, potentially leading to the loss of fitness. By its definition, locally adapted populations have higher fitness within their native region relative to an introduced population in the same environment (Savolainen et al. 2013). Genomic swamping from escaped cultured fish could eradicate localized genomic adaptation in distinct populations, and lead to lowered fitness across the formerly adapted populations.

2.2.3 Genetic Diversity Effects

Genetic diversity, which refers to the genetic differences among individuals of a population or in a species, is the material which evolutionary forces act upon and shape variation in physical and behavioral traits within populations over time (Frankham 1996, Palstra and Ruzzante 2008, Sonsthagen et al. 2017). Genetic diversity within populations or species is influenced primarily by the biology of species (e.g., distribution, population size, dispersal behavior, mating system, and generation time), but may also be influenced by anthropogenic actions such as harvest, species introductions, species propagation, and habitat loss and fragmentation (Amos and Hardwood 1998). Evolutionary forces can generate genetic diversity in a population through mutations (creation of new variations) and reduce diversity through genetic drift (stochastic events) or selective sweeps (e.g., natural selection) across a population (Amos and Hardwood 1998, Waples et al. 2012). Immigration of individuals from another population may also act to rapidly increase genetic diversity in a population.

Genetic diversity provides long-term resilience to natural populations from future stressors. A genetically diverse population where some genotype(s) (and resulting phenotypes) would provide a degree of additional benefit to withstand the novel stressors and help the species or population survive (Waples et al. 2012). Accordingly, the loss of genetic diversity in a population or species may result in the inability to respond to new selective pressure (e.g., environmental changes and novel pathogens) (Tringali and Bert 1998, Araki and Schmid 2010, Lorenzen et al. 2012, Waples et al. 2012), and rare alleles are the most vulnerable to being lost rapidly when genetic diversity is reduced (Roman and Darling 2007). Genetic diversity may also reflect locally adaptive genetic variation among populations. In that case, there is concern about escaped fish causing homogenization across populations, instead of, or in addition to, reduction in diversity within a population (Waples et al. 2012). Although loss of genetic diversity in artificially propagated populations has been documented for multiple species, the extent to which a reduction in genetic diversity has an impact on a species or population viability is not fully understood and difficult to quantify (Araki and Schmid 2010, Gruenthal and Drawbridge 2012, Hornick and Plough 2019). There are many factors that govern demographic and evolutionary processes for a given species, and the ability of a species to withstand or recover from a loss of genetic diversity varies (Milinkovitch et al. 2013, Sonsthagen et al. 2017).

2.2.3.1 Effective Population Size

The effective population size (N_e) of a population is a related metric which estimates the idealized population size (assuming random mating, and no selection, immigration, and mutation) that shows the same rate of genetic change as the census population (N) (i.e., the actual number of individuals in the non-ideal population) (Ryman and Laikre 1991, Tringali and Bert 1998, Husemann et al. 2016); and it can be thought of as a way to measure the fraction of the gene pool passed on to the next generation of offspring (Franklin et al. 1980). Waples et al. (2018) succinctly described these two populations as the census population size influences demographic and ecological processes (e.g., population growth, competition, predation, pathogen transfer), and Ne influences population processes such as inbreeding, genetic drift, genetic diversity, and adaptive potential. The ratio between the census and effective population size predicts the rate or extent to which the population processes may change under different scenarios (Waples et al. 2018).

Generally, large effective populations have higher genetic diversity and maintain that genetic diversity more effectively; natural selection is also most effective in these larger populations. Whereas small effective populations have less genetic diversity and lose genetic diversity at a higher rate. Small populations are also more susceptible to stochastic genetic drift randomly fixing alleles that could result in lower fitness for the population overall and there is a greater likelihood for inbreeding depression in smaller effective populations (Roman and Darling 2007, Ponzoni et al. 2010; Waples et al. 2012, Yáñez et al. 2014, Sonsthagen et al. 2017).

There is often a large discrepancy between the effective and census population sizes due to the biological characteristics of the species or population (e.g., unequal sex ratios, spawning or mating strategies) or unequal reproductive success where not all individuals contribute or contribute equally to the next generation (Waples et al. 2012, Sonsthagen et al. 2017). In marine fish and invertebrates, for example, N_e is often smaller, sometimes by two to six orders of magnitude, compared to the census population size (Hauser and Carvalho 2008, Waples et al. 2012). This phenomenon is believed to be due to large variances in reproductive success among individuals (Hedgecock and Pudovkin 2011). This results in N_e/N ratios much smaller than 0.01 (Hedgecock and Pudovkin 2011), and extremely low ratios have been reported in a variety of marine fish, e.g., Atlantic Cod (*Gadus morhua*) ($4\text{x}10^{-5}$; Hutchinson et al. 2003), Red Drum (*Sciaenops ocellatus*) ($1\text{x}10^{-3}$; Turner et al. 2002), Red Snapper *(Lutjanus campechanus*) ($1\text{x}10^{-3}$; Saillant and Gold 2006), New Zealand Snapper (*Pagrus auratus*) ($2\text{x}10^{-5}$; Hauser et al. 2002), Plaice (*Pleuronectes platessa*) ($2\text{x}10^{-5}$; Hoarau et al. 2005), and Striped Bass (*Morone saxatilis*) ($3\text{x}10^{-4}$; Diaz et al. 2000).

However, more recent research has indicated substantial downward biases in the N_e/N ratios (incorrectly reflecting smaller effective population sizes than is the reality) due to inadequate sample sizes and violations in the assumptions for the N_e calculation (Waples et al. 2016). Waples (2016) evaluated scenarios necessary to produce small N_e/N ratios in populations and found that even after accounting for longevity, fecundity, variance in reproductive success (that increases with age), and variation in egg quality, even more extreme conditions (or extreme types of variances) were required to reduce the N_e/N below approximately 0.01.

Recent approaches to understanding population estimates that utilize very large sample sizes, revealed much higher N_e/N ratios in the few marine species where this approach has been applied, e.g., the southern blue fin tuna (*Thunnus maccoyii*) (>0.1 and approaching 0.5; Waples et al. 2018), Red Drum (*Sciaenops ocellatus*) (~0.21; Tringali and Lowerre-Barbierri 2023), and New Zealand Snapper (*Chrysophrus auratus*) (0.33; Jones et al. 2019). While this does not discount smaller N_e/N ratios are possible, the similar life-history characteristics in those species and the lower samples sizes in those earlier studies with low N_e/N ratios, suggests that the estimates of N_e/N ratios in these other species may have been downwardly biased (Waples et al. 2018). This downward bias is not easily corrected since simulations have indicated that approximately 1% of the population needs to be sampled over a sufficient temporal range to provide more precise estimates of Ne, and for many marine species this could mean sampling many thousands to many hundreds of thousands of individuals (Marandel et al. 2019), which is rarely feasible.

2.2.3.2 Effective Population Size and Genetic Diversity of Cultured Fish

Cultured populations often show reduced genetic diversity compared to wild populations because the small subset of individuals used for broodstock may only contain a fraction of the wild diversity of the source population (Lorenzen et al. 2012). Araki and Schmid (2010) looked at 32 studies of effective population size and genetic diversity in cultured populations and in 21 of those studies, lower effective population sizes and lower diversity were reported. Some of these species include Atlantic Salmon (*Salmo salar*) (Blanchet et al. 2008), Japanese Flounder (*Paralichthys olivaceus*) (Sekino et al. 2002, Shikano et al. 2008), Red Drum (*Sciaenops ocellatus*) (Gold et al. 2008, Karlsson et al. 2008), Red Sea Bream (*Pagrus major*) (Kitada et al. 2009), Spotted halibut (*Verasper variegatus*) (Ortega-Villazán Romo et al. 2006), and Black Sea Bream (*Acanthopagrus schlegelii*) (Blanco Gonzalez et al. 2008). Loss of genetic variation has also been documented in farmed turbot (*Scophthalmus maximus*) stocks (Danancher and Garcia-Vazquez 2011, Prado et al. 2018), and in Coho Salmon (*Oncorhynchus kisutch*) (Yáñez et al. 2014). A similar pattern of loss of genetic diversity is also seen in many cultured shellfish species, for example in Pacific oysters (*Crassostrea gigas*) (Appleyard and Ward 2006, Miller et al. 2012), Suminoe oysters (*C. ariakensis*) (Xiao et al. 2011), the South African abalone (*Haliotis midae*) and black lip abalone (*H. rubra*) (Evans et al. 2004), and the Eastern oyster (*C. virginica*) (Hornick and Plough 2019).

Selection during culture can lead to even smaller effective population sizes (in comparison to wild conspecific effective sizes) leading to further loss of genetic diversity. It is known that reducing genetic diversity too far in a cultured population can make a breeding program unstable (Ponzoni et al. 2010) and reduce the additive genetic variance that selective breeding programs would target for economic benefit. However, the extent to which loss of genetic diversity in a cultured population may be acceptable is not well understood (Araki and Schmid 2010), and likely depends on the species' biology and the wild population.

Artificial propagation of fish is different than most other types of breeding programs because of the much larger number of animals produced, higher fecundities, and high mortality in early-life stages seen in most cultured fish and marine invertebrate species (Fisch et al. 2015). Further, only a relatively small number of fish (compared to wild population) are brought into a breeding program and then high reproductive variance contributes further to the disproportionate offspring production (Tringali and Bert 1998). Consistently, a much smaller number of mate-pairings are represented in the offspring compared to the potential maximum number of breeders. This has been detected in Red Drum (Gold et al. 2008, Karlsson et al. 2008), Steelhead (*O mykiss*) (Christie et al. 2012), Atlantic Halibut (*H. hippoglossus*) (Jackson et al. 2003), Japanese Flounder (Sekino et al. 2003), the Eastern Oyster (*C. virginica*) (Hornick and Plough 2019), and California Yellowtail (Schmidt et al. 2021). Differential survival in the larval and juvenile stages, and size grading may further skew how many broodstock fish are represented by the offspring (Frost et al. 2006, O'Leary et al. 2022). These factors create a setting where the effective population size of cultured fish may be greatly reduced compared to the number of broodstock individuals (Appleyard and Ward 2006, Waples et al. 2012). It may, in some cases, be half as large as the actual broodstock number or represent a small fraction of the total potential pairings (Jackson et al. 2003, Frost et al. 2006, Christie et al. 2012, Hornick and Plough 2019).

The effective population size of the broodstock and resulting offspring may be further reduced by intended or unintended selection in captivity (Fisch et al. 2015). Long-term sustainability and prevention of inbreeding due to small effective population size is a chief concern in aquaculture (Danancher and Garcia-Vazquez 2011, Prado et al. 2018), particularly as there is trend toward lower genetic diversity with increasing time since founding of a cultured population (Aho et al. 2006). Additionally, a small effective population size often leads to rapidly accumulated genetic differentiation between cultured and wild populations (Janssen et al. 2017). Strategies to achieve a large effective population size and maintain a high genetic diversity in a culture population may be difficult because of the costs and resources necessary to include a larger number of breeders in a program.

2.2.3.3 Risk of Escaped Fish on Genetic Diversity

The risk to the wild population comes when cultured fish escape, survive, and reproduce with the wild fish, and contribute a large portion to the next generation (Laikre et al. 2010, Lorenzen et al. 2012). The result could be a significant reduction in the total effective population size (N_{eT}; combined escapee-wild population) and loss of genetic diversity in the wild population (Laikre et al. 2010, Waples et al. 2016). This type of risk from the escape cultured individuals, and the resulting loss of genetic diversity in the mixed population is termed the Ryman-Laikre effect (1991) and occurs when few captive parents produce large numbers of offspring (Waples et al. 2016). While the effect may pose greater risk to population viability of small or fragmented populations, even species with large effective sizes the Ryman-Laikre effect could reduce the total effective population size to a fraction of the wild effective size and thus should be taken into consideration for aquaculture operations with the potential for cultured fish to interact with wild conspecifics (Waples et al. 2016).

The degree of risk from Ryman-Laikre effect depends on the species' population biology, demographics, and genetic structure; as demonstrated in Tringali and Bert (1998). They explored the potential for a Ryman-Laikre effect from supplementation programs for red drum and the Gulf sturgeon (*Acipenser oxyrinchus desotoi*), two species with quite different life-history and population dynamics. They found it may be possible for some species with modest cultured fish contributions to the wild population, effects on genetic diversity may be low to negligible for some geographically widespread species (Tringali and Bert 1998). However, in other instances (e.g., species that have experienced population crashes), release of cultured fish into the wild may lead to large reductions in N_e with negative effects for that population (Tringali 2023).

Furthermore, despite loss of genetic diversity in the cultured populations, no loss of genetic variation was detected in the wild populations of Red Drum (Tringali and Bert 1998, Laikre et al. 2010, Katalinas et al. 2018), Pacific Herring (*Clupea pallasii*) (Kitada et al. 2009), Japanese Spanish Mackerel (*Scomberomorus niphonius*) (Nakajima et al. 2014), Steelhead Trout (Gow et al. 2011), and the Eastern oyster (Hornick and Plough 2019). However, admixed populations have resulted in reduction in genetic diversity or genetic differentiation due to introgression from cultured conspecifics, for example, in Coho Salmon (*O. kisutch*) (Eldridge and Naish 2007, Eldridge et al. 2009), and Red Sea Bream (Kitada et al. 2009), and other populations of Steelhead Trout (Christie et al. 2012).

Katalinas et al. (2018) attributed the maintenance of genetic diversity in Red Drum to the species' long adult life span and benefits from overlapping generations, despite high contributions of cultured Red Drum in some years. Although it is beyond the scope of this report, the 'resilience' of this species may be better understood within the context of a recent report by Tringali and Lowerre-Barbieri (2023) and a preceding report by Lowerre-Barbieri et al. (2017). Whereas Kitada et al. (2009) attributed the loss of genetic diversity of Red Sea Bream to the use of a captive broodstock for extensive releases of this species for 30 years. These two examples highlight the complicated interactions between broodstock source, multiple generations of culture, and life history characteristics of the species cultured when considering the risks from Ryman Laikre effects on population diversity.

In thinking about the Ryman-Laikre effect, it is important to also consider consequences from the proportional reduction in the total effective size. While the absolute value of N_{eT} may be large enough to maintain population diversity and thus viability (according to theoretical models), N_e may be reduced by a few orders of magnitude, potentially resulting in a considerable loss of genetic diversity and adaptive potential that previously existed in the wild population. Wild populations at the greatest risk from Ryman-Laikre effects are those with large effective sizes (Waples et al. 2012) because of the potential for a substantial reduction in N_e. This aspect of risk to genetic diversity is often overlooked (Christie et al. 2012). Under some circumstances N_e may only need to be 'large enough' for selection, rather than genetic drift, to be the greater force acting on the population; if so, the population may retain its adaptive potential as long as both the lifetime variance in reproductive success among breeders and the generation length are adequately large for the species (Tringali 2023). There are also instances where the Ryman-Laikre effect may be of secondary concern. Loss of genetic diversity would be less important if the fitness of the population has been greatly affected by introgression with escaped cultured fish. A loss of fitness from introgression would be a more immediate concern. Finally, a Ryman-Laikre effect may not be a concern if cultured fish do not survive and reproduce well in the natural environment. In that case there would be little to no Ryman-Laikre effect on N_e from the escaped fish (Lorenzen et al. 2012, Waples et al. 2012, Waples et al. 2016, Glover et al. 2017).

2.2.3.4 Potential for Mitigation

Impacts on wild populations from a Ryman-Laikre effect are not easily predicted, but certain life-history characteristics may convey some buffer to avoid or minimize effects. These include long adult lifespans, overlapping generations, and large census population sizes (Tringali and Bert 1998, Katalinas et al. 2019). Migration from neighboring populations or from the outer population range may help to rebuild genetic diversity in the cultured-wild admixed population much more quickly than through mutational processes. However, that process may eventually work in the opposite direction where genetic diversity is lost across the species through migration away from the admixed population (Ingvarsson 2001, Waples et al. 2012). Strategies to minimize Ryman-Laikre effects also include keeping the percentage of genetic contribution to the next generation from cultured fish in the admixed population below 10%. A more conservative threshold sometime used is 5% (Waples et al. 2012, Waples et al. 2016). As described for potential fitness effects of escaped fish, if cultured fish do not survive or reproduce well in the natural environment then their genetic contribution would be much lower than a simple estimate of proportion based on census data (Waples et al. 2016). A rigorous monitoring program is important to evaluate the annual proportion of escaped fish in the admixed population, annual genetic contribution of cultured fish to the next generation in the admixed population, and to establish a genetic baseline in the wild population and regular genotyping of the admixed population to evaluate any changes over time (Waples et al. 2016).

Best practices during the culture phase to help mitigate possible Ryman-Laikre effects include steps to maximize effective number of adults used for broodstock, minimize inbreeding (e.g., through pedigree-reconstruction using genetic markers or careful tracking of family lines ahead of planning breeding crosses), and incorporate long-term genetic goals into the breeding program to preserve genetic diversity of the brood population (Ryman and Laikre 1991, Ponzoni et al. 2010, Yáñez et al. 2014, Fisch et al. 2015, Hargrove et al. 2015). Collecting broodstock that represent the population across both spatial and temporal scales would help capture a more representative portion of the existing natural variation (Waples et al. 2012). Breeding practices in a culture setting should aim to increase the effective population size in the cultured offspring by maximizing potential mating combinations per spawn (to account for spawning dynamics; a known issue in California Yellowtail), equalizing numbers of progeny generated per spawning event during larval grow out period, and maximizing the number of spawning events represented in the fingerlings transferred to offshore grow out pens (Gold et al. 2008, Christie et al. 2012, Schmidt et al. 2021). In stock supplementation programs (the intentional release of cultured fish to augment natural production), it has been suggested that a range between 50 to 200 breeders is able to maintain genetic variability in the cultured population, and possibly represent up to 99% of population diversity (Tringali and Bert 1998). Gruenthal and Drawbridge (2012) explored this idea for a White Seabass (*Atractoscion nobilis*) stock supplementation program and found that 74 effective breeders were able to represent 99% of wild genetic diversity in the surveyed population. Given spawning dynamics, mortality, and reproductive variance, observed for White Seabass, that would translate to maintaining between 140 and 200 broodstock fish distributed evenly across a free-breeding system where a subset of males and females are held in a tank to broadcast spawn. While the exact numbers would vary by species, it may be possible to retain most of the existing genetic diversity of the population using reasonable broodstock sizes for commercial operations even if the effective population size (N_{eT}) is reduced by orders of magnitude. The risk is low frequency gene variants in the wild population (e.g., those alleles under a frequency of 0.02 based on the White Seabass example) would still likely be lost (Tringali and Bert 1998, Gruenthal and Drawbridge 2012).

2.2.4 Ecological Effects

Ecological effects from escaped fish fall primarily into three categories: 1) competition, 2) predation, and 3) disease and each of these may impact wild populations of conspecifics independently from, or in combination with cultured-wild fish interbreeding (Bradbury et al. 2020). Ecological interactions may have immediate effects, acting on temporally co-occurring populations and may also affect the selective landscape experienced by other species in the ecosystem, resulting in multi-generational (or even permanent) changes to allele frequencies shifting to adapt to these new selective pressures (Bradbury et al. 2020). These 'non-reproductive genetic interactions', described by Bradbury et al., have been hypothesized to impact gene diversity associated with immune functioning non-conspecific wild fish (e.g., major histocompatibility complex or MHC) due to shifting selective pressures from pathogens carried by cultured fish (Bradbury et al. 2020, and references therein).

2.2.4.1 Competition

As a result of escaped fish, the frequency or intensity of competition within an ecosystem may increase, with the anticipated effects growing with increasing numbers of escaped fish (Naylor et al. 2005, Baskett et al. 2013, Glover et al. 2017, Atalah and Sanchez-Jerez 2020). Competition for resources (including food, habitat, and spawning mates) has primarily been studied for escaped salmonids (McGinnity et al. 2003, Naylor et al. 2005, Jonsson and Jonsson 2006), and the impacts were not limited to the conspecific species (Soto et al. 2001).

2.2.4.2 Predation

Predation pressures may also shift in the natural environment, either due to predatory behaviors of the escaped fish themselves (Valero-Rodriguez et al. 2015) or shifts in the responses of other predators in the environment because of the escaped fish (Naylor et al. 2005).

2.2.4.3 Disease

The spread of diseases or parasites from escaped fish the conspecific population and to other species is another ecological risk (Naylor et al. 2005, Baskett et al. 2013). Cultured fish may transmit novel pathogens to an environment (although farming of native or naturalized species reduces, but does not eliminate this risk), pathogens that have evolved under culture conditions (e.g., more virulent, more contagious than the wild-strain), or introduce cultured fish into the environment that have a lowered resistance to pathogens (and thus higher pathogen load and increased infectiousness when encountering other fish) (Lorenzen et al. 2012, Arechavala-Lopez et al. 2013). Escaped fish may also alter the distribution (spatially or temporally) of pathogens; the extent of this will depend on post-escape survival and behavior (Atalah and Sanchez-Jerez 2020).

3.0 Assessing Risks of Escape

National Marine Fisheries Service (NMFS) aided in the development of a scientific decision-support tool called the Offshore Mariculture Escapes Genetics Assessment (OMEGA) model to assess the potential risks of farmed escapees to their wild counterparts and to aid in the design of management strategies to address the potential risks of escapees to marine resources. OMEGA is intended to: 1) provide insights about factors affecting risks associated with escapes from aquaculture operations, 2) simulate the scale, frequency, and dispersal of escapes into the wild population and potential impacts to wild population fitness, genetic diversity, and long-term viability of the wild population, 3) aid in the assessment of proposed aquaculture projects and the development of management strategies to address potential escape risk, including evaluating the effects of regulatory and technical advances on fish containment, and 4) inform policy and management decisions related to the genetic and ecological risks of aquaculture.

3.1 OMEGA Model

OMEGA was developed jointly by ICF and NMFS in 2012 to evaluate the relative risks of escaped cultured fish in a wild population of conspecifics. The concepts used in OMEGA are an extension from the All-H-Analyzer (AHA) tool, which was used successfully in the U.S. Pacific Northwest to evaluate genetic and ecological interactions between hatchery and wild salmon and steelhead trout. A user guide for OMEGA containing model background and user instructions was produced the same year (ICF 2012 available at: https://www.fisheries.noaa.gov/offshore-aquaculture-escapes-genetics-assessment-omega-model). Version 2.0 developed in 2019 used for this assessment includes a Monte Carlo simulation frontend for conducting multiple iterations of a randomized simulation, varying one or more parameters based on user-specified distributions (ICF 2018). This feature is an add-on to OMEGA and requires @Risk for Excel, available from Palisade Software. @RISK operates by replacing one or more model input parameter values in OMEGA with a new value. The user also selects output model response variables to evaluate from the simulation. Model inputs and results are recorded for each iteration.

The OMEGA model is organized around three components (Figure 3.1):

1) The biology of the cultured population and details of the aquaculture operation, including the frequency and magnitude of fish escaping from the pens.

2) Factors affecting the potential for interaction between escapees and the wild population, including survival of escapees, location of the aquaculture operation relative to the wild population, and reproductive success of escapees in the wild.

3) The biology and population dynamics of the wild population, including abundance, distribution, survival, age and size at maturity, spawning characteristics, and age-specific harvest rates.

Figure 3.1. The three components of the OMEGA model.

OMEGA model input parameters describe size and growth characteristics of cultured fish, frequency and magnitude of escape events, mechanism of escape, survival of escapees in the wild, probability of escapees encountering a conspecific natural population and interbreeding, and population dynamics of the natural population. Model results describe the influence of aquaculture escapees on spawning biomass, juvenile production, and fitness of the composite population. Effects of interactions on fitness and abundance are based on the frequency and relative abundance of cultured fish that escape and survive to encounter a natural population, the difference in survival characteristics between the artificial and the natural environments, and the genetic legacy of the cultured and natural populations. More recent model developments now also evaluate potential impacts on effective population size and consequences for genetic diversity in the mixed population from escaped cultured fish.

OMEGA scenarios are modeled to assume a rate of survival of escapees based on size at escape relative to wild conspecifics. The survival rate may be adjusted to model a lower rate relative to wild conspecifics using a shaping function that is based on assumptions of predator avoidance and foraging behavior after escape, and time from escape. OMEGA also includes a parameter to describe the probability of escapees encountering the wild population. The probability of encounter is based on an understanding of distribution of wild juveniles and spawners and distance from a farm location. A third parameter is reproductive competency of escaped fish. At one extreme, cultured fish may be sterilized prior to stocking in cages and would have zero reproductive potential. At the other extreme, cultured fish from wild sourced broodstock may be as competent as spawners as wild conspecifics.

For fitness predictions and effects on wild population viability and abundance, OMEGA includes a model of stabilizing selection for a hypothetical trait, which describes the survivorship of offspring of naturally spawning wild and culture origin as described in Ford (2002). Effects on survivorship of the wild population are modeled using a relative fitness factor of the admixed wild population of conspecifics based on the modified trait value of the mixed population (Figure 3.2). Over successive generations of escapees interbreeding the mixed wild population moves away from the natural optimum and relative fitness is less than 1.0 based on assumed selection in nature for the trait.

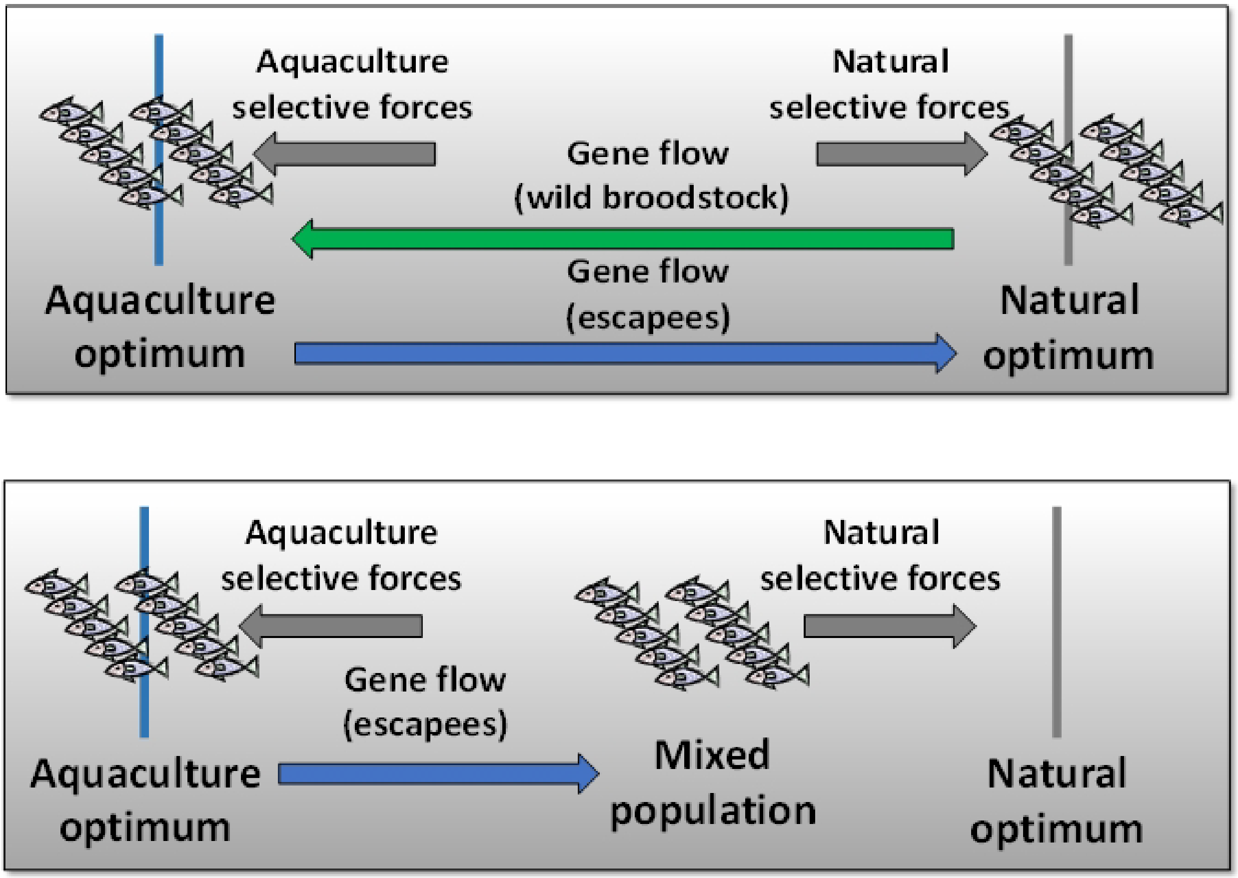

Figure 3.2. Schematic of Single Trait Fitness Model (top) and Gene flow to Wild Population with Mean Trait Value Change (bottom). Conceptual fitness model based on Ford 2002.

The potential for the wild population to experience Ryman-Laikre effects because of escapees is evaluated in terms of impacts on the effective population size (N_e) and related loss of genetic diversity. For this approach, OMEGA uses methods described in Waples et al (2011) to calculate generation length and effective population size absent escapees, and then the reduction in effective population size with escapees using Equation 8 in Waples et al (2016). A detailed discussion of methods to estimate impacts to genetic diversity is discussed in Section 5.4.2 *Population Genetic Diversity Effects*.

4.0 Project Description

In this study, the OMEGA model was used to assess the number, size and genetic consequences of California Yellowtail (*Seriola dorsalis*) escaping from a proposed commercial aquaculture operation off the coast of Southern California (Figure 4.1). Operational parameters for the offshore aquaculture site were provided by Pacific Ocean AquaFarms (Long Beach, California). For assessment, both the primary site 7.4 kilometers off the coast of San Diego and the alternative site 7.4 kilometers southwest of Huntington Beach in Long Beach were considered in building the model scenarios. After a review of the species, it was concluded escape risks (types and frequency of escape events) and impacts to the wild population would be the same at both sites and so the assessment is not site specific. Two production scenarios were assessed that represented 1) full production capacity planned by POA, and 2) 50% of production capacity.

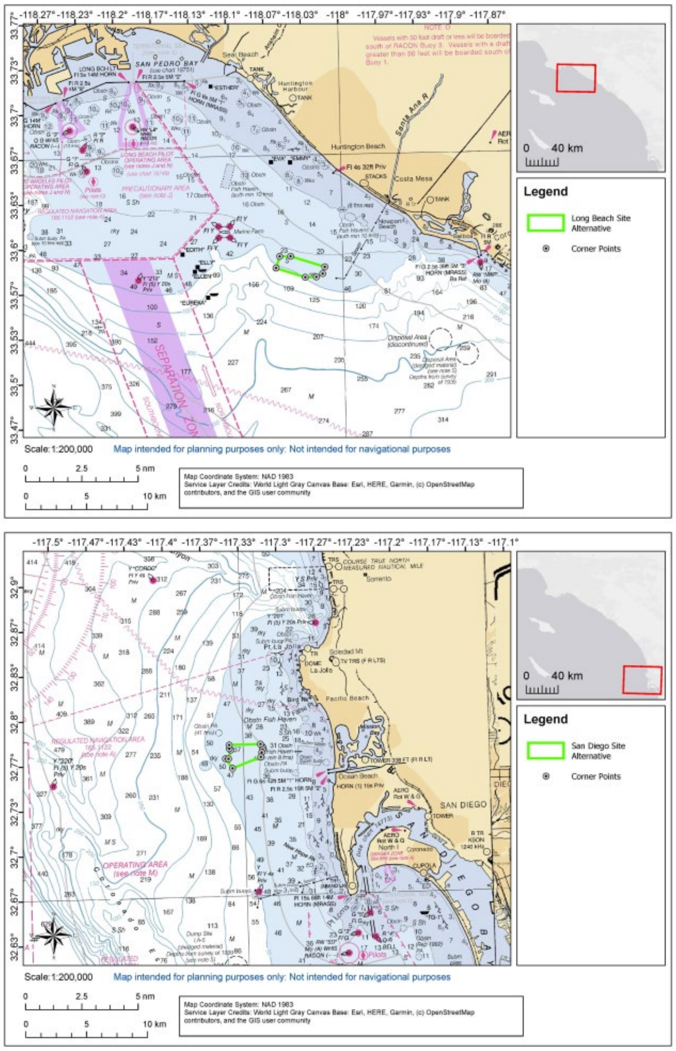

Figure 4.1. Long Beach (top) and San Diego (bottom) site alternatives (https://www.fisheries.noaa.gov/national/aquaculture/pacific-ocean-aquafarms-proposed-action-and-alternatives).

5.0 Model Parametrization

The following sections describe parameter values used for each of the three components of OMEGA: 1) the cultured population and aquaculture operations, 2) the wild population biology and demographics, and 3) the interactions between wild and escaped cultured fish. Parameter values were based on information provided by POA and values gleaned from a combination of lessons learned from use of cultured marine fish for stock enhancement, the wealth of information studying the consequences of Atlantic Salmon escapes from Norway, and the use of theoretical concepts to evaluate potential consequences of escapes.

5.1 Cultured Fish Biology and Aquaculture Operation Parametrization

The following sections present information on aquaculture operations, growth, and survival of cultured fish in cages, and potential mechanisms fish may escape from cages. This information was used to develop parameter values for time, size, and growth of fish while they are in cages and escape assumptions used in the OMEGA model for California Yellowtail.

5.1.1 Background Related to Aquaculture Operations

Information provided from Pacific Ocean Aquafarms (POA) and Hubbs-SeaWorld Research Institute (HSWRI) was used to parameterize components of the model related to aquaculture operations and the growth and survival of cultured California Yellowtail. All aquaculture parameter values were developed from production projections provided by POA in an Excel file from April 2021, a memo we prepared and reviewed with POA September 2021, and a review again with POA May 2022, and from communications with HSWRI scientists in September and October of 2021. As a precautionary measure, when selecting estimates for parameters, scenarios were developed to anticipate potential concerns the assessment of impacts of escapees on the wild population viability were not adequately addressed and to inform assessment of potential impacts of escapees from predation and competition interactions with California Yellowtail.

The full production POA pen culture system would be comprised of 28 floating net cages in two grids constructed of high-density polyethylene (HDPE) pipe and standards with a suspended copper-alloy mesh netting to control for biofouling and provide additional strength to the net cages. The half production alternative would be a single grid of 14 cages. Juveniles would be stocked in three cohorts per year (March, June, and September) at 30 grams (Table 5.1). At full production fish would be transferred to five cages per cohort across the two grids. Half-scale production also assumes stocking of the same three cohorts, but the number of cages seeded would range from two to three per cohort.

Fingerlings used to seed cages are produced from wild caught broodstock captured locally in Southern California. Because the offspring of these wild caught fish are F1s, selection for specific traits in the broodstock has not been considered in this study. However, simulations include the unintended selection of traits that are more advantageous during culture.

Table 5-1. Full production cohort schedule provided by Pacific Ocean AquaFarms.

Cohort	Number fish seeded per cage	# Cages	Total number fish seeded
March	118,007	5	590,036
June	103,256	5	516,282
September	118,007	5	590,036

Cohort growth to first harvest will take 65 to 74 weeks (15 to 17 months) (Table 5.2). The differences in the amount of time to initial harvest are a result of the timing of when a cohort of fish are transferred to the cages and sea temperatures experienced by the cohort while in cages. For example, the September cohort will have the slowest initial growth through the fall and winter, due to the expected low water temperatures, and the longest time to first harvest (Figure 5.1).

Table 5-2. Production cycle of California Yellowtail in cages; growout and harvest projections provided by Pacific Ocean AquaFarms.

Cohort	Number of fish seeded	Weeks to first harvest	Size of fish at first harvest (kg)	Number of fish harvested
March	590,036	65	3.5	498,779
June	516,282	70	4.0	430,914
September	590,036	74	3.5	489,947

Table 5.3 reports the projected number and weight of fish harvested by month. August would be the month with the largest number of fish of harvest size in the cages.

Table 5-3. Full- and half-scale harvest schedule of California Yellowtail provided by Pacific Ocean AquaFarms, harvest includes fish from multiple seedings.

Month	Full Production-Number of Fish Harvested	Half Production-Number of Fish Harvested	Full Production-Weight Harvested (kg)	Half Production-Weight Harvested (kg)
January	103,069	51,534	432,888	216,444
February	100,470	50,235	351,644	175,822
March	119,057	59,528	416,698	208,349
April	136,915	68,458	479,203	239,601
May	133,506	66,753	423,939	211,970
June	76,882	38,441	269,088	134,544
July	107,635	53,818	376,723	188,362
August	159,300	79,650	557,550	278,775
September	154,962	77,481	542,367	271,184
October	110,999	55,499	443,995	221,998
November	108,424	54,212	433,694	216,847
December	108,424	54,212	433,694	216,847
Total	1,419,641	709,821	5,161,484	2,580,742

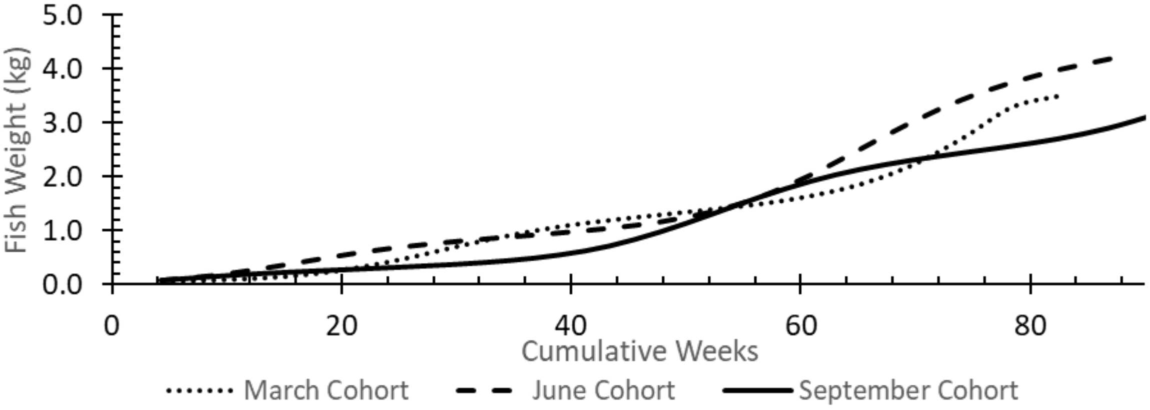

Figure 5.1. Growth projections provided by Pacific Ocean AquaFarms.

Fish transferred to cages will initially be contained in a nursery net of nylon mesh until fish reach 0.35-0.5 kg. Time from seeding to approximately 0.5 kg averaged 30.5 weeks and varied from 22 to 39 weeks. Again, the wide variance is due to the variable water temperatures experienced by a cohort as explained previously. Taking the September example again, with the colder fall and winter sea water temperatures, this cohort would likely remain in nursery nets until the end of May when they finally exceed 0.5 kg.

Fish will be held in the same cage until harvest. Harvests will occur on an as-needed basis as a cohort of fish reach the harvest size. POA anticipates deployment of the harvest vessel at least five times per week at full production over a 17-week period per cohort. Fish will be size-graded in a cage using Flexi-Panel[2] and transferred to a harvest pen for final processing.

The survival rate of fish in pens from seeding to harvest is calculated to be 0.86 based upon POA production projections.

The escape risk analysis evaluates the impacts of escapees for three size bins:

- Bin 1 <0.5 kg,
- Bin 2 0.5 kg to 3.2 kg, and
- Bin 3 >3.2 kg.

Bin 1 was defined to describe the period fish will be contained in nursery nets. Bin 2 represents the period of growout to harvest, and Bin 3 describes the period when fish will be graded for harvest. Each bin represents a different potential for escape events discussed below in Section 5.2, *Escape Category Parameters*.

Monthly production projections provided by POA were apportioned to each size bin based on the size of fish at the beginning of the month. Table 5.4 summarizes the number of fish in each size bin by month based on size at the beginning of the month. The number of fish in each bin is approximate as fish size at the beginning of the month do not align perfectly with the size bins.

Table 5-4. POA production projections; number of fish in cages by size bin by month for full-scale production scenario.

Month	Bin 1 (<0.5 kg)	Bin 2 (> 0.5 kg to 3.2 kg)	Bin 3 (>3.2 kg)	Total
January	545,159	1,498,229	106,255	2,149,643
February	541,070	984,919	502,349	2,028,337
March	1,127,319	979,531	396,855	2,503,705
April	1,099,956	975,152	273,830	2,348,938
May	1,084,893	970,793	134,177	2,189,863
June	1,065,837	980,513	512,548	2,558,898
July	1,040,789	976,064	430,541	2,447,394
August	1,026,788	971,636	318,600	2,317,024
September	1,608,180	967,228	156,114	2,731,522
October	1,043,449	1,050,195	443,995	2,537,639
November	555,106	1,517,830	328,556	2,401,492
December	549,555	1,509,279	216,847	2,275,681

Substantial differences are expected in both the size of fish in cages by month and the total number of fish in cages within a year (Figure 5.2). September would be the month with the

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[2] https://www.gradingsystems.com/home

maximum number of fish in cages. However, most of these fish would be in the smallest size bin representing fish from the June and September cohorts. November would be the month with the maximum number of fish in the intermediate size category. Finally, June would be the month when the maximum number of fish will be in cages during harvest (Bin 3). The distribution of fish across size bins is the same for the half production alternative based on the assumption that seeding will consist of the same three cohorts under this alternative. These differences in number of fish and size of fish by month will be used to evaluate a range of escape scenarios discussed in Section 2.1 *Escape Background and Categories*.

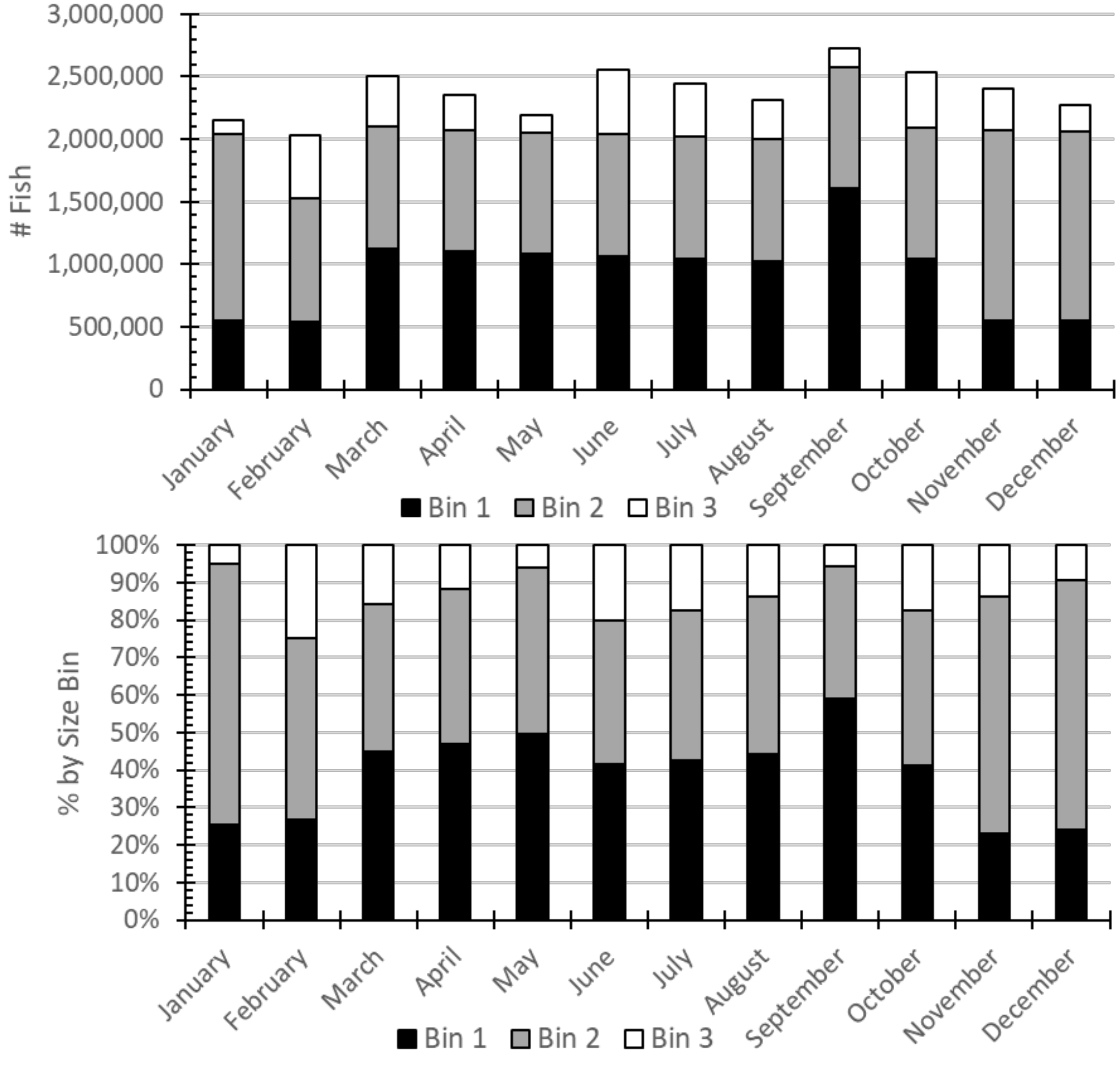

Figure 5.2. Distribution of fish on station by size bin and by month.

5.1.2 Escape Category Parameters

A key component of the OMEGA model is identifying ways fish may escape from cages and determining reasonable simulation parameter values for those escapes. Each escape type is discussed in detail above; in the following sections, proposed parameter values are presented based on information provided by POA and a survey of published information from salmon aquaculture operations from various regions and from aquaculture escapes of Kingfish (*Seriola lalandi*) in South Australia.

5.1.2.1 Leakage Escape

In this modeling exercise, leakage rates across the production cycle were estimated based on discussions with POA, and these estimates reflect points in the operation when more or less leakage may be expected. For the smallest fish (Bin 1), which are contained in a nursery net, the highest amount of leakage for the on-station period is expected. This is expected due to potential size mismatches between the mesh size of the nursery net, cage mesh sizes, and the sizes of fish in that cage, both at the time of initial seeding and at the time of nursery net removal (i.e., some fish may be too small to be contained by the nursery net upon seeding, or to be contained in the regular cage once the nursery net is removed). Some loss is also expected during the seeding process and from maintenance activities related to the nursery nets, if required (e.g., replacing the net if/when biofouling is an issue). Based on communications with POA, a leakage rate of 0.05% for Bin 1 was applied during this period fish are in cages (Table 5.5).

Very little loss is expected in the intermediate grow out production pen (Bin 2), and leakage is approximated to be 0.01% for that bin (Table 5.5). This low level of leakage reflects the superior cage construction using copper-alloy mesh which eliminates small holes from chaffing, holes caused by biting predators, or holes due to general wear from fish inside the pen (Dwyer and Stillman 2009, Berillis et al. 2017, Yigit et al. 2017). The rigidity provided by this type of mesh also reduces the likelihood of pen damage from incidents with boat propellers. In addition, fish during this portion of the grow out do not usually require handling (e.g., no size sorting, transferring between cages, etc.), so the risk of escapes during this period is assumed to be minimal.

Leakage risk increases with the largest fish (Bin 3), this is due to more frequent handling and activities such as size-grading, transfer of fish to harvest pens, and harvesting of fish which is expected to occur five times weekly at maximum production. Based on discussions with POA, a value of 0.02% leakage was estimated for this stage (Table 5.5).

Table 5-5. Leakage escape rates across size bins approximated for *S. dorsalis* based on producer conversations, and application of the Skilbrei et al. 2015 multiplier to account for underestimation.

Bin size	Producer informed leakage rate	Skilbrei et al. 2015 (4x) multiplier applied
Bin 1	0.05%	0.20%
Bin 2	0.01%	0.04%
Bin 3	0.02%	0.08%
Total Leakage	0.08%	0.32%

With the estimates provided by POA, one more step was added to obtain the final leakage estimates used in this study. It has been documented that reported or approximated leakage rates underestimate true levels of escape (Glover et al. 2017, Skilbrei et al. 2015) likely because the loss of one to a few fish at a time may go unnoticed while working in a challenging marine environment. An analysis of catch statistics and tagging studies in Norway determined that the true number of escaped fish was two to four times higher than numbers reported by producers (Skilbrei et al. 2015). While based on salmonid culture, this multiplier is the best science available to correct for this potential under-reporting of leakage and small episodic escapes. Importantly, this multiplier (at the 4x level) has been used in recent modeling of Atlantic salmon escapes in Canada and Iceland (Bradbury et al. 2020, MFRI 2020). To err towards a high potential for effects, the upper end of this multiplier (4x) has similarly been applied to the POA estimated escape rates to obtain the leakage estimates of 0.20%, 0.04 %, and 0.08% used in this OMEGA modeling exercise for Bins 1, 2, and 3, respectively (Table 5.5). For each bin, leakage escape estimates are applied independently and apportioned in weekly increments according to the length of time in the bin (e.g., 0.20% total over 30 weeks, or 0.0067% per week, in Bin 1).

Interestingly, the sum of the multiplier-based estimate, 0.32%, is close to the escape value of 0.3% of total farmed salmon (or 0.8 escapes per metric ton) used in the Canadian and Icelandic escape modeling referenced above (Bradbury et al. 2020 and MFRI 2020). Arriving at a similar value lends confidence to the use of 0.32% for this difficult to estimate parameter.

5.1.2.2 Episodic Escape

In modeling episodic escape events, parameters for both the frequency and the magnitude of an episodic escape event need to be developed. The highly variable pattern of escape numbers by year reported in Skilbrei et al. (2015) and in MFRI (2020) suggest medium to large episodic escape events occur in combination with the previously discussed leakage type escape. Norwegian studies of Atlantic salmon suggest unreported episodic escape events occur on a regular basis (Glover et al. 2008, Glover 2010). Thus, it seems reasonable to assess episodic escapes in combination with leakage escapes to anticipate a pattern of low-level escapes (leakage) interacting with the wild population with an occasional larger influx of escapees (episodic cage failures).

It is challenging to determine the frequency of episodic escapes. While no data is available for California Yellowtail (*S. dorsalis*) culture operations, escape data has been collected in South Australia[3] for aquaculture escapes of another Seriolid, the Kingfish (*S. lalandi*), a closely related species with similarly sized aquaculture operations. Based on reported data from South Australia, three locations (Arno Bay, Boston Bay, and Louth Bay) were used to determine frequencies of escapes of 1000 fish or more. Fitzgerald Bay, another *Seriola* farming site, was not included due to inconsistent operations in that location. Smaller pulses of fish (<1000) are captured within the leakage rate using the 4x multiplier and are not included in this scenario.

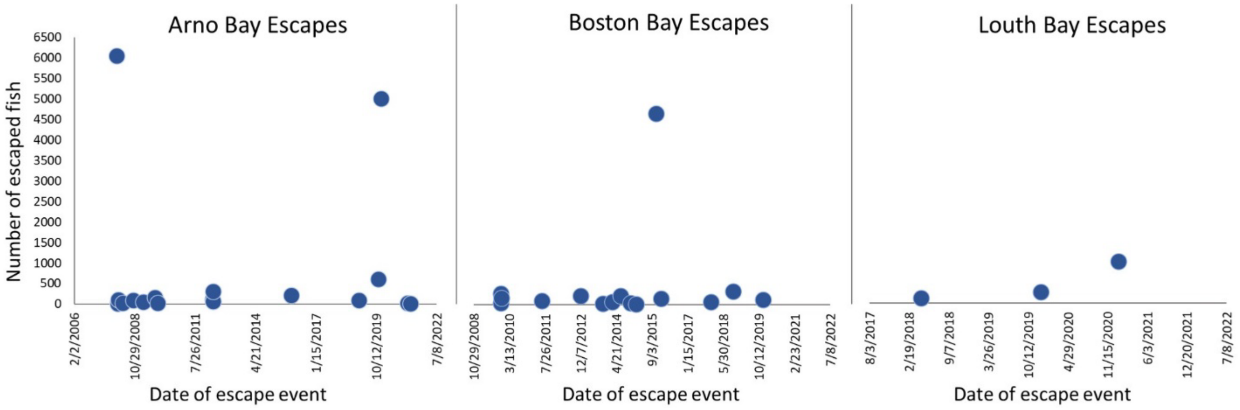

Figure 5.3. Dates of escape events and number of fish (S*eriola lalandi*) that escaped in each event reported across three sites, Arno Bay, Boston Bay, and Louth Bay in South Australia.

Frequency of the episodic events varied among locations, with a low of one event every 10 years (10%) in Boston Bay to one event every four years (25%) in Louth Bay (Table 5.6). However, the Louth Bay site with the highest frequency was also based on the fewest number of years (four) compared to the two longer running locations with lower frequencies. While these estimates are not directly transferable for several reasons (e.g., likely different cage materials, in a bay versus offshore, and a different Seriolid), some of these differences may offset each other and still represent the closest proxies available at the present time. Given this uncertainty, and to explore the impact that episodic loss frequency has on the results, the frequencies from the three sites were independently simulated to explore the range (10%, 15%, and 25% annual likelihood) of episodic escapes.

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[3] (https://pir.sa.gov.au/primary_industry/aquaculture/monitoring_and_assessment/register_-_finfish_escape)

Table 5-6. Frequency of Kingfish (*Seriola lalandi*) escapes of over 1,000 fish and corresponding likelihood of occurrence over a year based on reported escape data from three locations in South Australia.

Location	Escape frequency	Likelihood of escape occurring over course of a year
Arno Bay	Every 6.5 years	15%
Boston Bay	Every 10 years	10%
Louth Bay	Every 4 years	25%

To more realistically simulate episodic escapes, the OMEGA model was set to randomize the number of fish lost in an event between a half and a full cage of fish. The number of fish in a full cage was estimated from the month with the greatest number of fish on station and taking an average of the number of fish per cage based on that number (i.e., total number of fish on station / 28 cages). Based on the POA data, this was September (Table 5.4) with an estimated 2,789,542 fish on station, or an average of 99,627 fish per cage. The model also randomly assigned the cage loss to one of the three size bins of fish.

5.1.2.3 Large-scale Escape and Catastrophic Events

Given the scale of the large-scale losses, impacts from this type of escape event will be modeled independently to simulate the number of fish escaping into the environment, and explore the potential impact on the wild conspecific population.

Impacts from large-scale losses were explored for the full and half production scenarios. The Scenario II catastrophic scenario would be the complete loss of two grid systems (two grids with 28 cages) for the full production scenario, and one grid system (one grid with 14 cages) for the half production scenario.

Previous sensitivity modeling using OMEGA has demonstrated that the size of fish escaping affects outcomes from escape events, this is due largely to varying survival rates based on size of escapees, and the amount of time from escape to sexual maturity. Based on the production schedules provided by POA, there is considerable variation in both the number of harvest-sized and small-size skewed fish on station over the course of the year.

To account for the size variation on station, impacts were assessed by modeling the large escape events in three ways (Table 5.7). The first was to model the escape with a relatively even distribution of fish sizes on station; this is represented by May when equal numbers of fish would be in Bin 1 (50%) and Bins 2 and 3 (50% combined).

The second approach was to skew the distribution towards a greater number of larger sized fish on station, based on production data this will reflect the size of fish in February. In February 74% of the fish would be in Bins 2 and 3. The last approach was to skew the distribution towards a greater number of smaller sized fish on station; this will be modeled using the size distribution in September when 59% of the fish would be in Bin 1 and 94% of the fish in Bin 1 and 2, combined. Including this size variation in the modeling will help to capture the full range of impacts that may result from a rare large-scale escape event.

Table 5-7. Distribution (in percentages) of fish across size bins selected to model the range of large-scale escape events.

Type	Month of operation	Bin 1	Bin 2	Bin 3
Even Distribution	May	50%	44%	6%
Skewed Large Fish	February	27%	49%	25%
Skewed Small Fish	September	59%	35%	6%

5.1.2.4 Gamete-based Escape

The analysis assumed fish will be harvested prior to sexual maturation, as such, gamete-based escape was not included in these modeling scenarios. Size at harvest is within the range of sizes that wild California Yellowtail are sexually mature (~60 cm and ~2.8 kg, Baxter 1960) suggesting a potential for spawning in net pens, but at a younger age compared to wild California Yellowtail.

5.1.2.5 Recapture Rates

Impacts from episodic and large-scale escape events may potentially be mitigated by attempts to recapture escaped fish. As described above, recapture rates vary based on the species, the number of fish, and the size of fish escaping. Given the low observed recapture rate in Dempster et al. (2018), and the uncertainty of success in recapturing smaller size classes of escaped fish, the Scenario II approach is to use a value of zero percent recapture in the modeling exercise.

5.1.3 Culture Parameter Values

The sections above describe how the estimates based on cultured fish biology, aquaculture operations, and the escape scenarios were selected from input provided by POA and HSWRI, and from the scientific literature. Parameter values are summarized in Table 5.8 for aquaculture operations and escape scenario parameter values are summarized in Table 5.9.

Table 5-8. OMEGA Aquaculture Parameter Values for POA Proposed Operation

Aspect	Parameter	Value	Range	Units	Source
Culture Program Operation	Annual production goal	5,000 (full-scale); 2500 (half-scale)	Initial production 1,000 mt/year, expanding to 5,000 mt.	metric tons (mt)	POA
	Fish size at harvest	3.65 kg average	3.2-4.2 kg	kilograms (kg)	POA
	Time to reach harvest size	70 wks average	Time to first harvest 65 to 74 wks	weeks (wks)	POA
	Survival to harvest	0.86	0.85 to 0.87	proportion	
On-station inventory	Fish size class (bins):			kg	POA
	Bin 1 [a]	0.03	none	kg	
	Bin 2 [a]	0.5	none	kg	
	Bin 3 [a]	3.2	none	kg	
	Number of cages per production unit	28 cages full production 14 cages half production	none	cage	POA
	Duration in each size class			wks	POA
	Bin 1	30 wks	none	wks	
	Bin 2	51 wks	none	wks	
	Bin 3	17 wks	none	wks	
Broodstock management	Natural origin	100	none	%	POA and HSWRI
	Age youngest spawner	3 yrs	2.5 to 4	years (yrs)	
	Age oldest spawner	22 yrs	18+	yrs	
Program operations schedule	Begin year and period years	2 cohorts seeded years 1 and 2 3 cohorts seeded starting year 3		yrs	POA
Cultured length (cm) to wt (kg) conversion	Length weight conversion, ln(alpha)	-10.626	none	none	L-Wt based on HSWRI data (Oct. 2021)
	Length weight conversion, beta	2.8745	none	none	
Cultured von Bertalanffy growth model	VBGF L_{Max}	167 cm	none	cm	Approximated from cohort growth curves provided by POA (Figure 5.1)
	VBGF $L_{Initial}$	11.9 cm	none	cm	
	k	0.0046	none	growth rate	

[a] *Bins were categorized by initial fish weight during time in cages. Average weight at harvest was used for Bin 3.*

Table 5-9. OMEGA Escape Scenario Parameter Values for POA Proposed Operation

Escape Type	Parameter	Value	Details of estimate
Leakage Escapes	Bin 1	0.20%	Based on initial POA estimates with Skilbrei et al. 2015 4x multiplier applied to initial estimates
	Bin 2	0.04%	
	Bin 3	0.08%	
Episodic Escapes	Episodic escape frequency	Low – 10% annual likelihood (once every 10 years); Medium - 15% annual likelihood (1.5 times every 10 years); High – 25% annual likelihood (2.5 times every 10 years)	Based on *S. lalandi* escape data from sites in South Australia.
	Episodic escape size	Varying between full-cage (99,627 fish) and half-cage (49,814 fish).	Based on POA production data for month with highest on-station inventory.
Large-scale Escapes or catastrophic events	Full-scale	2 grids	Total of 28 cages
	Even Distribution	1,084,893 (Bin 1), 970,793 (Bin 2), 134,177 (Bin 3) fish	Based on production in May; total 2,189,863 fish.
	Small fish skewed	1,608,180 (Bin 1), 967,228 (Bin 2), 156,114 (Bin 3) fish	Based on production in September; total 2,731,522 fish.
	Large fish skewed	541,070 (Bin 1), 984,929 (Bin 2), 502,349 (Bin 3) fish	Based on production in February; total 2,028,337 fish.
	Half-scale	1 grid	Total of 14 cages
	Even Distribution	542,447 (Bin 1), 485,397 (Bin 2), 67,089 (Bin 3) fish	Based on half of reported full-scale May production; total of 1,094,932 fish.
	Small fish skewed	804,090 (Bin 1), 483,614 (Bin 2), 78,057 (Bin 3) fish	Based on half of reported full-scale September production; total of 1,365,761 fish.
	Large fish skewed	270,535 (Bin 1), 492,460 (Bin 2), 251,175 (Bin 3) fish	Based on half of reported full-scale February production; total of 1,014,169 fish.
Gametic Escape	Gamete-based Escape	Not considered	Assume fish will be harvested before maturity

5.2 Natural Population Parametrization

The following sections present information on the wild population of California Yellowtail and development of parameter values used in the OMEGA model simulations. Biological characteristics (age at maturity, length-weight, growth, and maximum age) are largely taken from Ben-Aderet et al. (2020) and Baxter (1960). A stock assessment has not been conducted for this species; therefore, population abundance and recruitment are uncertain. Some of the model assumptions for the wild population were loosely based on parameters used for stock assessment modeling for Gulf of America Greater Amberjack (*Seriola dumerili*) and Almaco Jack (*Seriola rivoliana*).

5.2.1 Background Related to the Natural Population

California Yellowtail is a coastal pelagic species found along the eastern Pacific coast from Cabo San Lucas in Baja California Sur, Mexico, north to Point Conception, California (Ben-Aderet et al. 2020). Southern California is the northern edge of the California Yellowtail distribution (Figure 5.4). This species is rarely observed north of the Southern California Bight (SCB) except in years with high water temperature anomalies (Ben-Aderet et al. 2020). The abundance of California Yellowtail in Southern California is believed to be dependent on ocean temperatures, and higher catches are reported in years when water temperatures were at least three to five degrees (°F) above normal in the spring (Baxter 1960). Although a smaller number of California Yellowtail are present in the SCB year-round (Ben-Aderet 2017, Madigan et al. 2018), in spring and summer, abundance increases with a seasonal migration of fish moving north from the greater abundance of fish offshore of central Baja California (Baxter 1960).

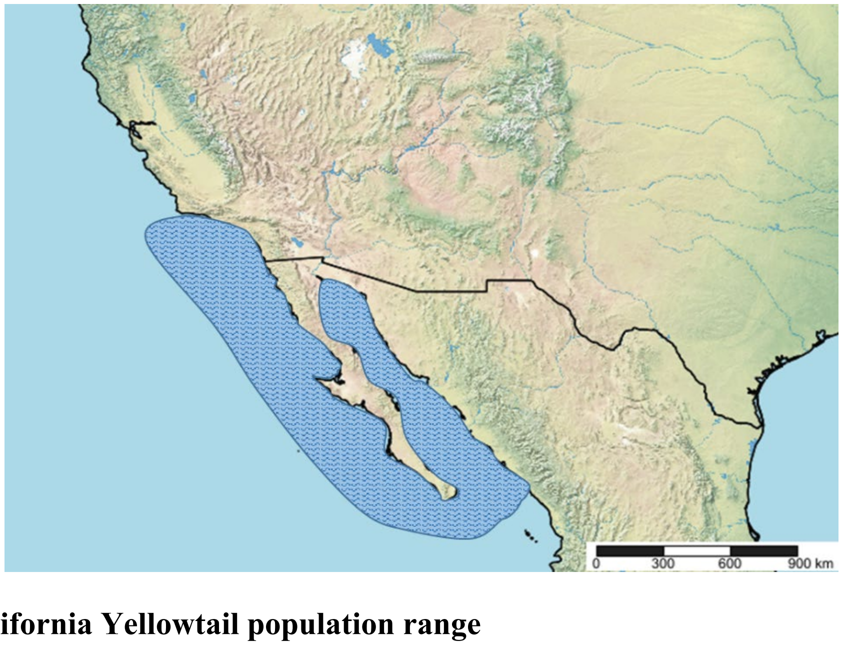

Figure 5.4. California Yellowtail population range

Within Southern California, differences have been detected in the size distribution and migratory behavior between inshore and offshore fish (Madigan et al. 2018). Smaller fish are found offshore, often in association with floating kelp paddies, which may offer these fish both protection and food forage, whereas larger fish are often found inshore in kelp forests, where, as apex predators in that system the availability and variety of prey items is greater (Madigan et al. 2018, Ben-Aderet et al. 2020). As reported in Ben-Aderet, Baxter (1960) found younger, smaller fish were more likely to move farther from their tagging site while most of the larger fish were captured closer to their tagging site.

There has been some debate as to whether the localized populations of California Yellowtail in the SCB may be self-recruiting and distinct from the larger population that seasonally shifts northward from Mexico (MacCall 1996). While this possibility cannot be excluded, population genetic studies only support a single population in the NE Pacific, with no significant genetic structure detected between fish sampled in Southern California and Baja California, Mexico (Purcell et al. 2015).

Although California Yellowtail are a popular sport fishery species, an estimate of fishing mortality is not available. CDFW (2020) acknowledged population status of California Yellowtail is unknown, but based on consistent sport catches in U.S. waters, the overall population is “healthy”.

California Yellowtail mature in three to four years and have high fecundity suggesting the species may be resilient to heavy fish pressure (CDFW 2020). Ben-Aderet (2017) tagged 182 Yellowtail between September 2014 and January 1, 2016. He reported a 21.4% recovery rate of tags from the Southern California sport fishery. He was not able to make an estimate of abundance from the data but concluded the high recovery rate indicated a high fishing mortality on the species in the region. Baxter (1960) made the same observation from a tagging study conducted in the 1950s. Ben-Aderet suggests because of the high fishing mortality in the SCB that this portion of the species range is a sink on the overall population (total mortality including fishing and natural mortality exceeds a sustainable level) and the sustainability of the species is largely dependent on the core stock in Baja California where fishing pressure is assumed to be lower.

California Yellowtail annual catch from U.S. waters varies substantially from year to year (Figure 5.5); consistent with the movement of the species into Southern California from Baja California reported by Baxter (1960). U.S. catch was highest in 1997 and 1998 during the very warm El Niño years (>2,500 mt). U.S. catch has averaged approximately 260 mt for the years 2000 to 2020 and varied from 10 mt in 2011 to 877 mt in 2015. Annual catches from Baja Mexico are reported in Enciso and Trasviña (2022) for *Seriola spp.* for the years 2000 to 2020. This species group can include 32 different species in reported catch, of which, *S. dorsalis* is the most common species (Cisneros-Soberanis 2018). Cisneros-Soberanis (2018) reported the annual catch of *Seriola dorsalis* for the years 1980 to 2017. In both reports, catch is reported in charts and annual catch reported here is approximate based on a visual review of the charts. The two catch assessments closely match, with Enciso and Trasviña, (2022) being slightly higher suggesting catch reported are almost entirely *S. dorsalis*. Reported annual catch in Enciso and Trasviña for the years 2018 to 2020 was adjusted downwards based on the average difference between the two assessments. Mexico catch has averaged approximately 2,040 mt for the years 2000 to 2020 and varied from 1,175 mt in 2000 and 2002 to 2,800 mt in 2013. Total catch from U.S. and Mexico for the years 2000 to 2020 has averaged 2,300 mt. Annual catch has varied from 1,460 mt in 2002 to approximately 3,500 mt in 2015. Catch from Mexico has averaged about 90% of the total catch for the years 2000 to 2020. From 1983 to 2020 the largest annual catch was in 1998 from the very large catch in U.S. waters combined with a moderate catch of 1,200 mt in Mexico. Overall, there is a trend of larger annual catch in Mexico representing a growing commercial harvest of this species in Baja Mexico and some concern for the future status of this loosely managed species (Enciso and Trasviña 2022).

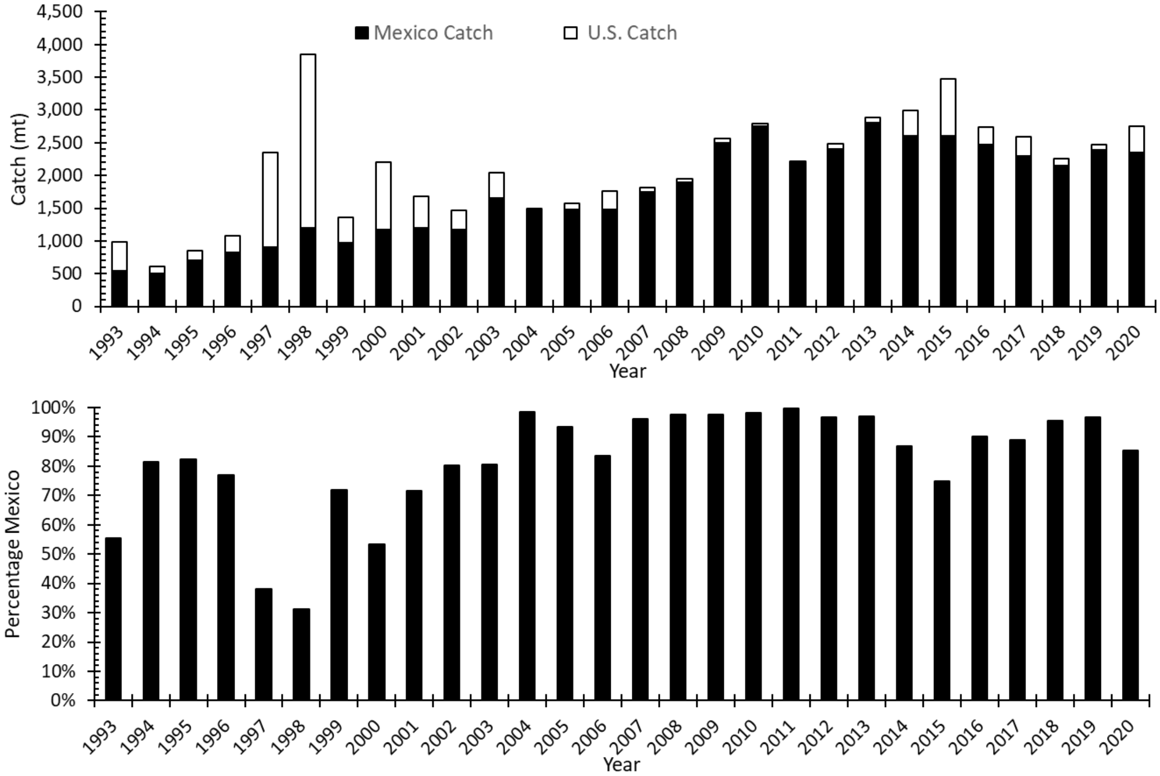

Figure 5.5. California Yellowtail Landings Sources: U.S. catch: https://www.fisheries.noaa.gov/foss/, Mexico catch: Cisneros-Soberanis, 2018 and Enciso and Trasviña 2022)

Despite the popularity of this species in sport and commercial fisheries, there are only two assessments of life history and biological characteristics (Ben-Aderet et al. 2020 and Baxter 1960) and limited demographic information. We reviewed a population assessment completed by Enciso and Trasviña, (2022) for Jurel (Mackerel) *(Seriola spp.)* in Baja Mexico for consistency with our model parameterization. This assessment did not report life history information that we could use in our modeling.

The absence of a formal population assessment required modeling escape risk for a range of possible population abundances. Female spawning biomass was varied from 8,000 mt to 18,000 mt. This range corresponds to a total population biomass (males and females aged 2 and older) of 17,000 mt to 34,000 mt. This is a very wide range, and the lower end of the range may lead to a conclusion of higher impact that may need to be qualified when evaluating results at the lower abundance.

5.2.2 Natural Population Model Structure

The preceding section describes the natural population model structure and parameter values used in the natural population component of OMEGA.

The wild population simulation in OMEGA is an age-structured single population model with age-specific assumptions for survival, harvest, and maturity (ICF 2014). The life cycle process is separated into four phases: 1) spawning biomass, 2) egg production, 3) juvenile recruitment, and 4) subadult/adult survival. Harvest is included during the subadult and adult phase and is shaped by an age-specific double logistic function. The population model in OMEGA was developed based on many of the concepts and the life stage structure of the Stock Synthesis population assessment model for marine fish management (Methot 2000). OMEGA is a much simpler construct of the population model in Stock Synthesis and does not include the analytical components in Stock Synthesis to estimate population parameters.

The number of spawners for wild and cultured are calculated as follows:

$$N_{Wild,a,yr} = \sum_{a=1}^{A} \left(N_{Wild,a,yr} * M_a \right)$$

$$N_{Cultured,a,yr} = \sum_{a=1}^{A} \left(N_{Cultured,a,yr} * M_a \right)$$

Where $N_{a,yr}$ is the number of wild and cultured fish in the population by age a in year yr and M_a is the fraction fish mature at age a. The same maturation schedule for females and males was assumed in this model. To account for the observation that cultured fish, when they escape, would be larger than wild fish at a given age, the age of the cultured fish at the time of escape was advanced based on their size relative to size of wild fish.

Female spawning biomass (SPB) of wild fish is calculated as follows:

$$SPB_{Wild,yr} = \sum_{a=1}^{A} \left(N_{Wild,a,yr} * SexRatio_a * W_{f,a} \right)$$

and cultured fish:

$$SPB_{Cultured,yr} = \sum_{a=1}^{A} \left(N_{Cultured,a,yr} * SexRatio_a * W_{f,a} * RRS_{Cultured} * f_{Cultured}\right)$$

Where *SexRatio*$_a$ is ratio females to males at age a, and $W_{f,a}$ is the body weight of females at age a. For cultured fish in the population *RRS* is the user input relative reproductive success of escapees, and $f_{Cultured}$ is the fitness of cultured fish in nature based on calculated cultured fish trait value. Relative reproductive success and calculated fitness were included at this stage to report effective spawning biomass of cultured fish in nature versus census abundance estimated previously.

Egg production is calculated by the following for wild and cultured:

$$Eggs_{Wild} = \mathrm{SPB}_{\mathrm{Wild}} * \frac{Eggs}{Kg} * f_{Spawn}$$

$$Eggs_{Cultured} = \mathrm{SPB}_{\mathrm{Cultured}} * \frac{Eggs}{Kg}$$

Where f_{Spawn} is fitness of wild fish allocated to spawning life stage.

Egg to end of juvenile recruit period is based on the two parameter Beverton-Holt survival function (assumption of density-independent productivity and maximum number recruits or capacity). The modeled recruitment stage for California Yellowtail was one year. The Beverton-Holt function is as follows:

$$Recruits = (P * f_{Recruit}) * Eggs)/(1 + \frac{(P * f_{Recruit}) * Eggs}{C * f_{Recruit}})$$

where Eggs is sum of eggs following spawning from wild and cultured, *P* is the density-independent productivity, *C* is capacity and $f_{Recruit}$ is fitness of wild fish allocated to the recruit life stage.

The number of subadult and adult fish surviving to the next year is calculated by the following:

$$N_{a+1,yr+1} = N_{a,yr} e^{-Z_a}$$

where Z is age specific instantaneous mortality ($M_a + F_a$) where *M* is natural mortality and *F* fishing mortality. Natural mortality is adjusted for relative fitness allocated to subadult and adult life stage by calculating annual survival adjusted for relative fitness and then calculating fitness adjusted M_a.

To remove any initial parameter effects on results the simulation includes a 50 step/year initialization period absent stochastic variation and cultured fish escapes. This is done to eliminate any initial parameter effects prior to analysis of effects of escapees.

5.2.3 Natural Population Parameter Values

Natural mortality rate of adults was based on Ben-Aderet et al. (2020) and age-specific rates calculated using a logistic function approximated from a review of Greater Amberjack modeling in the Gulf of America (SEDAR 33) (Table 5.10). Fishing mortality was assumed based on a comparison of model predicted annual catch with a total population of 25,000 mt and annual combined U.S. and Mexico catch (Figure 5.5). Fecundity was from Baxter (1960). The von Bertalanffy Growth model parameters are from Ben-Aderet et al. (2020).

Natural population parameters for California Yellowtail are summarized in Table 5.11.

Table 5-10. Life history information used to simulate California Yellowtail. Natural mortality (M) for older fish is from Ben-Aderet et al. (2020) and Fishing Mortality (F) is assumed. Age specific mortality approximated based on review of Gulf of America stock assessments for Greater Amberjack (SEDAR 33). Maturity schedule and fecundity is from Baxter (1960).

Age	Natural Mortality (M)	Fishing Mortality (F)	% Mature	Fecundity (x1,000)
1	0.600	0.000	0%	---
2	0.313	0.002	42%	155
3	0.268	0.025	90%	381
4	0.262	0.048	99%	675
5	0.261	0.050	100%	1003
6	0.261	0.050	100%	1340
…	….	….	…	…
22	0.261	0.050	100%	3755

Table 5-11. OMEGA Natural population parameter values based on the California Yellowtail wild population.

Component	Parameter	Value	Range	Units	Source
von Bertalanffy Growth Model (both sexes)	VBGF L_{Max}	117.96	--	cm	Ben-Aderet et al. 2020
	VBGF $L_{Initial}$	0	--	cm	
	k	0.196	--	year	
	Max age	22	--	years	
Length (cm) to Weight (kg) (both sexes)	Ln(a)	-10.64163	--	--	Baxter 1960
	b	2.85	--	--	
Maturity schedule	~50% Mature	Age 2(50 cm; 1.7 kg)	--	Years, (cm; kg)	Ben-Aderet et al. 2020 (size at age); Baxter 1960 (maturity schedule)
	100% Mature	Age 3 (63 cm; 3.2 kg)	--		
Recruitment	Fecundity	2000000	--	# eggs per kg	Baxter 1960
	Recruitment DI survival	0.0000125	--	--	Assumed
	BH Capacity	--	2000 to 4000	x1,000	Assumed range
	Steepness (h)	--	0.75 to 0.90	--	Calculated range
Natural Mortality	M Initial (age 1)	0.60	--	Yearly instantaneous	Assumed based on size of fish and rapid growth during YOY recruitment phase
	M – age 3 and older	0.26	--		Ben-Aderet et al. 2020
Fishing Mortality	F	0.05	--	Yearly instantaneous	Assumed based on area and remote portions of range of population
Population size	Population biomass	--	17000 to 34000	mt	Assumed range
	Female spawning biomass	--	8000 to 18000	mt	

5.3 Interactions Between Wild and Escaped Cultured Fish

The following sections present information on the potential interactions between escaped cultured and wild California Yellowtail, OMEGA model structure, and the development of parameter values used in the OMEGA model simulations for California Yellowtail.

5.3.1 Interaction Parameter Values

The potential interactions of escapees with wild conspecifics and the consequences are dependent on survival of escaped fish, their encounter probability with wild conspecifics, and their reproductive competency in nature when they encounter breeding wild California Yellowtail. Effects of mixed breeding are dependent on genetic differences between cultured and wild fish resulting from unintentional or intentional selection for morphological, physiological, ecological, or behavioral traits during culture. In addition, escaped fish may result in loss of genetic diversity of the wild population through low genetic diversity of cultured fish. Finally, escaped fish may pose ecological risk through competition for resources, predation on smaller fish, and potential transfer of pathogens to the wild population.

5.3.1.1 Survival of Escaped Fish

As described previously, escaped cultured fish may experience lower survival than similarly sized wild conspecifics (e.g., escaped Yellowtail kingfish (*S. lalandi*) observed with empty stomachs or stomachs containing atypical non-food contents; see Fowler et al. 2003). However, in taking a high potential for effects approach for modeling purposes, the assessment assumed survival would reflect wild population size-based on mortality for adults estimated by Ben-Aderet et al. (2020). Although age-specific mortalities were not available for younger California Yellowtail, the analysis assumed higher mortality for age one-, two- and three-year aged wild fish (see Table 5.11 and associated text). Modeled first year in nature survival rates of escapees from Bin 1, Bin 2, and Bin 3 are shown in Table 5.12.

Table 5-12. Survival of escaped California Yellowtail in first year in nature.

Size Bin	Fish Size (kg)	Length (cm)	Wild Age Equivalent	Relative Survival Assumption	First Year Survival Rate
1	0.03 – 0.50	12.0 – 32.0	1	1.0	0.550
2	0.50 – 3.20	12.0 – 60.5	3	1.0	0.765
3	3.20 – 4.20	60.5 – 66.5	4	1.0	0.770

5.3.1.2 Encounter Probability of Escaped Fish with Wild Populations

The probability of escaped cultured fish encountering wild conspecifics is strongly influenced by the location of the farm and the range of the species at different life stages. Escaped California Yellowtail of any size (Bins 1 to 3) would likely immediately encounter wild conspecifics based on the locations of the proposed site off the coast of San Diego and the alternative site off the coast of Long Beach and the overlapping population range (Figure 5.4).

The smallest sized fish (Bin 1) may interact with other juvenile or subadult fish associated with nearby floating kelp paddies. These kelp paddies are known to provide both food and forage for young California Yellowtail (Madigan et al. 2018, Ben-Aderet et al. 2020), and may serve as a mechanism for the smallest escaped fish to interact with wild populations. In addition, the pens themselves may act as floating aggregation devices (FADs) and attract assemblages of wild fish, including California Yellowtail. Subadult and adult fish are present within the area of the farm sites. Madigan et al. (2018) found California Yellowtail sampled in inshore areas were larger than fish sampled offshore suggesting evidence of habitat segregation. However, they also found evidence that larger inshore fish made forays offshore for feeding. Baxter (1960) and Sumida et al. (1983) concluded primary spawning areas of California Yellowtail are in Mexican waters off Baja California based on observations of larvae, although some spawning occurs in U.S. waters based on observation of larvae and large mature fish with enlarged gonads (Madigan et al. 2018).

Both farm sites are located north of the greater abundance of fish off of central Baja California (Baxter 1960), however, as reported in Baxter (1960), California Yellowtail can travel long distances suggesting a high potential for subadult fish to disperse south to encounter the more abundant portion of their range off Baja California.

In taking a high potential for effects approach for modeling purposes the probability of encountering wild California Yellowtail was set at 1.0 (or 100%) across the size bins in the OMEGA model.

5.3.1.3 Relative Reproductive Success (RRS)

RRS describes the reproductive fitness of escapees, i.e., their fitness as it relates to spawning success, with values generally between 0 (reproductively sterile escapees) and 1.0 (same spawning contribution as wild fish). It is possible that escapees may have a RRS that exceeds 1.0 if evidence supports a higher contribution to the next generation per individual compared to wild fish, although probably not likely for wild broodstock sourced California Yellowtail. A low RRS can be both a function of environmental effects (i.e., non-genetic factors such as culture methods or sterilization of farmed fish) and genetic factors resulting from domestication selection (e.g., time of spawning or fecundity).

While studies have shown that species with a long history of captive breeding tend to have lower reproductive fitness compared to wild conspecifics (Berejikian and Ford 2004; Araki et al. 2008, Meager et al. 2010), in the proposed operation, fingerling production will be using non-domesticated California Yellowtail. It is therefore less likely that escaped fish would experience reduced RSS relative to wild counterparts. In taking the high potential for effects approach for modeling purposes, the RRS was assumed to be 1.0, escapees would have the same potential contribution to the offspring generation as wild California Yellowtail.

5.3.2 Parameter Values for Interactions Between Wild and Escaped Fish

The previous sections describe the parameter categories included in the interactions between wild and natural population and provide the basis for estimates used to parameterize OMEGA. The values applied for California Yellowtail interactions are summarized in Table 5.13.

Table 5-13. OMEGA parameter values describing interactions between the wild and cultured escaped fish.

Component	Parameter	Value	Units	Source
Survival of Escapees in Nature	Bin 1 Bin 2 Bin 3	0.550 (55%) 0.765 (76.5%) 0.770 (77%)	proportion proportion proportion	Survival estimated from size-based mortality curves of wild California Yellowtail in Ben-Aderet et al. 2020
Relative Survival of Escapees in Nature	Fixed rate	1.0 (100%)	None	Escapees assumed to survive same rate as wild fish
Encounter Rate with Wild Yellowtail	Fixed rate	1.0 (100%)	None	Madigan et al. 2018, Ben-Aderet et al. 2020
Relative reproductive success	Fixed rate	1.0 (100%)	None	Escapees assumed to have same reproductive success as wild fish

5.4 Impact Assessments

The following sections describe methods and parameter values used to assess the impacts of escaped California Yellowtail. Described are how OMEGA computes fitness effects and provides a qualitative assessment of effects of escaped fish on genetic diversity. Although ecological effects are not evaluated in this assessment, also included is a section discussing how model results might be used to assess ecological effects of escapees.

5.4.1 Fitness Effects

Impacts on conspecific fitness from escaped California Yellowtail were predicted using a simple phenotypic, single trait fitness model described by Ford (2002). The phenotypic fitness model is a two-population analysis of different environmental selection regimes acting on the two populations and the effect of gene flow between populations on mean trait value of the receiving populations. Assumptions of the model are as follows:

- A single trait is under selection with different optimum values for the two environments.
- The trait is normally distributed and subject to bell-shaped (Gaussian) selection.
- All mating is random; fish do not sort by origin (escapee and wild).
- Population size is large so that random drive, phenotypic plasticity, and other stochastic forces can be ignored.
- Changes in mean trait value are deterministic based on selection and gene flow.
- Selection does not reduce population size, variance or heritability of the trait over time.

Our analysis of California Yellowtail assumes 100% locally sourced wild broodstock, thus the initial condition modeled assumes the mean trait value of fish used for broodstock is equal to the wild population, representing the natural environment optimum. In our analysis, gene flow is two directions with use of 100% wild broodstock and escapees breeding with the wild population.

The resulting condition from escapees spawning with the wild population is a change in the mean trait value of the now mixed wild population (see Figure 3.2). In this case the mean trait value of the mixed wild population is intermediate between the two environmental optimums.

The deviation of the wild population from the optimum phenotypic value is $\bar{P}_{Wild} - \theta_{Nat}$.

The mean phenotypic trait values of wild and cultured progeny in year y are calculated by the following equations (Ford 2002):

$$\begin{aligned} \bar{P}_{Wild,y} = {} & \left(1 - pHOS_{sp}\right)\left[\bar{P}_{Wild,sp} + \left(\left(\left(\bar{P}_{Wild,sp}\omega_{Nat}^2 + \theta_{Nat}\sigma^2\right)/\left(\omega_{Nat}^2 + \sigma^2\right)\right) - \bar{P}_{Wild,sp}\right)h^2\right] \\ & + pHOS_{sp}\left[\bar{P}_{Escapee,sp}\left(\left(\left(\bar{P}_{Escapee,sp}\omega_{Nat}^2 + \theta_{Nat}\sigma^2\right)/\left(\omega_{Nat}^2 + \sigma^2\right)\right)\ \bar{P}_{Escapee,sp}\right)h^2\right] \end{aligned}$$

and

$$\begin{aligned} \bar{P}_{Culture,y} = {} & \left(1 - pNOB_{brood}\right)\left[\bar{P}_{Culture,brood}\left(\left(\left(\bar{P}_{Culture,brood}\omega_{Culture}^2 + \theta_{Culture}\sigma^2\right)\right.\right.\right. \\ & \left.\left.\left./\left(\omega_{Culture}^2 + \sigma^2\right)\right) - \bar{P}_{Culture,brood}\right)h^2\right] \\ & + pNOB_{brood}\left[\bar{P}_{Wild,brood}\right. \\ & \left. + \left(\left(\left(\bar{P}_{Wild,brood}\omega_{Culture}^2 + \theta_{Culture}\sigma^2\right)/\left(\omega_{Culture}^2 + \sigma^2\right)\right) - \bar{P}_{Wild,brood}\right)h^2\right] \end{aligned}$$

where:

$pHOS_{sp}$ = Proportion of spawning biomass in nature that is escapees

$pNOB_{Brood}$ = Proportion of aquaculture brood stock that is wild fish

θ_{Nat} = Phenotypic optimum or expected value (mean) of the phenotypic probability distribution for the natural environment

$\theta_{Culture}$ = Phenotypic optimum or expected value (mean) of the phenotypic probability distribution for the culture environment

σ^2 = Phenotypic variance for the trait in question

h^2 = Phenotypic trait heritability

ω_{Nat}^2 = Variance of the probability distribution of fitness as a function of phenotypic values for individuals in the natural environment

$\omega_{Culture}^2$ = Variance of the probability distribution of fitness as a function of phenotypic values for individuals in the culture environment

$\bar{P}_{Wild,sp}$ = Mean phenotypic value of the wild population spawning in year y

$\bar{P}_{Escapee,sp}$ = Mean phenotypic value of cultured adults (escapees) spawning in year y

$\bar{P}_{Wild,brood}$ = Mean phenotypic value of the wild brood stock in year y

$\bar{P}_{Culture,brood}$ = Mean phenotypic value of the cultured brood stock in year y

Because OMEGA is an annual simulation model and the trait model is a generational analysis, OMEGA includes a step that computes the average trait value for the wild population in each year that accounts for fish contributing to spawning from multiple cohorts, each with a potentially different trait value resulting from the level of escape introgression at spawning. In the above equations, $\bar{P}_{Wild,sp}$ and $\bar{P}_{Escapee,sp}$ are calculated as the mean phenotypic value of the escapee and wild adults spawning in year y comprised of age classes (a):

$$\bar{P}_{Wild,sp} = \frac{\sum_{a=i}^{A} N_{Wild,a}\bar{P}_{Wild,a}}{\sum_{a=i}^{A} N_{Wild,a}}$$

and

$$\bar{P}_{Escapee,sp} = \frac{\sum_{a=i}^{A} N_{Escapee,a}\bar{P}_{Escapee,a}}{\sum_{a=i}^{A} N_{Escapee,a}}$$

These equations assume that cohort contributions to spawning is proportional to abundance in the spawning biomass. This approach is a simplification as it overlooks the potential of unequal spawning contribution among cohorts due to differences in age specific female fecundity and, more importantly, fitness.

A similar issue arises when computing annual trait value for the cultured broodstock. In the previous equation the trait value of wild adults in the brood stock ($\bar{P}_{Wild,brood}$) is assumed to be the same as wild spawners ($\bar{P}_{Wild,sp}$).

Finally, the mean relative fitness (RF) of the wild fish cohort, offspring from spawning in year y, is calculated by the following:

$$RF_{Cohort,y} = e^{\frac{-\left(\bar{P}_{Wild,sp}-\theta_{Nat}\right)^2}{2\left(\omega_{Nat}^2+\sigma^2\right)}}$$

The effect of relative fitness on cohort survival is likely a function of the trait in question, which would possibly affect different life stages in different ways, including during spawning, subadult phase, or adult phase across multiple years up to and beyond first spawning. Allocation of fitness effect across the life cycle is included as parameter values in OMEGA.

Our use of the Ford model in OMEGA to predict fitness impacts includes several caveats:

1) The Ford model is only one of several possible ways to model domestication and although it includes several important concepts (heritability, strength of selection on trait, effects of differences in cultured and wild environments on evolutionary adaptation, and the degree of introgression during spawning) it is incomplete in its approach in that it is not modeling specific genetically controlled traits per models developed for Atlantic Salmon (see Bradbury et al. 2020),
2) We are using a single-trait model that is likely a simplification of a multi-trait phenomenon, and
3) Available data on California Yellowtail are inadequate for confident parameterization.

However, the Ford model was used because it is useful for exploring scenarios, evaluating relative impacts of escapees, and because data are incomplete on specific genotypic traits for California Yellowtail that may be subject to domestication selection.

Results from the OMEGA model are very sensitive to the input parameters in the fitness function, and as such, the model outputs of fitness effects should be considered as guidelines useful for assessment of the magnitude of potential impact of escapes of California Yellowtail, but not precise quantitative predictions. The approach used for California Yellowtail is consistent with other methods that applied phenotypic trait modeling methods (Yang et al. 2019, Baskett et al 2013, Basket and Waples 2013). For the purpose of risk assessment and decision-making support, the approach used in OMEGA is scientifically sound and correctly identifies the relative consequences of cultured fish escaping and surviving to breed with a wild population.

The parameter values used in this assessment of fitness effects from escapees on wild California Yellowtail are presented in Table 5.14. To examine relative effects of escapees on fitness, the parameters were held constant in all model simulations, with one exception. With wild fish captured for broodstock, the first year of the simulations starts with the wild population trait value and then the model is configured to calculate the trait value of fish captured from the mixed wild population in subsequent years. In other words, in subsequent years the trait value of wild sourced broodstock is calculated based on selection that may occur on the F1 generation (cultured offspring of wild broodstock) and degree of introgression of escapees in the wild population.

Consistent with the intent to consider a high potential for effects approach the fitness assessment assumed strong selection. Strong selection would infer a more severe loss of fitness in the wild population as the mean trait value moves away from the wild optimum. The inverse of ω^2, i.e. $1/\omega^2$ is the intensity selection towards the phenotypic optimum. In other words, as ω^2 increases the selection intensity decreases. According to Ford (2002), $\omega^2 = 10\sigma^2$ is considered "strong selection", whereas $\omega^2 = 100\sigma^2$ would be considered "weak selection", where $\sigma^2 = 10$ in both cases. This analysis used $\omega^2 = 5\sigma^2$, a "very strong" selection assumption to evaluate a maximum potential effect on fitness for a marine fish with an unknown trait selection profile (Table 5.14). Sensitivity analyses were made to explore relative fitness effects under different selection assumptions and even under the "very strong" selection assumption effects on relative fitness were very small when assuming all wild origin broodstock in the program. Similarly, the analysis used a relatively high trait heritability assumption of 0.5. Measurements of heritability for growth rate range from 0.2 to 0.3 for Atlantic salmon (Gjedrem 2000). Ferrari et al. (2016) reported higher heritability of behavioral traits in European seabass (0.45 +/- 0.14). The model parameterization for California Yellowtail used a high heritability assumption to capture a potential maximum effect of escaped fish on relative fitness.

Table 5-14. OMEGA fitness model parameter values used in simulations of impacts of escapees on fitness of the California Yellowtail wild population.

Parameter	Description	Parameter Value
Initial Trait Value	The initial phenotypic trait value for the aquaculture and wild population $\bar{P}_{Culture,Initial}$ and $\bar{P}_{Wild,Initial}$. The wild population is nearly always 100 and the aquaculture trait value something less if originating with a cultured brood stock or 100 if originating with wild fish.	100
Culture Environmental Trait Optimum:	Phenotypic optimum for the culture environment $\theta_{Culture}$. The aquaculture optimum is always something less than then natural environment optimum to represent differential selection pressure.	80
Natural Environmental Trait Optimum:	The natural optimum $\theta_{Natural}$ is always something greater than the aquaculture environment to represent differential selection pressure.	100
Trait Heritability	The analysis assumes moderate trait heritability h^2. Trait heritability is assumed to be the same for cultured and wild fish.	0.5
Trait Variance	This is the phenotypic variance σ^2 of the trait in question. Trait variance is assumed to be the same for wild and cultured.	10
Strength of Selection	Variance of the probability distribution of fitness ω^2 as a function of phenotypic values for individuals in the population. The analysis assumed ω^2 to be the same for wild and cultured.	$\omega^2 = 5\sigma^2$

5.4.2 Population Genetic Diversity Effects

In addition to loss of fitness, a second major concern when cultured fish escape is the potential loss of genetic diversity within populations and loss of genetic diversity among populations (Waples et al. 2012). California Yellowtail is a single intermixed population across their range and wild broodstock collected for the project would presumably represent the entire population; thus, loss of genetic diversity within the population is the primary concern from escapees. As described in Section 2.2.3, *Genetic Diversity Effects*, conservation of genetic diversity in managed populations requires maintenance of sufficiently large (genetic) effective population sizes. Relatively few mature fish are needed to supply broodstock for the POA project, and so offspring produced in any given cohort may be generated from only a few parents. If, or when, offspring escape and then subsequently contribute to spawning in the wild at high rates, there is potential to reduce the effective size of the mixed population due to the relatively low genetic diversity of the escaped culture fish compared to the wild population. The lower effective size may strengthen genetic drift processes acting on the population, and result in a loss of genetic diversity population-wide (Waples et al. 2012).

Waples et al. (2018) published a model to calculate the change in effective population size that includes parameters on the number of effective broodstock fish used to produce cultured fish in a breeding program, the demographics of the wild population, and the predicted contribution of cultured fish to natural spawning. Values for several of these parameters are unknown for California Yellowtail but can be estimated using inputs assumed to model California Yellowtail in OMEGA.

Demographic estimates of effective population size across the range of abundances modeled in OMEGA for California Yellowtail were computed using the program AgeNe (Waples et al. 2011). California Yellowtail are broadcast spawners, spawning in large aggregations in offshore waters suggesting reproductive success is highly variable among individuals. Two theories propose different mechanisms dictating reproductive success among individuals. The "Sweepstakes Reproductive Success (SRS)" hypothesis (Hedgecock and Pudovkin 2011) proposes that stochastic (i.e., random) survival under variable oceanographic conditions results in the highly variable and unequal offspring distributions frequently associated with in broadcast spawning species with high fecundity and high early mortality. Alternatively, the "Recurrent Selective Sweepstakes (RSS)" hypothesis (Tringali 2023) proposes that multiple independent stages of early-life stage selection due to the variable oceanographic conditions results in the highly variable and unequal offspring distributions. Put more simply, surviving offspring (or successful breeders) either result from genetic drift or selection, respectively. For either (or both) of the dynamics impacting recruitment life stages in marine species, large variance in reproductive success may be expected. Accordingly, an extremely large variance in reproductive success was also modeled for consideration.

Estimates of N_e and ratio of N_e/N were made with random reproductive success where variance in reproductive success at age x (V_x) is equal to the expected lifetime reproductive success of a group of fish that die at age x, given by $\bar{k}_x = \sum b_{i(i<x)}$, where k is the number of gametes contributed by an individual to the next generation. Also calculated were estimates of N_e and ratio of N_e/N assuming overdispersed variation in reproductive success at age x where $V_x = 3\bar{k}_x$ (i.e., a Poisson scaling factor of 3). Results are summarized in Table 5.16. The ratio of N_e to total N varied between 0.307 (random) and 0.274 (overdispersed). The ratio of N_e to adult N (N_A) varied between 0.456 (random) and 0.406 (overdispersed). A Poisson factor of 100 was modeled to explore the ratio of N_e/N_A for an extremely large variance in reproductive success as proposed by Hedgecock and Pudovkin (2011). In that case the ratio of N_e/N_A was 0.065 and the annual number of breeders with the low abundance assumption was extremely low (~70,000 adults).

In this analysis birthrate (b_x) is assumed to be proportional to mean weight at age (Baxter 1960) and the same for males and females. Generation length varied slightly with stochastic variation in survival values used in OMEGA. The median calculated generation length was 7.7 years and varied from 6.0 years to 10.1 years with stochastic variation in survival.

Table 5-15. Life table for California Yellowtail with 100% of fish mature at 4 years and maximum age of 22 years. Notation is from Waples et al. (2011) [4].

Age (x)	s_x	m_x	b_x	l_x	b_xN_x	b'_x	b'_xN_x	N_x	B_x	$xB_x/N1$
1	0.549	0.0	0.0	1.000	0	0.00	0	2187409	0	0.000
2	0.730	0.4	0.1	0.549	75748	0.04	43459	1200450	54324	0.040
3	0.746	0.9	0.3	0.400	290866	0.19	166879	875838	208599	0.229
4	0.734	1.0	0.6	0.299	420057	0.37	241001	653379	301251	0.441
5	0.733	1.0	1.0	0.219	463513	0.55	265933	479480	332416	0.608
6	0.733	1.0	1.3	0.161	454404	0.74	260706	351298	325883	0.715
7	0.733	1.0	1.6	0.118	414198	0.92	237639	257458	297049	0.760
8	0.733	1.0	1.9	0.086	358650	1.09	205769	188555	257211	0.753
9	0.733	1.0	2.2	0.063	299658	1.24	171924	138244	214905	0.707
10	0.733	1.0	2.4	0.046	243338	1.38	139611	101277	174514	0.638
11	0.733	1.0	2.6	0.034	193391	1.50	110955	74153	138694	0.558
12	0.733	1.0	2.8	0.025	151080	1.60	86679	54248	108349	0.476
13	0.733	1.0	2.9	0.018	116893	1.68	67065	39811	83831	0.399
14	0.733	1.0	3.1	0.013	89151	1.76	51149	29093	63936	0.327
15	0.733	1.0	3.2	0.010	67314	1.82	38620	21218	48275	0.265
16	0.733	1.0	3.3	0.007	50678	1.87	29076	15531	36344	0.213
17	0.733	1.0	3.3	0.005	37978	1.92	21789	11375	27237	0.169
18	0.733	1.0	3.4	0.004	28278	1.95	16224	8312	20280	0.134
19	0.733	1.0	3.5	0.003	21158	1.98	12139	6125	15174	0.105
20	0.733	1.0	3.5	0.002	16068	2.01	9219	4594	11524	0.084
21	0.733	1.0	3.5	0.002	11595	2.03	6653	3281	8316	0.064
22	0	1.0	3.6	0.001	8575	2.04	4920	2406	6150	0.049
										Generation length (L) 7.7

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[4] From Waples et al. 2011: b_x is the mean number of newborns produced by an individual at age x, s_x is the probability of surviving from age x to age $x+1$, m_x is the assumed maturation schedule for California Yellowtail, l_x is the fraction of the newborn cohort alive at age x, a stable population is generated by dividing each b_xN_x by the sum of b_xN_x to get b'_x and $b'_x\mathrm{N_x}$ to get the number of births by individuals of age x for a stable population. The number of individuals in each age group is given by $N_x=N1l_x$ where N1 is the total number of individuals alive in the population at any time (subadult and adult fish). In the case of California Yellowtail this is 6.7 million fish associated with a total biomass of 20,800 mt. Finally, generation length L is the average age of parents of a newborn cohort given by $L = \sum xB_x/N1$.

Table 5-16. Calculated values of effective population size (N_e) with random and overdispersed variation in reproductive success using equations in Waples et al. 2011 and AgeNe program [5].

Scenario	N_T	N_A	N_b	N_e	N_e / N_T	N_e / N_A
Low abundance, random reproductive success (Poisson factor = 1)	5,569,338	3,753,789	1,907,650	1,710,971	0.307	0.456
High abundance, random reproductive success (Poisson factor = 1)	11,194,899	7,552,804	3,838,284	3,442,555		
Low abundance, overdispersed (Poisson factor = 3)	5,569,338	3,753,789	1,250,619	1,525,348	0.274	0.406
High abundance, overdispersed (Poisson factor = 3)	11,194,899	7,552,804	2,516,306	3,069,074		
Low abundance, extreme variation reproductive success (Poisson Factor 100	5,569,338	3,753,789	70,639	243,598	0.044	0.065
High abundance, extreme variation reproductive success (Poisson Factor 100	11,194,899	7,552,804	142,129	490,131		

The rate of loss for genetic diversity is inversely proportional to N_e and increases rapidly as N_e declines. As discussed in Section 2.2.3, *Genetic Diversity Effects*, the loss of genetic diversity arising when cultured fish escape and spawn with wild California Yellowtail is known as the Ryman-Laikre effect (Ryman and Laikre 1991). They showed that in assessing the effects of fish culture on genetic diversity, it is not sufficient to know only N_e in the cultured or wild population; instead, it is necessary to consider the effective size of the cultured-wild system as a whole (N_{eT}). Waples et al (2018) provided a model to calculate N_{eT} as a function of effective size of the captive (N_{eC}) broodstock and wild (N_{eW}) spawners and the proportion of cultured fish in the mixed cultured/wild spawning (x) that are offspring of the captive broodstock (i.e., escapees). The modified Ryman-Laikre model in Waples et al. was used to calculate the reduction in N_e *(i.e.,* N_{eT}*)* for the escape scenarios assessed for the POA project. Results were evaluated against a general rule-of-thumb that N_{eT} values should exceed 5,000 fish (Waples et al. 2012).

Waples et al. (2012) also recommended that an assessment of potential loss of genetic diversity consider the "proportional reduction in N_{eW}". The extreme low-end estimate of effective annual breeders of California Yellowtail was approximately 70,000 adults (Table 5.16). Scenarios that satisfy the criterion that N_{eT} exceed 5,000 could mean a reduction of several orders of magnitude in N_e thus based on Waples et al. the analysis also considers the proportional reductions in N_{eW}.

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[5] N_T = Total number of individuals age 1 and older
N_A = Total number of adults
N_b = Effective number of breeders
N_e = Effective population size

Waples et al. 2012 recommend this “should be considered, along with the absolute levels of N_{eT}, in evaluating risks to within-population diversity”.

Results of model scenarios from OMEGA considered both criteria when evaluating potential loss of diversity. However, as discussed in in Section 2.2.3, *Genetic Diversity Effects,* while the concept of the Ryman-Laikre effect is undisputed, the consequences of a reduced N_{eT} in the population on long-term viability of the population is largely theoretical.

Calculated effects on N_e were explored for the range of N_e/N presented in Table 5.16 and found to have a minor effect on results, thus all calculations used the mid-range ratio (Poisson factor = 3). Also explored was the effect of the number of broodstock used in the program. It was found that results were insensitive to a range of reasonable broodstock abundance (100 to 500 adults) and effective broodstock spawners. All simulations used an abundance of 200 broodstock adults and the ratio of effective spawners of 0.125.

5.4.3 Ecological Effects

As described in Section 2.2.4, ecological effects from escapes include predation, competition, and disease. These factors cause ecological pressure on natural populations, including, but not limited to conspecifics. OMEGA is not designed to evaluate or assess ecological impacts on natural populations. The utility of OMEGA as regards ecological effects is that, for a given farm simulation, model outputs may be used to help evaluate ecological effects and pressures on natural stocks over time by using these outputs to inform other platforms and methods to evaluate the ecological effects. These model outputs include, for example, the numbers and size-classes of escaped fish anticipated under operational scenarios or predicted following a large-scale loss scenario, and the percentages of cultured fish in the population biomass and spawning abundance at time points following those escape events.

6.0 Model Simulations

Model simulations in OMEGA were developed to describe escape levels and potential impacts to natural populations under different types of escape scenarios. The scenarios are intended to cover a wide range of possible escape levels, from a high degree of containment (escape levels are low and infrequent) to an absolute catastrophic failure (the entire program fails and all fish escape). In this way, effects can be evaluated for all potential outcomes and mitigation for escapes can be focused on certain aspects of the program.

The model parameters described in Section 5.0, *Model Parameterization* were used to develop boundary values within OMEGA based on conditions likely encountered culturing California Yellowtail in offshore cages in Southern California and data from the literature of experiences elsewhere culturing fish in open water cages. The boundary values are used to describe a mode of anticipated continuous operation, with a baseline condition that fish may escape at a low level (leakage). The boundary values also allow that events may happen occasionally such as operational errors that may lead to accidents causing cage failure resulting in a partial or complete loss of fish from a cage. While the model accounts for these types of (potentially) more routine events, experiences elsewhere have shown that even worse failures may occur resulting in a large-scale escape of cultured fish from a number of factors, such as storms, anchoring failures, or collapses of the pen structure. To account for program level uncertainty, scenarios were developed to determine consequences of large-scale or catastrophic escape events resulting in the total loss of fish from the cages.

6.1 Model Scenarios

Based on the considerations described above, a total of four escape scenarios were modeled (Table 6-1).

Table 6-1. Modeled California Yellowtail escape scenarios.

Scenario	Leakage[a]	Episodic[b]	Large Scale[c]	Other
Scenario I	0.32%	2,500 mt – 5%, 7.5%, & 12.5% 5,000 mt – 10%, 15%, & 25% Half to three-quarters of fish in cage escape	Not Modeled	Escaped fish survive as well as wild
Scenario II	Not Modeled	Not Modeled	One time escape of all fish in cages	
Scenario III	0.32%	2,500 mt – 5% 5,000 mt – 10% A quarter to half of fish in cage escape	Not Modeled	Escaped fish survive at half the rate of wild fish
Scenario IV	Not Modeled	Not Modeled	One time escape of 75% of fish in cages	

[a] Leakage is the percentage of fish escaping while held in a cage, leakage varied by size of fish – smallest size 0.20%, mid-size 0.04%, and largest size 0.08%. See Section 2.1.1, *Leakage Escape* for additional details.

[b] Episodic escapes are often the result from individual or multi-cage failures and the escape of half to all fish in cage. Shown are the annual likelihood of an episodic event (e.g., 10% -= 1 event every 10 years and 25% = 1 event every 4 years). See Section 2.1.2, *Episodic Escape* for additional details.

[c] Large-scale escapes are the one-time loss of all fish in cages from catastrophic events. This type of loss may result from extreme storm or weather events, or other disasters such as fires, collisions, or tsunamis that cause the failing of the mooring system and/or grid infrastructure. See Section 2.1.3, *Large-scale Events and Catastrophic Events* for additional details.

The modeled escape scenarios are as follows:

- **Scenario I - Leakage and Episodic Cage Failure:** This scenario describes a range of operational scenarios that account for the continuous escape of fish (i.e., small scale leakage discussed in Section 2.1.1, *Leakage Escape*) and episodic escape events (i.e., cage failures as discussed in Section 2.1.2, *Episodic Escape*). The parameters used in this scenario fall within a defined set of boundary values that are intended to include a high frequency of episodic events with loss of half to all fish in a cage and an assumption escaped fish would survive at the same rate as wild fish and would encounter spawning wild California Yellowtail. This scenario assumes a constant rate of program leakage for all years of operation. Simulations were run for a range of cage failure probabilities: the 5,000 mt alternative assumed 1 event every ten years, 2) 1.5 events every ten years, and 3) 2.5 events every ten years (i.e., 10, 15, and 25% annual likelihood of an episodic escape event) and the 2,500 mt alternative assumed 0.5 events every ten years, 2) 0.75

events every ten years, and 3) 1.25 events every ten years (i.e., 5, 7.5, and 12.5% annual likelihood of an episodic escape event). This scenario would be used to describe potential impacts from continuous operations.

- **Scenario II - Large-scale Escape Events:** The impacts from the large-scale escape event scenario are distinct from the leakage and episodic assessment and are therefore modeled separately as a large-scale assessment. The large-scale escape assumes the loss of 100% of fish on station due to a program-level failure and all escaped fish would survive at the same rate as wild fish and would encounter spawning wild California Yellowtail. This scenario is modeled as a single occurrence, assuming a stop to operations following a loss of this scale. The large-scale escape simulation reflects a very unlikely scenario. However, the analysis of a large-scale escape event is included for due diligence to describe an extreme escape condition. The size of fish at the time of escape affects the outcomes from escape events due to varying size-specific survival rates and differing amounts of time from escape to sexual maturity. To capture the range of outcomes, impacts were assessed by modeling fish at three points in time over the production cycle that reflect when fish are skewed towards a greater number of smaller fish on station, a greater number of larger fish on station, and a more even distribution of fish sizes on station (hereafter referred to as small-size skewed, large-size skewed, and evenly-sized fish distribution, respectively).

- **Scenario III - Lower Range of Leakage and Episodic Frequency:** This scenario was developed to describe a more likely set of conditions for both routine operations and large-scale escape event to include a more likely set of outcomes within the range of possible outcomes. Scenario III assumed leakage and episodic events occurring at the lower end of the episodic frequency range modeled in the Scenario I (i.e., 5,000 mt alternative assumed 1 event every 10 years and the 2,500 mt alternative assumed 1 event every 20 years), the magnitude of loss would be lower (only a quarter to half of the fish would escape from a cage), and escaped fish would survive at half rate of wild California Yellowtail of the same size.

- **Scenario IV - Modified Large-scale Escape Events:** This scenario was developed to describe a large-scale escape event still assuming the loss of 100% of fish on station due to a program-level failure however this scenario assumes not all fish would escape, it assumed a recapture rate of 25% accounting for the recovery of some fish and some fish getting trapped in the collapsed cages. The scenario also included a lower rate of survival of escapees following a large-scale event, like with Scenario III, with escapees surviving only 50% as well as wild California Yellowtail of the same size.

6.2 Model Alternatives

As discussed in Section 4.0, *Project Description* two production levels are being considered for the POA program: 1) a full-production level of 5,000 mt per year with stocking five cages per cohort at three different times each year, and 2) a half-production level of 2,500 mt per year and stocking between two and three cages per cohort at three different times each year .

Two different locations are being evaluated for siting the offshore cages: 1) San Diego and 2) Long Beach. These locations were qualitatively evaluated for differences in escape risk, in terms of range of California Yellowtail and other factors, and no evidence was found to suggest escape risk or impacts to the wild population would differ between these sites. Thus, separate model simulations were not conducted for the two site alternatives.

Therefore, two alternatives were modeled for each of the scenarios described above: full-production (5,000 mt) and half-production (2,500 mt).

6.3 Stochastic Variability in OMEGA Parameters

The @RISK (v. 7.6 Lumivero, formerly Palisade) add-in to Excel was programmed as an overlay to OMEGA[6]. @RISK was used to replace one or more model input parameter values in an Excel spreadsheet with a new value using a probability distribution function specified in the @RISK add-in. For each scenario 1,000 to 5,000 iterations were modeled. @RISK was used to specify model output variables for reporting. Uncertainty in population size, reported as female spawning biomass, was varied between 8,000 and 18,000 mt using @RISK and a uniform distribution. Population size was varied by varying the recruitment phase capacity parameter in OMEGA.

Uncertainties in escape assumptions were addressed by running multiple simulation scenarios at different parameter values, for example low, medium and high escape assumptions discussed previously. The number of fish escaping from cage failure and the simulation year of a cage failure was determined using a randomization method in the OMEGA VBA code.

An OMEGA simulation is to run the model for 300 years to evaluate potential legacy impacts from escapes in long-lived marine species. In the case of the POA analysis we summarized long-term results to evaluate legacy effects using summary metrics for years 10 to 100 (90-year Simulation Results) and summary metrics within the permit period (30 years) to evaluate short-term effect (Short-term Simulation Results). Simulations included stochastic variability in survival during the recruitment stage and subadult and adult stages. This variability was incorporated into the analysis using a randomization method in the OMEGA VBA code.

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[6] @RISK software is an add-in tool for Microsoft using a technique known as Monte Carlo simulation. The @RISK Monte Carlo analysis was used to compute and track multiple OMEGA inputs and results for by scenario.

6.4 Simulation Time Scales

The OMEGA model response is reported for different time scales, assuming continuous operation. Results are reported for a 90-year time horizon and for short term (5, 10, and 25 years of production.

A schematic of model cases for the Leakage and Episodic Cage Failure and Large-scale Escape Event scenario is shown in Figure 6.1. Model cases for the Scenario III and IV simulations are shown in Figure 6.2.

6.4.1 90 Year Simulation Methods

The 90-year simulation period started with year 10 to ignore model initiation influences and is used to demonstrate longer-term impacts on the wild population of California Yellowtail from a succession of escape events occurring from continuous operation within this time frame, with escapes entering and maturing in the wild, effectively breeding in the mixed cultured/wild population over multiple generations. The year-over-year mixing of escapes in the wild would result in a cumulative effect of gene flow and the mean trait value of the mixed cultured/wild population would potentially shift towards the culture optimum. As such, the 100-year point of this simulation period would describe the point at which effects of introgression would be most pronounced.

6.4.2 Short-Term Simulation Methods

Model simulations were conducted for 5, 10, and 25 years at full and half production. The results of these short-erm simulations are presented to describe potential effects within a time frame applicable for environmental impact analyses and permitting applications. The results presented for the short-term simulations differ from the 90-year simulations in that the values do not represent the median of the minimum, or median of the maximum values, but rather the actual highest maximum and/or lowest minimum values across the 1000 simulations at Year 5, Year 10 and Year 25. This distinction is important when comparing results between the 90 year and short-term simulations (e.g., in maximum values and upper tails in the box-and-whisker plots).

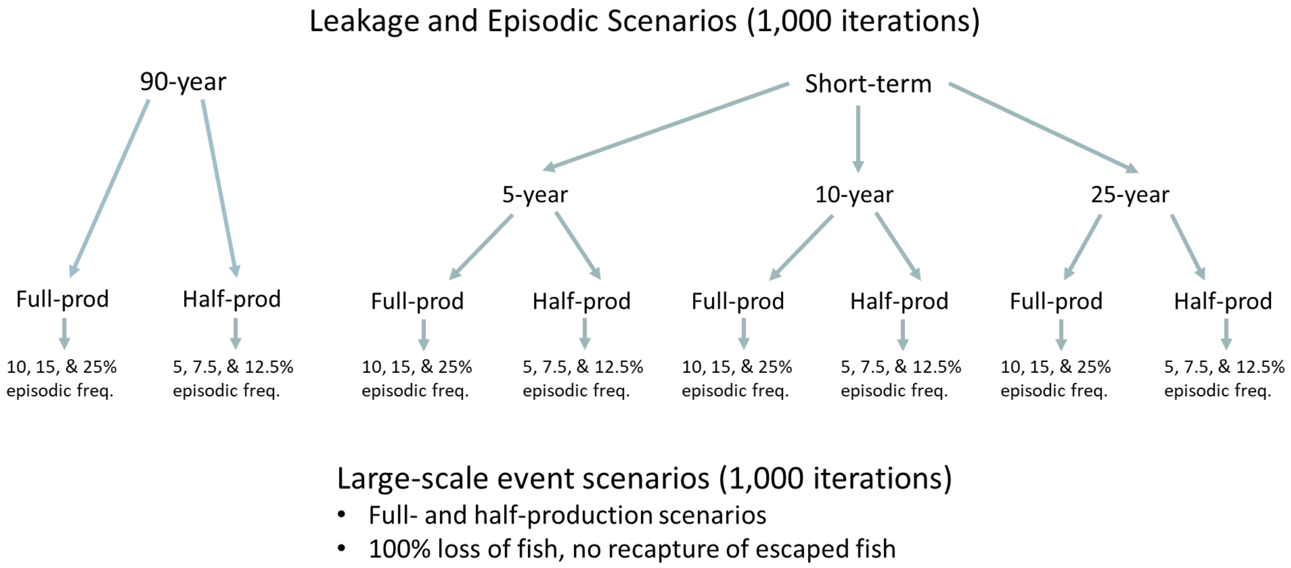


Figure 6.1. A schematic of model cases for Leakage/Episodic Cage Failure and Large-scale Event Scenarios (Scenarios I, and II).

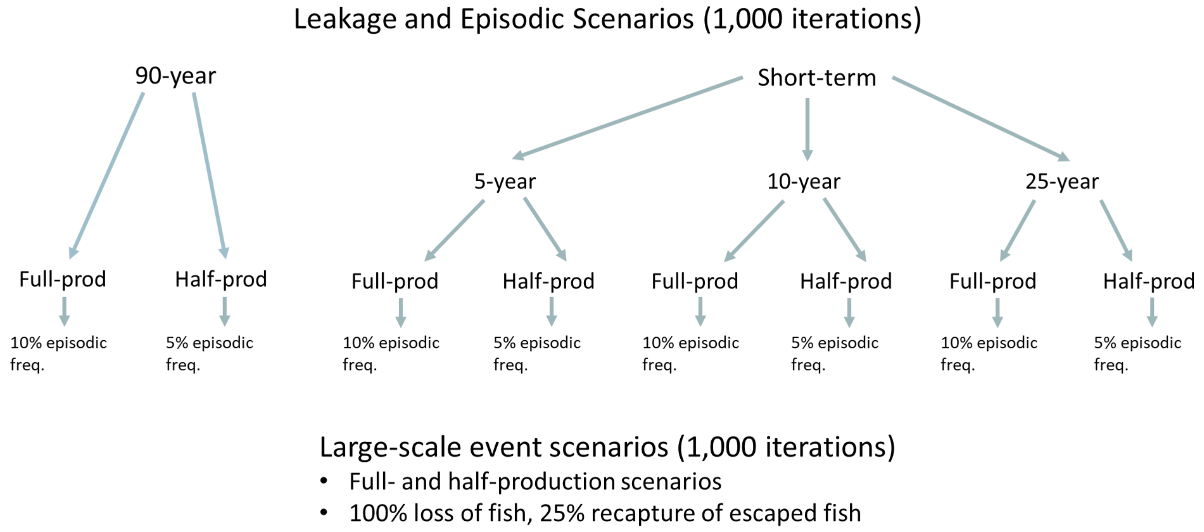


Figure 6.2. A schematic of model cases for Scenario III and IV simulations.

7.0 Results

Results are presented for the leakage and episodic scenarios and large-scale scenarios separately for the full production and half production alternatives. These results are followed by the Scenario III and IV model runs for leakage and episodic scenarios, and the large-scale scenario. One specific distinction that differs between analyses, is the term 'cumulative results'; this refers to the number of fish escaping from the current operational year and fish surviving from previous years in the population.

While OMEGA does not explicitly assess ecological interactions (e.g., predation and competition), the range in numbers of escaped fish entering the ecological system(s) under the different scenarios could be used to help inform those types of analyses.

7.1 Leakage and Episodic Cage Failure: Scenario I

The impacts from the leakage and episodic are modeled to represent Type 1, Type 2, and Type 3 escape events (see Figure 2.1). As described in Section 5.1.2.1 *Leakage Escape*, leakage rates across the production cycle were estimated based on discussions with POA, and these estimates reflect points in the operation when leakage may be expected. Episodic escapes often result from individual or multi-cage failures, or other malfunctions where all or a portion of fish escape from a cage(s). Episodic escapes of varying magnitude may be frequent enough that pulses of fish escaping into the environment in this way should be modeled combined with chronic leakage (see Section 5.1.2.2 *Episodic Escape*). Leakage and episodic escapes create a pattern of low annual escape levels with occasional pulses of fish escaping to enter the wild population. Because episodic escape events may occur throughout the production cycle with equal probability, cage failure was randomized across all size bin categories. A low, medium and high frequency of cage failure was modeled to capture a range of possible episodic escape frequencies.

7.1.1 Full Production Alternative

The full production analysis represents the 5,000 mt per year alternative with five cages per cohort stocked three times a year. The number of fish escaping from leakage was calculated based on the previously described leakage rates (see Section 5.1.2.1 *Leakage Escape*). As described in Section 5.1.2.2 *Episodic Escape*, three rates of episodic escape frequencies were modeled: 1) one event every 10 years, 2) 1.5 events every 10 years, and 3) 2.5 events every 10 years (10, 15, and 25% annual likelihood of an episodic escape event). Under the full production alternative, 5,173 fish escape annually due to leakage and 48,777 to 97,554 fish escape in a cage failure (half to all fish in a cage).

7.1.1.1 90-year Simulation Results

The 90-year simulation period (simulation years 10 to 100) was used to demonstrate longer-term impacts on the conspecific wild population due to escape events occurring from continuous operation within this time frame. The cumulative number of escaped fish in the population resulting from leakage and episodic losses is presented in Table 7.1 for the full production alternative and with the three modeled episodic loss scenarios.

As expected, the cumulative number of escaped fish increases based on the frequency of episodic events as observed in the median, 25%, 75%, and max values shown in Table 7.1. Minimum values over the three modeled frequencies had a much narrower range; this is due in part to the continuous annual leakage and to simulations where, by chance, episodic events occurred less often. Maximum values represent simulations where routine operational (i.e., leakage and episodic escape) scenarios occur in terms of maximum potential for impacts (i.e., larger episodic events occurring with maximal frequency). However, note that 75% of simulations, across the episodic escape frequencies, fall at or below roughly half of the maximum values.

Table 7-1. The cumulative number of cultured fish in the population resulting from leakage and episodic losses from current year escapes and surviving fish from previous years under the full production alternative - years 10 – 100 simulation results.

Model scenario:	**Cumulative number of escaped fish in population (Simulation years 10 – 90 summaries)**				
Full Production at 5,000 mt	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (10% annual likelihood)	20866	13455	40363	11250	103346
Leakage + Episodic (15% annual likelihood)	31813	17689	54260	11708	119965
Leakage + Episodic (25% annual likelihood)	52625	32352	77232	13548	145808

In Table 7.2, the percentage of escaped fish in the population biomass and spawning abundance (which includes both male and female fish) is presented for the 90-year simulations at the three modeled episodic frequencies. To account for wild population size uncertainty, simulations were conducted across a range of wild female biomasses (8,000 to 18,000 metric tons). Results described in Table 7.2 are presented graphically for the population biomass and spawning abundance in Figures 7.1 and 7.2, respectively.

As expected, escaped fish made up the largest percentages of the biomass and abundance at the smallest ranges of wild female biomass (Table 7.2). Under the full production alternative, when values of wild population abundance were lowest and the episodic escape frequency was highest at an annual likelihood of 25%, the maximum values of escaped fish in the population biomass was 3.1%, and 3.8% in the spawning abundance. This represents a high episodic condition for the full-production alternative.

Individual simulation values, shown in the scatterplots in Figure 7.1 and Figure 7.2, reveal the variation around median values. A small number of the individual simulations ranged to just over or below 5% in the population biomass (Figure 7.1), and to almost 6% in the spawning abundance at the highest episodic frequency and at the low end of the wild female spawning biomass range (Figure 7.2). However, as noted previously, the distribution is highly skewed with more than 75% of the simulations below 2% in both the population biomass and spawning abundance even at the low end of the wild female spawning biomass range.

Table 7-2. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under the full production (5,000 mt) alternative.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Full production at 5,000 mt		Median	25%	75%	Min.	Max.	Median	25%	75%	Min.	Max.
Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.4%	1.0%	0.3%	1.9%	0.5%	0.3%	0.9%	0.3%	2.6%
	10,000 to 12,000	0.5%	0.3%	0.9%	0.2%	1.7%	0.4%	0.2%	0.7%	0.2%	2.2%
	12,000 to 14,000	0.4%	0.3%	0.7%	0.2%	1.4%	0.3%	0.2%	0.6%	0.2%	1.8%
	14,000 to 16,000	0.4%	0.2%	0.6%	0.2%	1.2%	0.3%	0.2%	0.6%	0.2%	1.6%
	16,000 to 18,000	0.4%	0.2%	0.6%	0.2%	1.1%	0.3%	0.2%	0.5%	0.1%	1.5%
Leakage + Episodic (15% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.9%	0.5%	1.3%	0.3%	2.4%	0.7%	0.4%	1.2%	0.3%	3.0%
	10,000 to 12,000	0.7%	0.5%	1.1%	0.3%	2.0%	0.6%	0.3%	1.0%	0.2%	2.6%
	12,000 to 14,000	0.6%	0.4%	0.9%	0.2%	1.7%	0.5%	0.3%	0.9%	0.2%	2.2%
	14,000 to 16,000	0.5%	0.3%	0.8%	0.2%	1.5%	0.4%	0.3%	0.7%	0.2%	1.9%
	16,000 to 18,000	0.5%	0.3%	0.8%	0.2%	1.3%	0.4%	0.2%	0.7%	0.2%	1.7%
Leakage + Episodic (25% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	1.4%	1.0%	2.0%	0.4%	3.1%	1.2%	0.8%	1.8%	0.3%	3.8%
	10,000 to 12,000	1.2%	0.8%	1.6%	0.4%	2.6%	1.0%	0.6%	1.5%	0.3%	3.0%
	12,000 to 14,000	1.0%	0.7%	1.3%	0.3%	2.2%	0.8%	0.5%	1.2%	0.2%	2.6%
	14,000 to 16,000	0.8%	0.6%	1.2%	0.3%	1.9%	0.7%	0.5%	1.1%	0.2%	2.4%
	16,000 to 18,000	0.8%	0.6%	1.1%	0.2%	1.8%	0.7%	0.4%	1.0%	0.2%	2.1%

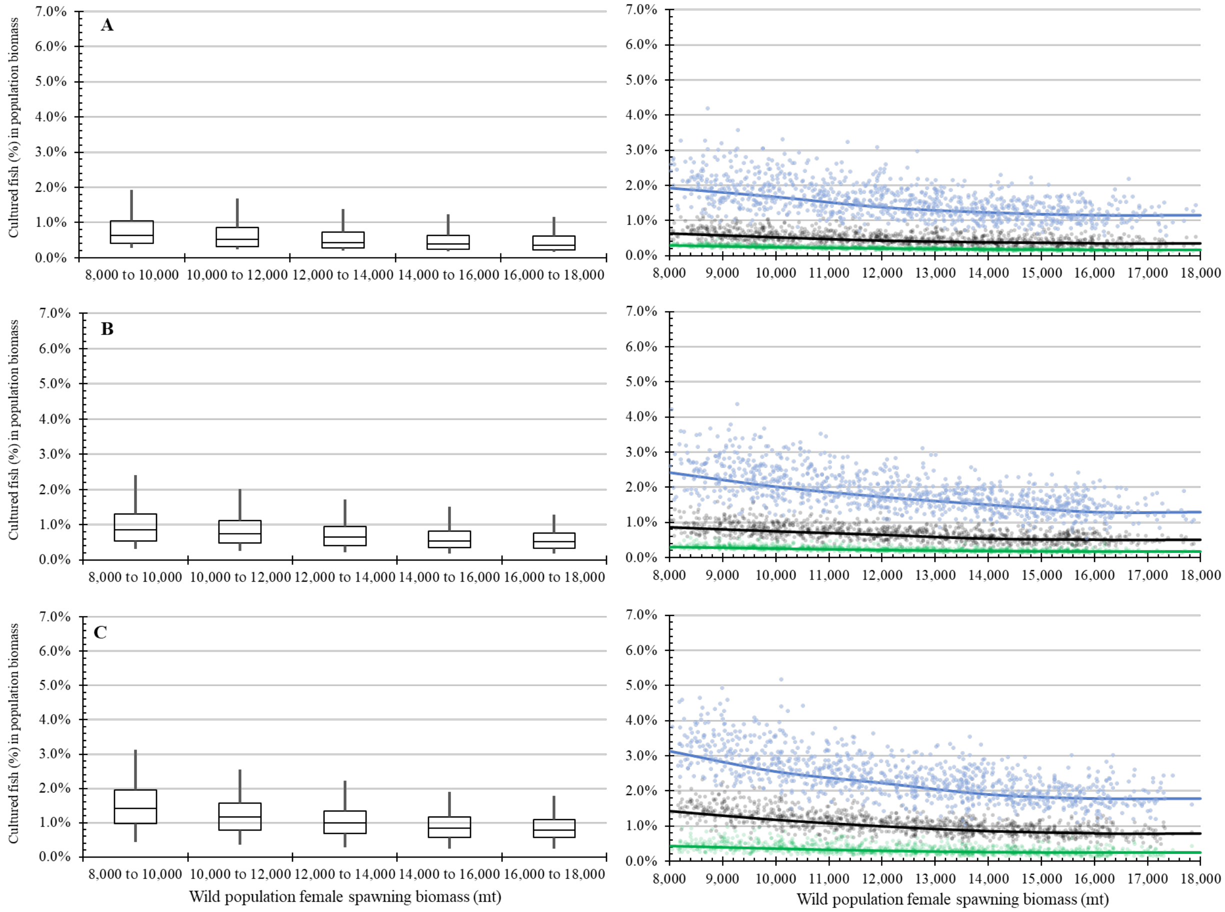


Figure 7.1. The percentage of cultured fish at full production (5,000 mt) in the population biomass resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the maximum (blue), median (gray), and minimum (green) values for each iteration and solid lines represent the respective median value over the range in female spawning biomass (in metric tons).

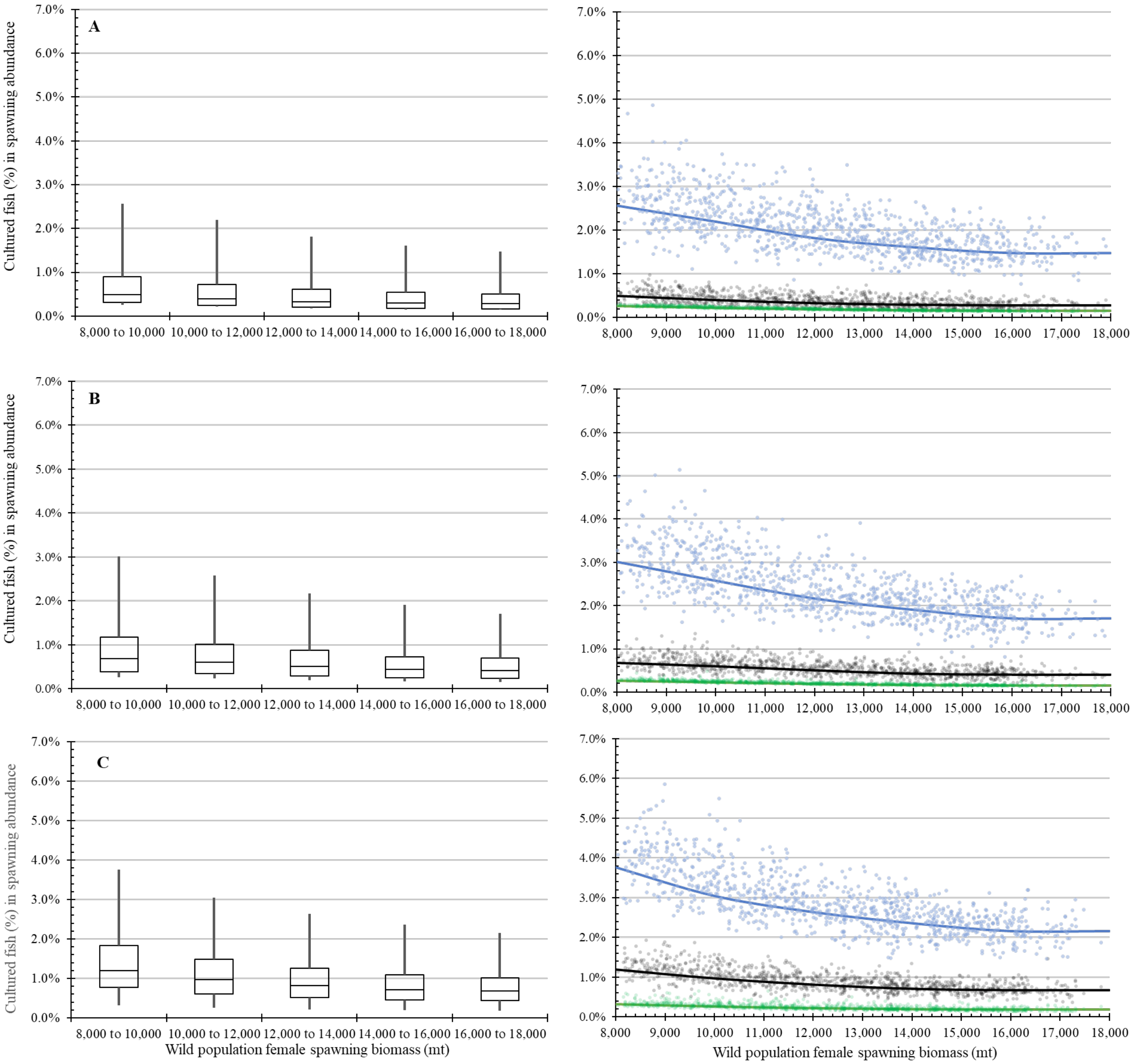


Figure 7.2. The percentage of cultured fish at full production (5,000 mt) in the population spawning abundance resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the maximum (blue), median (gray), and minimum (green) values for each iteration and solid lines represent the respective median value over the range in female spawning biomass (in metric tons).

7.1.1.2 Short-term Simulation Results

Model simulations were conducted for 5, 10, and 25 years at full production. The results of these short-term simulations are presented to describe potential effects within a time frame applicable for environmental impact analyses and permitting applications. Like the 90-year simulations, results are based on three rates of episodic escape frequencies – one event every ten years, 1.5 events every ten years, and 2.5 events every ten years (10, 15, and 25% annual likelihood of an episodic escape event). Table 7.3 presents the cumulative number of fish from leakage and episodic losses at the three time points of the simulations. The results presented for the short-term simulations differ from the 90-year simulations in that the values in Table 7.3 do not represent the median of the minimum, or median of the maximum values, but rather the actual highest maximum and/or lowest minimum values across the 1000 simulations at Year 5, Year 10 and Year 25. This distinction is important when comparing results between the 90 year and short-term simulations (e.g., in maximum values and upper tails in the box-and-whisker plots).

In each year 5,173 fish escape from leakage due to the constant assumed leak rate. In years when an episodic event occurs, somewhere between 48,000 and 98,000 fish escape (half to full loss of fish from a single cage). The number of cumulative escaped fish in the wild increases as episodic escape frequency increases, but the minimum numbers of escaped fish in population are largely consistent within timepoints as they represent the annual leakage and the number of fish surviving from leakage from previous years. Results for each of the time points are presented below.

Table 7-3. The cumulative number of escaped fish in the population in years 5, 10 and 25 resulting from leakage and episodic losses at full production under Scenario I.

Model scenario:	**Cumulative number escaped fish in population**				
Full production at 5,000 mt	**Median**	**25%**	**75%**	**Min.**	**Max.**
Number of Cultured Fish in Year 5					
Leakage + Episodic (10% annual likelihood)	9994	9512	35791	8296	152268
Leakage + Episodic (15% annual likelihood)	24243	9655	47259	8305	156181
Leakage + Episodic (25% annual likelihood)	40469	20474	65132	8288	176254
Number of Cultured Fish in Year 10					
Leakage + Episodic (10% annual likelihood)	20191	11950	40176	9916	148319
Leakage + Episodic (15% annual likelihood)	30653	16290	54796	9799	164883
Leakage + Episodic (25% annual likelihood)	51095	29974	76405	10074	188761
Number of Cultured Fish in Year 25					
Leakage + Episodic (10% annual likelihood)	21273	13369	42746	10185	151852
Leakage + Episodic (15% annual likelihood)	31476	17334	54540	10764	171429
Leakage + Episodic (25% annual likelihood)	53177	31762	79163	10862	190334

In year five, simulations revealed that the predicted cumulative median number of escaped fish in the population ranged between 9,994 fish (at the 10% likelihood) and 40,469 fish (at the 25% likelihood) (Table 7.3). Simulations with the worst outcomes indicated that a maximum between 152,268 (at the 10% likelihood) and 176,254 (at the 25% likelihood) escaped fish may accumulate in the wild population. Again, as noted previously, the results are highly skewed with most simulations resulting in numbers far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 35,791 escaped fish (at the 10% likelihood) and 65,132 escaped fish (at the 25% likelihood) accumulating in the population after five years of full production, which represents less than 25% and 40% of the maximum values, respectively.

The percentage of escaped fish, as a proportion of population biomass and spawning abundance, after five years of production is shown in Table 7.4. The composition of escapees in the wild population is highest at the low end of the wild female biomass range, with a median between 0.1% (at the 10% likelihood) and 0.4% (at the 25% likelihood) cultured fish in the population biomass and between 0.2% (at the 10% likelihood) and 0.7% (at the 25% likelihood) in the spawning abundance. At the 10% annual episodic escape frequency, 75% of simulations did not exceed 0.3% cultured fish in the population biomass, and 0.5% in the spawning abundance across the modeled wild population size range. These percentages increased with increasing likelihood of episodic escape occurrence in a year, as expected. At the highest frequency (25% annual episodic escape frequency), 75% of simulations did not exceed 1.0% and 1.3% escaped fish in the population biomass and spawning abundance, respectively.

Table 7-4. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from Scenario I leakage and episodic escape events under the full production (5,000 mt) alternative in year 5 of the simulation.

Model Scenario: Full production at 5,000 mt		**Percentage of population biomass that are cultured fish**					**Percentage of population spawning abundance (males and females) that are cultured fish**				
		Median	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.2%	0.1%	2.5%	0.2%	0.2%	0.5%	0.1%	3.9%
	10,000 to 12,000	0.1%	0.1%	0.3%	0.1%	2.0%	0.1%	0.1%	0.5%	0.1%	2.7%
	12,000 to 14,000	0.1%	0.1%	0.3%	0.1%	1.5%	0.1%	0.1%	0.5%	0.1%	2.0%
	14,000 to 16,000	0.1%	0.1%	0.2%	0.1%	1.9%	0.1%	0.1%	0.4%	0.1%	2.4%
	16,000 to 18,000	0.1%	0.1%	0.3%	0.1%	1.3%	0.1%	0.1%	0.4%	0.1%	2.0%
Leakage + Episodic (15% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.7%	0.1%	2.7%	0.2%	0.2%	0.8%	0.1%	3.6%
	10,000 to 12,000	0.1%	0.1%	0.6%	0.1%	2.7%	0.2%	0.1%	0.8%	0.1%	3.4%
	12,000 to 14,000	0.1%	0.1%	0.5%	0.1%	1.7%	0.1%	0.1%	0.7%	0.1%	2.5%
	14,000 to 16,000	0.1%	0.1%	0.5%	0.1%	1.8%	0.1%	0.1%	0.6%	0.1%	2.3%
	16,000 to 18,000	0.1%	0.1%	0.4%	0.1%	1.6%	0.1%	0.1%	0.5%	0.1%	2.5%
Leakage + Episodic (25% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.4%	0.1%	1.0%	0.1%	3.3%	0.7%	0.2%	1.3%	0.1%	4.4%
	10,000 to 12,000	0.4%	0.1%	0.8%	0.1%	2.7%	0.6%	0.1%	1.1%	0.1%	3.5%
	12,000 to 14,000	0.3%	0.1%	0.7%	0.1%	2.1%	0.5%	0.1%	0.9%	0.1%	2.7%
	14,000 to 16,000	0.3%	0.1%	0.6%	0.1%	1.8%	0.4%	0.1%	0.8%	0.1%	2.3%
	16,000 to 18,000	0.2%	0.1%	0.6%	0.1%	1.7%	0.4%	0.1%	0.8%	0.1%	2.3%

These results are displayed graphically in Figure 7.3 (population biomass) and Figure 7.4 (spawning abundance). As mentioned previously, the upper and lower whiskers in the figures reflect the greatest (single) impact detected across all simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range. While difficult to see in the 10% and 15% episodic frequency figures because of the low value, the black line in the scatterplots reflects the median values across the population size range; the densities of the smaller values below the median are similarly difficult to detect.

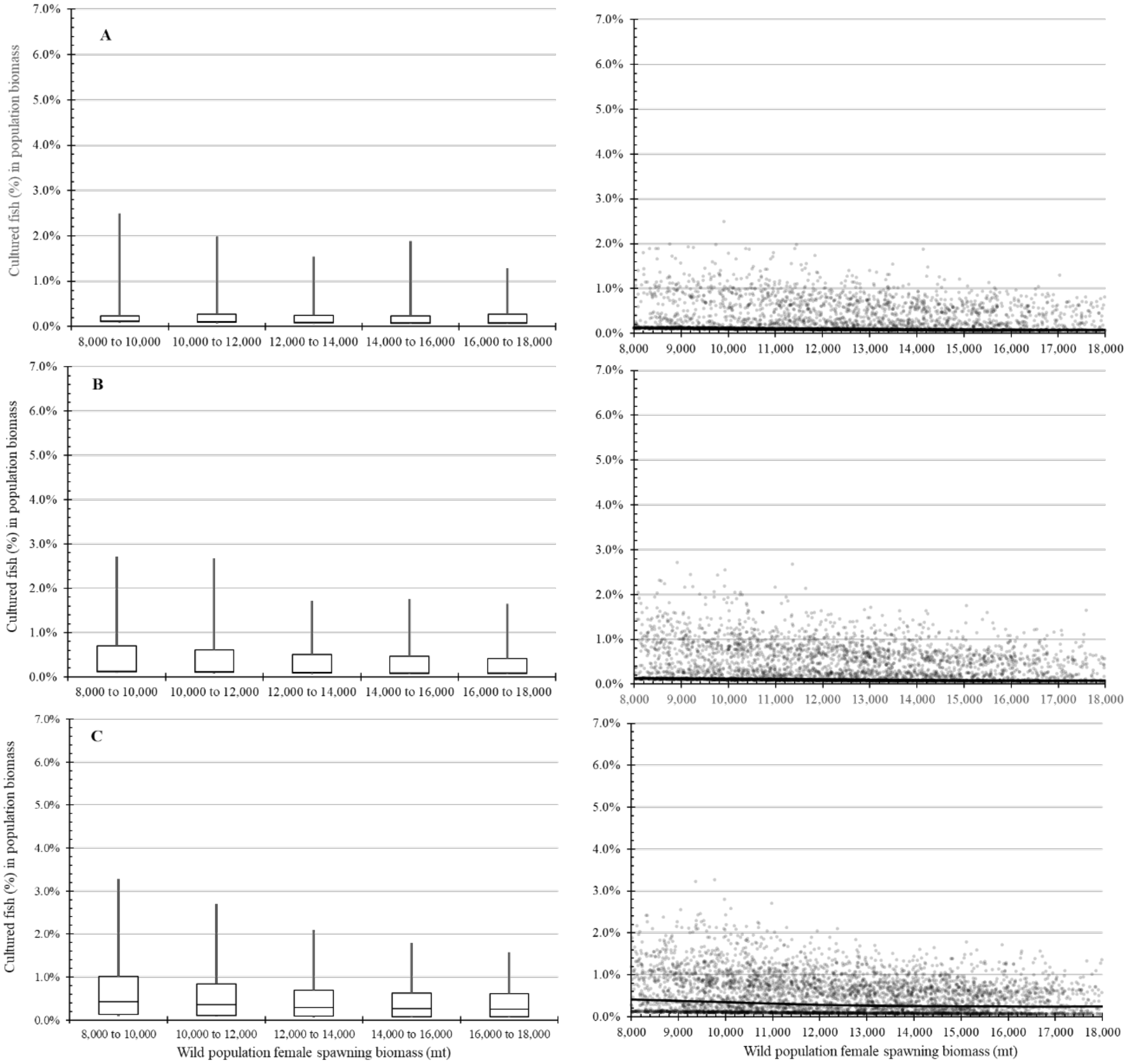


Figure 7.3. The percentage of cultured fish at full production (5,000 mt) in the population biomass in Year 5 resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line represents the median value over the range in female spawning biomass (in metric tons).

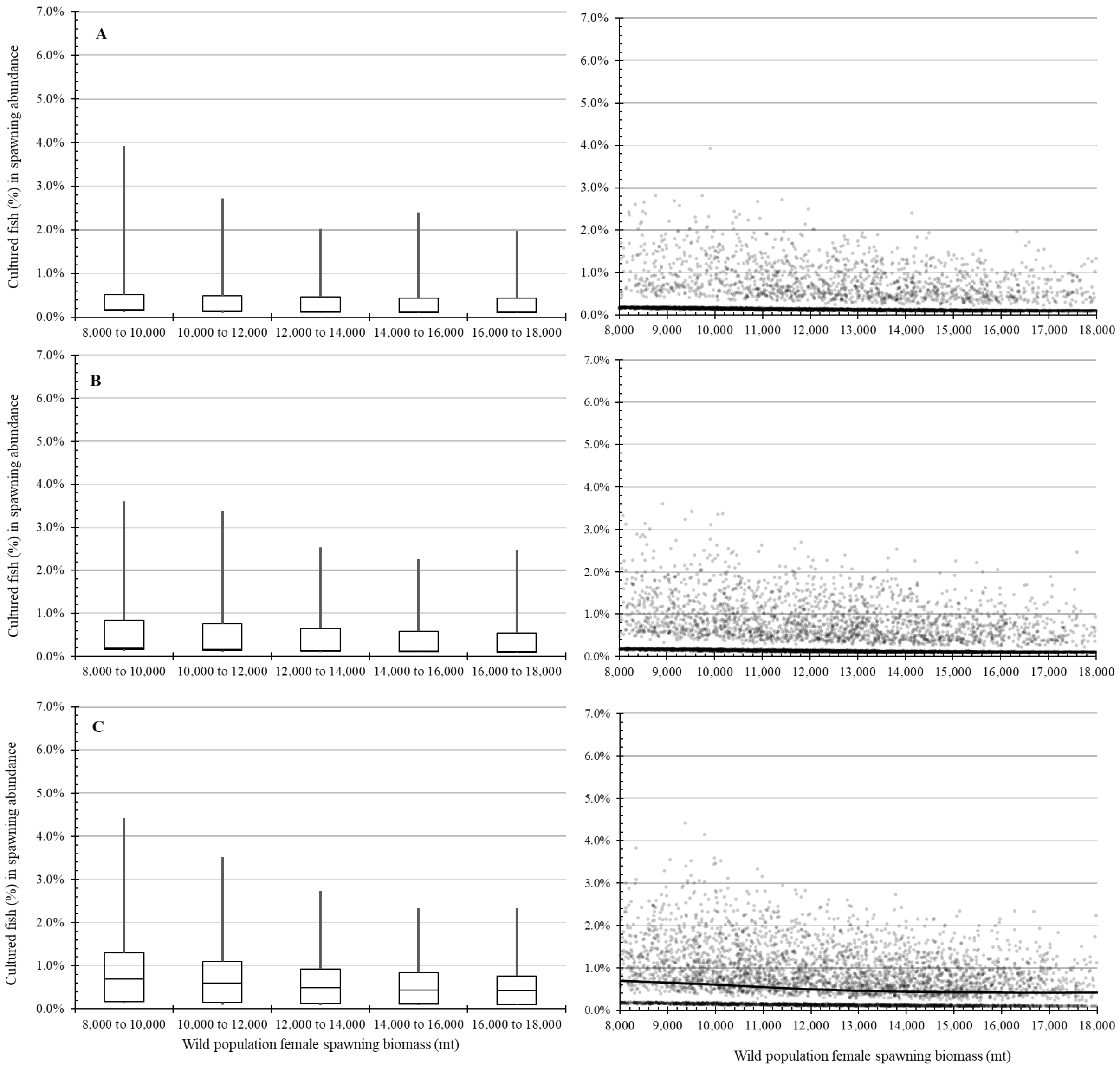


Figure 7.4. The percentage of cultured fish at full production (5,000 mt) in the population spawning abundance in Year 5 resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line represents the median value over the range in female spawning biomass (in metric tons).

In the year 10 simulations, the predicted cumulative median number of escaped fish in the population ranged between 20,191 fish (at the 10% likelihood) and 51,095 fish (at the 25% likelihood) (Table 7.3). Simulations with the worst outcomes indicated that a maximum between 148,319 (at the 10% likelihood) and 188,761 (at the 25% likelihood) escaped fish may accumulate in the wild population. Again, the results are highly skewed with 75% of the simulations far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 40,176 escaped fish (at the 10% likelihood) and 76,405 escaped fish (at the 25% likelihood) accumulating in the population after ten years of full production.

The percentage of escaped fish as a proportion of population biomass and spawning abundance after ten years of production is shown in Table 7.5. Again, the composition of escapees is highest at the wild female biomass range of 8,000 to 10,000 mt, with a median between 0.4% (at the 10% likelihood) and 1.1% (at the 25% likelihood) cultured fish in the population biomass and between 0.4% (at the 10% likelihood) and 1.0% (at the 25% likelihood) in the spawning abundance. At the 10% annual episodic escape frequency, 75% of simulations did not exceed 0.9% cultured fish in the population biomass, and 0.8% in the spawning abundance across the modeled wild population size range. At the 25% annual episodic escape frequency, 75% of simulations did not exceed 1.6% and 1.7% escaped fish in the population biomass and spawning abundance, respectively, across the modeled wild population size range.

Table 7-5. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under the full production (5,000 mt) alternative in year 10 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Full production at 5,000 mt		Median	25%	75%	Min.	Max.	Median	25%	75%	Min.	Max.
Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.4%	0.2%	0.9%	0.2%	2.9%	0.4%	0.2%	0.8%	0.2%	3.8%
	10,000 to 12,000	0.4%	0.2%	0.7%	0.2%	2.4%	0.4%	0.2%	0.7%	0.2%	2.8%
	12,000 to 14,000	0.4%	0.2%	0.7%	0.1%	2.9%	0.3%	0.2%	0.6%	0.1%	2.8%
	14,000 to 16,000	0.3%	0.2%	0.6%	0.1%	1.6%	0.3%	0.2%	0.6%	0.1%	2.0%
	16,000 to 18,000	0.3%	0.1%	0.5%	0.1%	1.4%	0.3%	0.1%	0.5%	0.1%	2.1%
Leakage + Episodic (15% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.8%	0.4%	1.2%	0.2%	3.2%	0.7%	0.3%	1.2%	0.2%	4.5%
	10,000 to 12,000	0.6%	0.3%	1.0%	0.2%	3.4%	0.5%	0.3%	1.0%	0.2%	3.0%
	12,000 to 14,000	0.5%	0.3%	0.9%	0.1%	2.1%	0.5%	0.2%	0.8%	0.1%	2.5%
	14,000 to 16,000	0.5%	0.2%	0.8%	0.1%	2.2%	0.4%	0.2%	0.8%	0.1%	2.6%
	16,000 to 18,000	0.4%	0.2%	0.7%	0.1%	1.6%	0.4%	0.2%	0.7%	0.1%	2.0%
Leakage + Episodic (25% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	1.1%	0.7%	1.6%	0.2%	3.8%	1.0%	0.6%	1.7%	0.2%	4.7%
	10,000 to 12,000	1.0%	0.6%	1.4%	0.2%	3.9%	0.9%	0.5%	1.5%	0.2%	3.6%
	12,000 to 14,000	0.8%	0.5%	1.2%	0.1%	3.1%	0.7%	0.4%	1.2%	0.1%	3.2%
	14,000 to 16,000	0.7%	0.4%	1.1%	0.1%	2.4%	0.7%	0.4%	1.1%	0.1%	2.9%
	16,000 to 18,000	0.7%	0.4%	1.0%	0.1%	2.1%	0.6%	0.4%	1.0%	0.1%	2.6%

The results after 10 years of production are displayed graphically in Figure 7.5 (population biomass) and Figure 7.6 (spawning abundance). As mentioned previously, the upper whisker in the figures reflects the greatest (single) impact detected during the simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range.

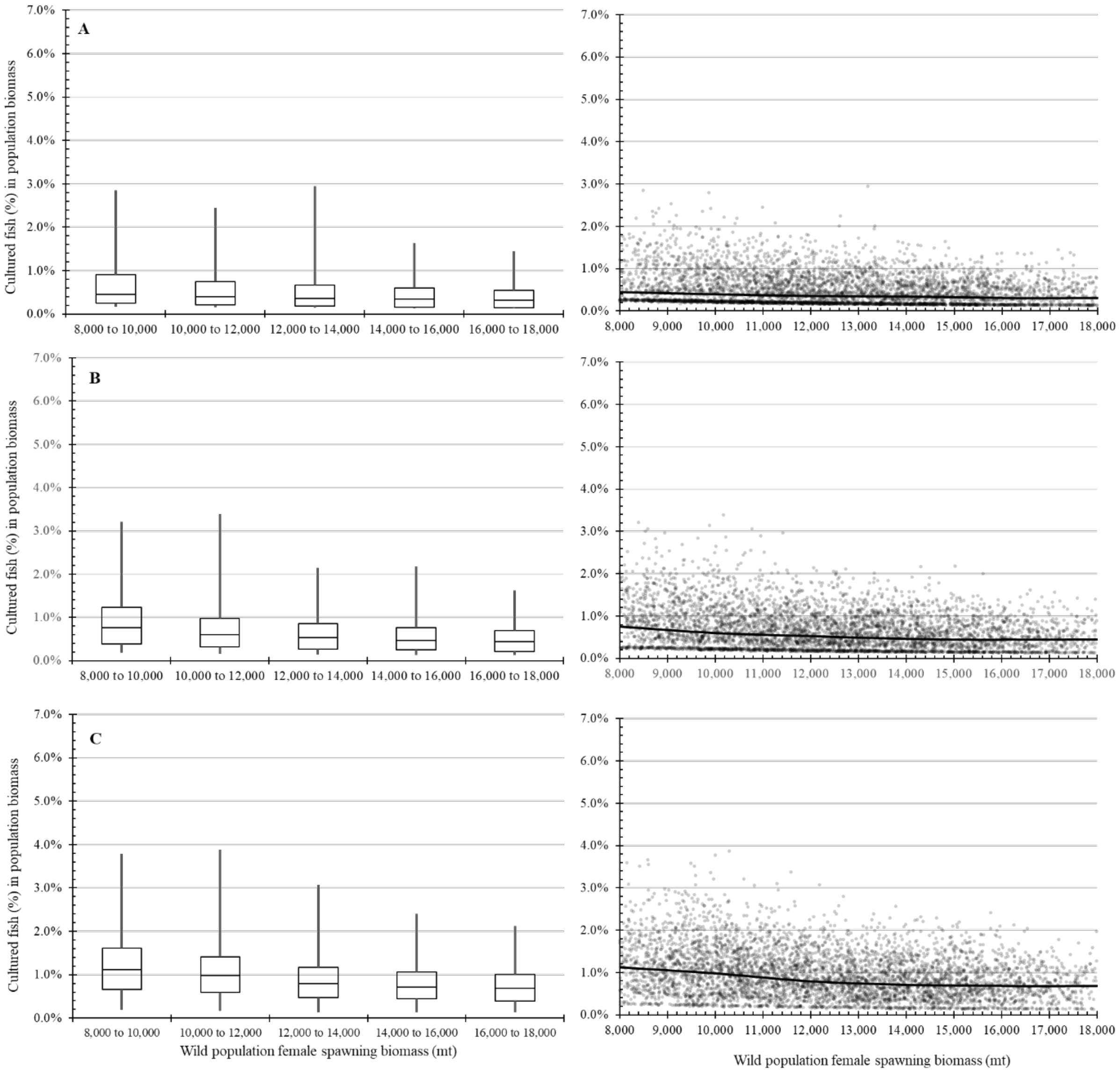


Figure 7.5. The percentage of cultured fish at full production (5,000 mt) in the population biomass in Year 10 resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

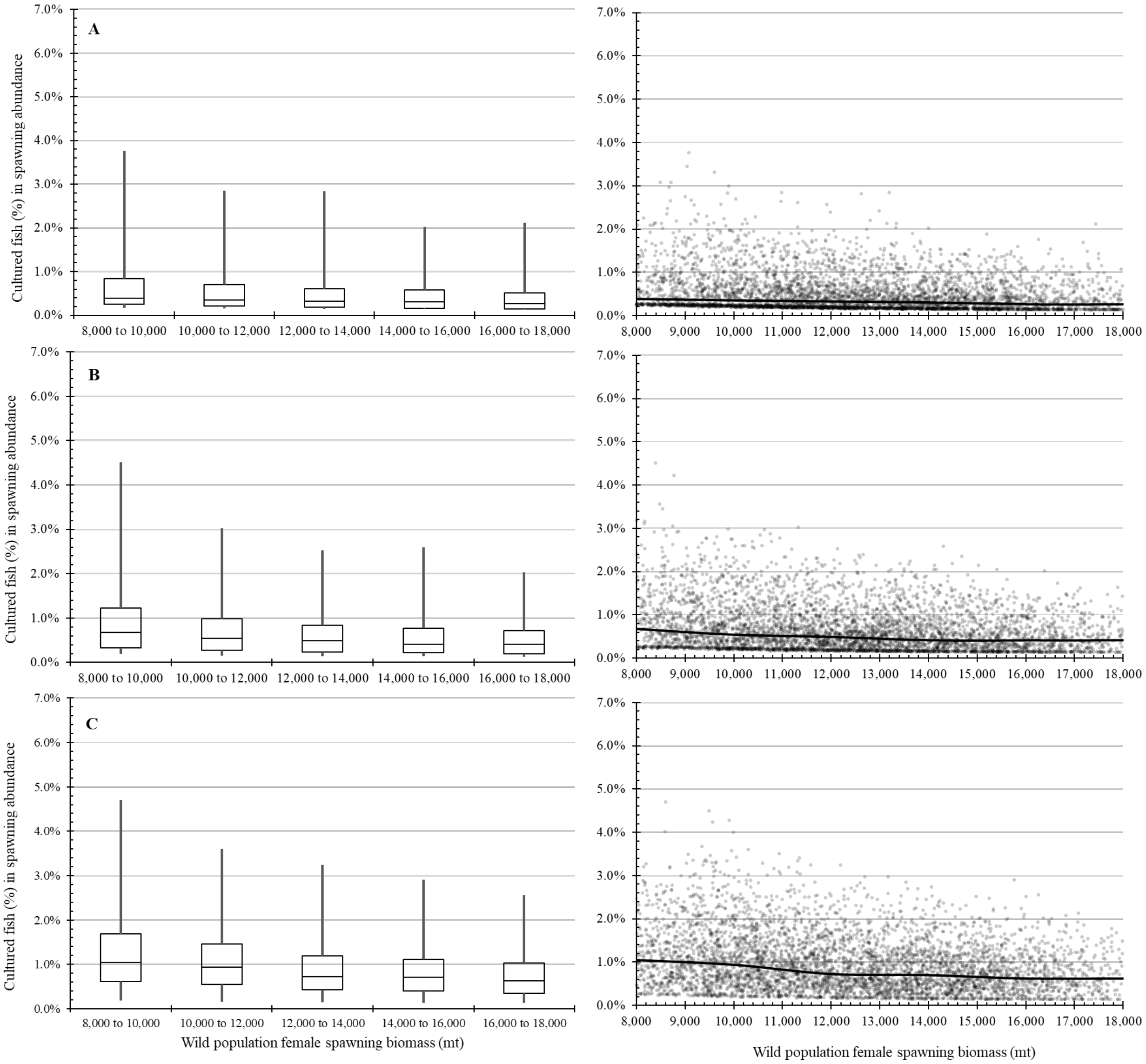


Figure 7.6. The percentage of cultured fish at full production (5,000 mt) in the population spawning abundance in Year 10 resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

In year 25, simulations revealed that the predicted cumulative median number of escaped fish in the population ranged between 21,273 fish (at the 10% likelihood) and 53,177 fish (at the 25% likelihood) (Table 7.3). Simulations with the worst outcomes indicated that a maximum between 151,852 (at the 10% likelihood) and 190,334 (at the 25% likelihood) escaped fish may accumulate in the wild population. Again, the results are highly skewed with 75% of the simulations far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 42,746 escaped fish (at the 10% likelihood) and 79,163 escaped fish (at the 25% likelihood) accumulating in the population after 25 years of full production.

The percentage of escaped fish as a proportion of population biomass and spawning abundance after 25 years of production is shown in Table 7.6. Again, the composition of escapees is highest at the female biomass range of 8,000 to 10,000 mt, with a median between 0.6% (at the 10% likelihood) and 1.3% (at the 25% likelihood) cultured fish in the population biomass and between 0.5% (at the 10% likelihood) and 1.1% (at the 25% likelihood) in the spawning abundance. At the 10% annual episodic escape frequency, 75% of simulations did not exceed 1.1% cultured fish in the population biomass, and 1.0% in the spawning abundance across the modeled wild population size range. At the 25% annual episodic escape frequency, 75% of simulations did not exceed 1.8% and 1.7% escaped fish in the population biomass and spawning abundance, respectively, across the modeled wild population size range.

Table 7-6. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under the full production (5,000 mt) alternative in year 25 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Full production at 5,000 mt		Median	25%	75%	Min.	Max.	Median	25%	75%	Min.	Max.
Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.4%	1.1%	0.2%	3.5%	0.5%	0.3%	1.0%	0.2%	3.6%
	10,000 to 12,000	0.5%	0.3%	0.9%	0.2%	2.8%	0.4%	0.3%	0.8%	0.2%	3.7%
	12,000 to 14,000	0.5%	0.3%	0.7%	0.2%	2.5%	0.3%	0.2%	0.6%	0.1%	3.1%
	14,000 to 16,000	0.4%	0.2%	0.7%	0.2%	2.5%	0.3%	0.2%	0.6%	0.1%	2.5%
	16,000 to 18,000	0.4%	0.2%	0.6%	0.2%	1.8%	0.3%	0.2%	0.5%	0.1%	2.0%
Leakage + Episodic (15% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.9%	0.5%	1.3%	0.2%	3.2%	0.7%	0.4%	1.2%	0.2%	4.1%
	10,000 to 12,000	0.7%	0.5%	1.1%	0.2%	3.2%	0.6%	0.3%	1.0%	0.2%	3.3%
	12,000 to 14,000	0.7%	0.4%	1.0%	0.2%	3.0%	0.5%	0.3%	0.9%	0.1%	3.1%
	14,000 to 16,000	0.6%	0.4%	0.9%	0.2%	2.8%	0.5%	0.3%	0.8%	0.2%	2.7%
	16,000 to 18,000	0.5%	0.3%	0.8%	0.2%	2.4%	0.4%	0.2%	0.7%	0.1%	3.0%
Leakage + Episodic (25% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	1.3%	0.9%	1.8%	0.3%	4.1%	1.1%	0.7%	1.7%	0.2%	4.4%
	10,000 to 12,000	1.1%	0.8%	1.6%	0.2%	4.2%	0.9%	0.6%	1.5%	0.2%	4.1%
	12,000 to 14,000	1.0%	0.7%	1.4%	0.2%	3.1%	0.8%	0.5%	1.3%	0.2%	4.2%
	14,000 to 16,000	0.9%	0.6%	1.2%	0.2%	3.4%	0.7%	0.5%	1.2%	0.2%	3.5%
	16,000 to 18,000	0.9%	0.6%	1.2%	0.2%	2.5%	0.7%	0.5%	1.1%	0.2%	2.5%

The results after 25 years of production are displayed graphically in Figure 7.7 (population biomass) and Figure 7.8 (spawning abundance). As mentioned previously, the upper whisker in the figures reflects the greatest (single) impact detected during the simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range.

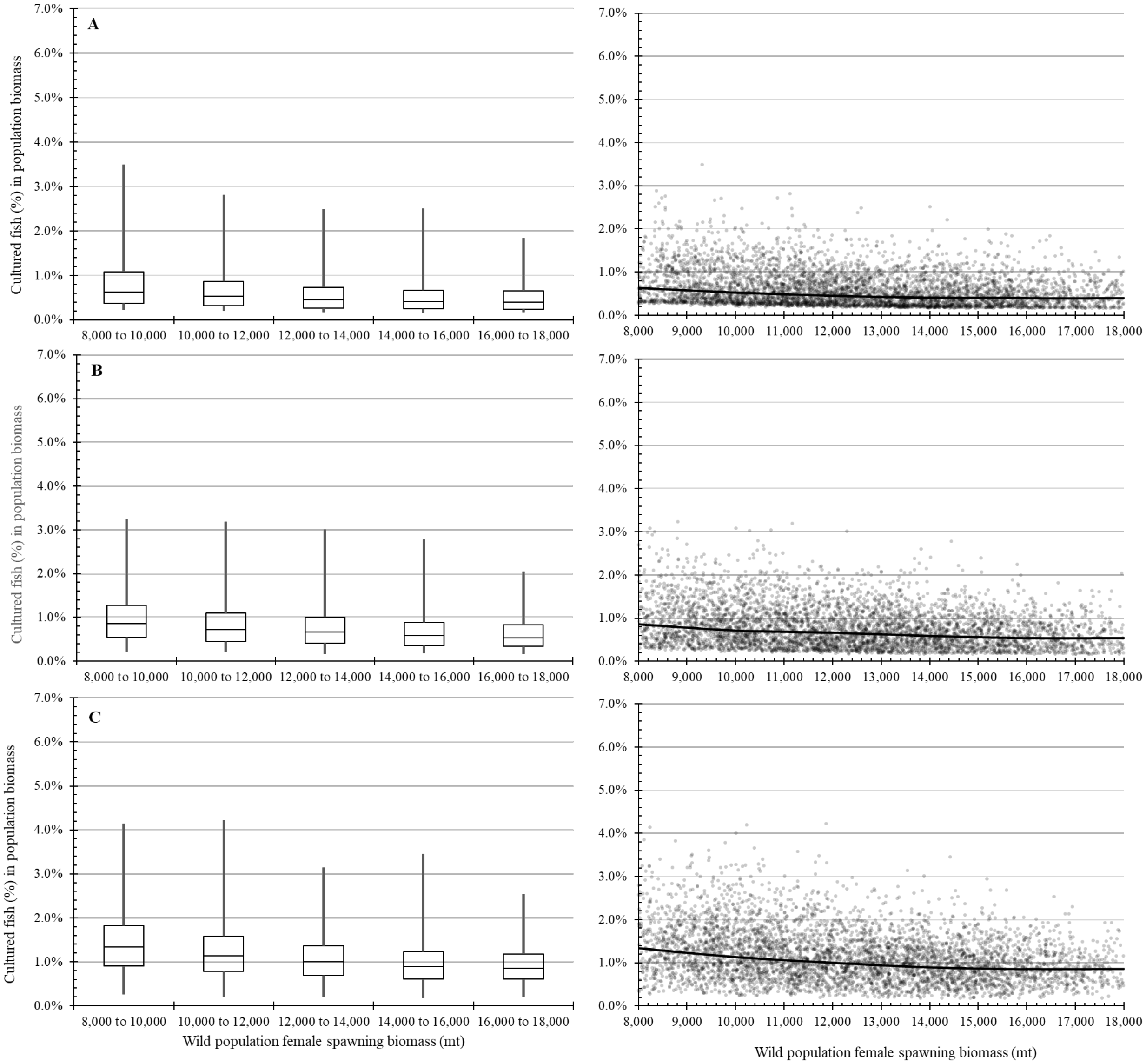


Figure 7.7. The percentage of cultured fish at full production (5,000 mt) in the population biomass in Year 25 resulting from leakage and episodic escapes. Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

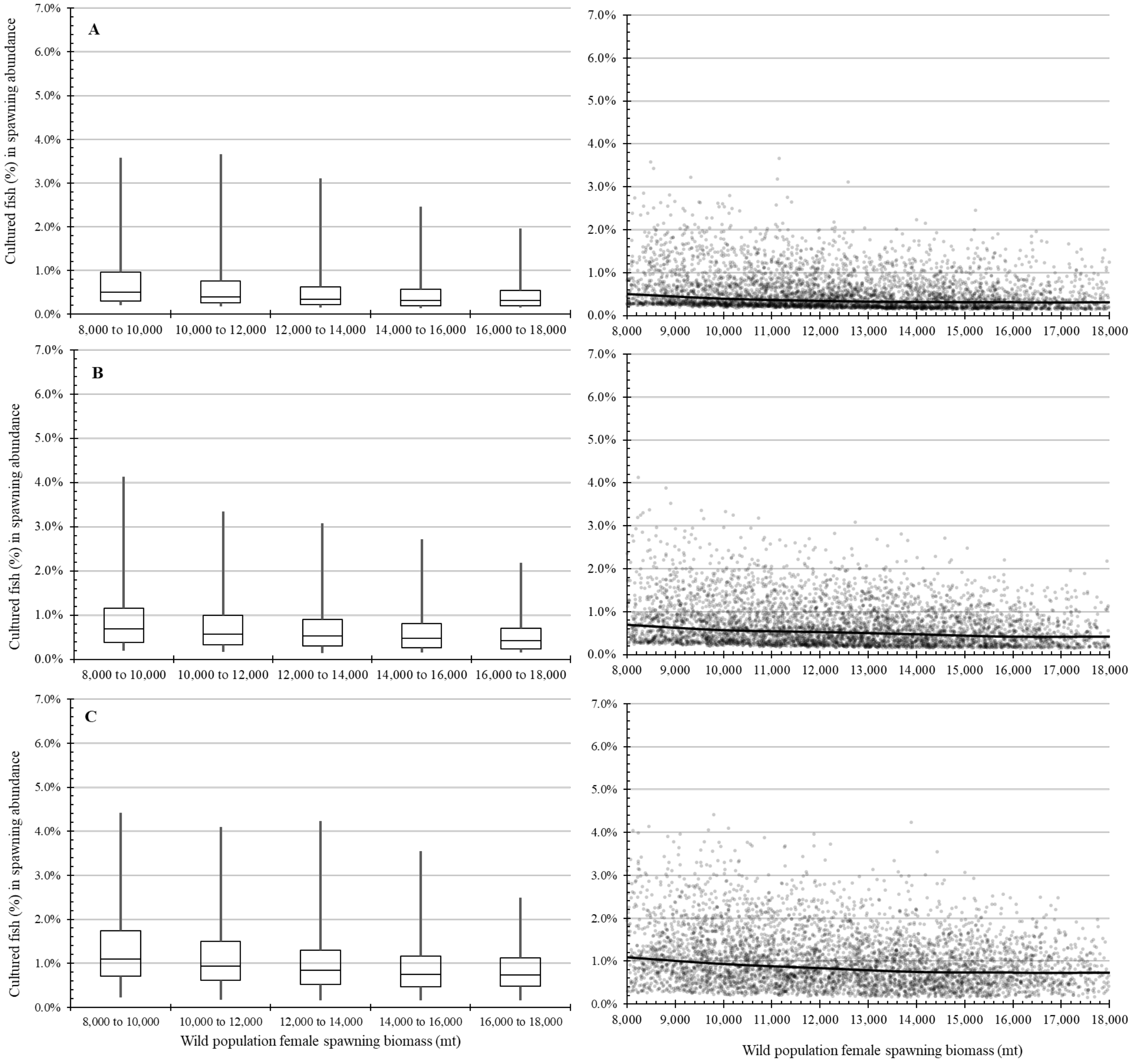


Figure 7.8. The percentage of cultured fish at full production (5,000 mt) in the population spawning abundance in Year 25 resulting from leakage and episodic escapes Episodic events were modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

7.1.2 Half Production Alternative

The half-production analysis represents the 2,500 mt per year alternative with two to three cages per cohort stocked three times a year. The half production alternative assumes half the number of cages compared to the full production alternative. The number of fish escaping from leakage was based on the previously described leakage rates (see Section 5.1.2.1 *Leakage Escape*). Under the half production alternative, 2,687 fish escape annually due to leakage. Although the leakage rate per cage is the same for the two alternatives, the number of fish escaping due to leakage under the half production alternative is lower because of fewer cages with this alternative. Three rates of episodic escape frequencies were modeled: 1) 0.5 events every ten years, 2) 0.75 events every ten years, and 3) 1.25 events every ten years (i.e., 5, 7.5, and 12.5% annual likelihood of an episodic escape event). These rates are half of what was assumed under the full-production alternative to account for the fewer number of cages with this alternative. However, in years when an episodic escape event occurs, the magnitude of those escapes is the same as full-production alternative, the loss of between half and all fish in a cage (48,777 to 97,554 fish) escaping in an episodic event.

7.1.2.1 90-year Simulation Results

As with the full production alternative, the 90-year simulation period (simulation years 10 to 100) was used to demonstrate longer-term impacts on the conspecific wild population due to escape events occurring from continuous operation within this time frame. The cumulative number of escaped fish in the population resulting from leakage and episodic losses is presented in Table 7.7 for the half production alternative and with the three modeled episodic loss scenarios.

Like the full production alternative, the cumulative number of escaped fish in the population increases as the modeled frequency of episodic events increases (Table 7.7). Again, the maximum values represent simulations where Scenario I operational scenarios occur (i.e., based on leakage and episodic escape) in terms of impacts (e.g., larger episodic events occurring with maximal frequency). However, 75% of simulations, across the episodic escape frequencies, fell at or below 40% of the maximum values.

Table 7-7. The cumulative number of cultured fish in the population resulting from leakage and episodic losses from current year escapes and surviving fish from previous years under the half production alternative – years 10 – 100 simulation results.

Model scenario:	**Cumulative number of escaped fish in population (Simulation years 10 – 100 summaries)**				
Half Production at 2,500 mt	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (5% annual likelihood)	7129	6152	16786	5499	77586
Leakage + Episodic (7.5% annual likelihood)	20206	9335	41042	5786	105793
Leakage + Episodic (12.5% annual likelihood)	20600	9444	41632	5804	104927

In Table 7.8, the percentage of escaped fish in the population biomass and spawning abundance (which includes both male and female fish) is presented for the 90-year simulations with the three modeled episodic frequencies across a range of wild female biomasses (8,000 to 18,000 metric tons). Figure 7.9 and Figure 7.10 present these data graphically for the population biomass and spawning abundance, respectively.

As expected, escaped fish made up the largest percentages of the biomass and abundances at the smallest ranges of wild female biomass (Table 7.8). Under the half-production alternative, where values of wild population abundance were lowest and episodic escape had an annual likelihood of 12.5%, the maximum values of escaped fish were 2.0% (population biomass) and 2.7% (spawning abundance). This represents a high episodic escape condition for the half-production alternative.

Individual simulation values, shown in the scatterplots in Figure 7.9 and Figure 7.10 reveal the variation around median values. A small number of the individual simulations ranged to just over 3.5% or below 4.0% in the population biomass (Figure 7.9), and almost 4.5% in the spawning abundance at the highest frequency and low end of the wild female spawning biomass range (Figure 7.10). However, as noted previously the distribution is highly skewed with more than 75% of the simulations below 1.0% in both the population biomass and spawning abundance, even at the low end of the wild female spawning biomass range.

Table 7-8. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under half production (2,500 mt) alternative – years 10 – 100 simulation results.

Model Scenario:		**Percentage of population biomass that are cultured fish**					**Percentage of population spawning abundance (males and females) that are cultured fish**				
Half production at 2,500 mt		**Median**	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.2%	0.2%	0.5%	0.1%	1.4%	0.2%	0.1%	0.4%	0.1%	2.0%
	10,000 to 12,000	0.2%	0.1%	0.4%	0.1%	1.2%	0.1%	0.1%	0.3%	0.1%	1.6%
	12,000 to 14,000	0.1%	0.1%	0.3%	0.1%	0.9%	0.1%	0.1%	0.3%	0.1%	1.4%
	14,000 to 16,000	0.1%	0.1%	0.3%	0.1%	0.8%	0.1%	0.1%	0.2%	0.1%	1.2%
	16,000 to 18,000	0.1%	0.1%	0.3%	0.1%	0.8%	0.1%	0.1%	0.2%	0.1%	1.1%
Leakage + Episodic (7.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.3%	1.0%	0.2%	2.0%	0.5%	0.2%	0.9%	0.1%	2.7%
	10,000 to 12,000	0.5%	0.3%	0.9%	0.1%	1.7%	0.4%	0.2%	0.8%	0.1%	2.2%
	12,000 to 14,000	0.4%	0.2%	0.8%	0.1%	1.5%	0.4%	0.2%	0.7%	0.1%	1.9%
	14,000 to 16,000	0.4%	0.2%	0.6%	0.1%	1.3%	0.3%	0.1%	0.6%	0.1%	1.7%
	16,000 to 18,000	0.4%	0.2%	0.6%	0.1%	1.1%	0.3%	0.1%	0.5%	0.1%	1.5%
Leakage + Episodic (12.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.3%	1.0%	0.1%	2.0%	0.5%	0.2%	0.9%	0.1%	2.7%
	10,000 to 12,000	0.5%	0.3%	0.9%	0.1%	1.7%	0.4%	0.2%	0.7%	0.1%	2.3%
	12,000 to 14,000	0.4%	0.2%	0.8%	0.1%	1.5%	0.3%	0.2%	0.7%	0.1%	1.9%
	14,000 to 16,000	0.4%	0.2%	0.7%	0.1%	1.3%	0.3%	0.1%	0.6%	0.1%	1.7%
	16,000 to 18,000	0.4%	0.2%	0.6%	0.1%	1.2%	0.3%	0.1%	0.5%	0.1%	1.6%

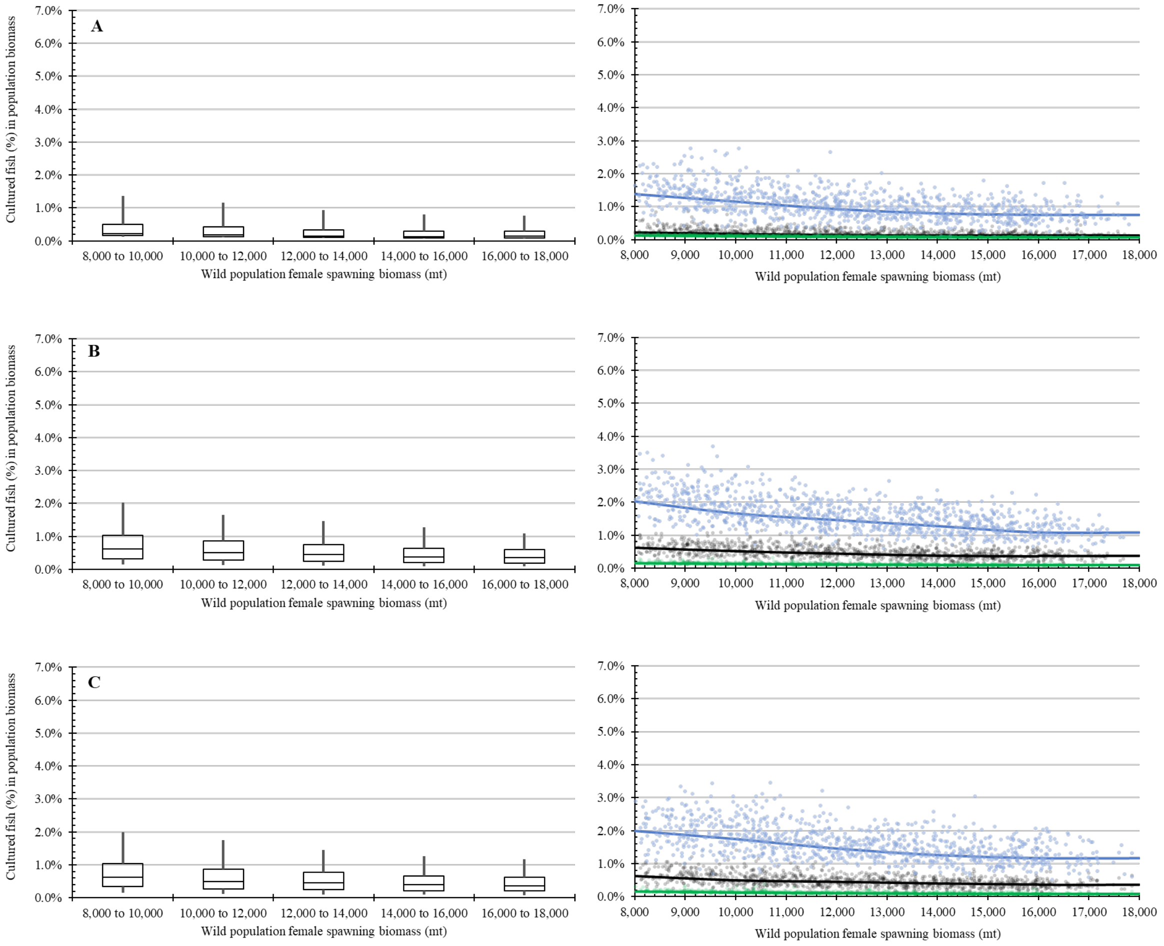


Figure 7.9. The percentage of cultured fish at half production (2,500 mt) in the population biomass resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the maximum (blue), median (gray), and minimum (green) values for each iteration and solid lines represent the respective median value over the range in female spawning biomass (in metric tons).

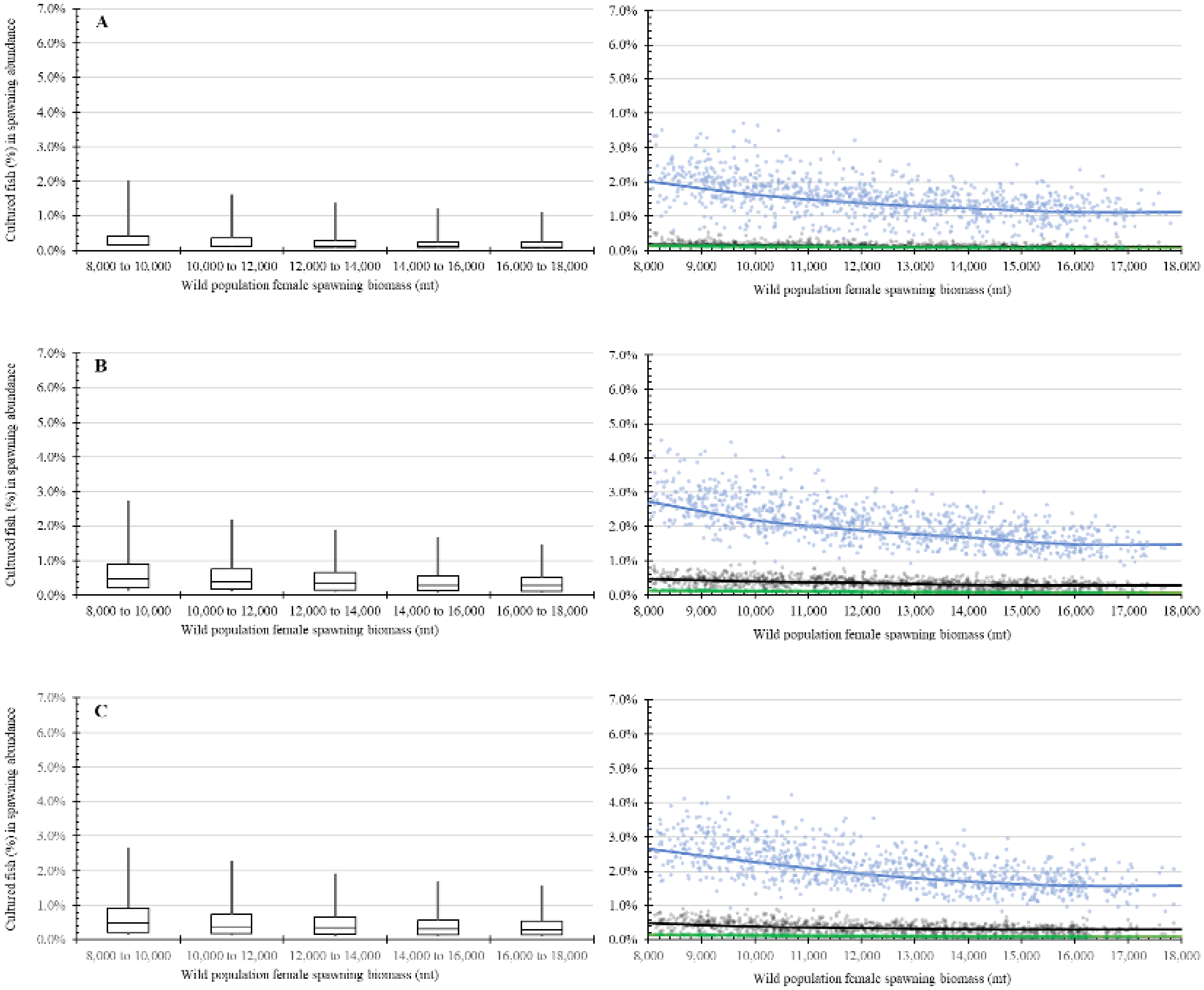


Figure 7.10. The percentage of cultured fish at half production (2,500 mt) in the population spawning abundance resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the maximum (blue), median (gray), and minimum (green) values for each iteration and solid lines represent the respective median value over the range in female spawning biomass (in metric tons).

7.1.2.2 Short-term Simulation Results

Model simulations were conducted for 5, 10, and 25 years at half production. Like the results from the full production alternative, the results of these short-term simulations are presented to describe potential effects within a time frame applicable for environmental impact analysis and permitting applications. Like the 90-year simulations, results are based on three rates of episodic escape frequencies – 0.5 events every ten years, 0.75 events every ten years, and 1.25 events every ten years (5, 7.5, and 12.5% annual likelihood of an episodic escape event). Table 7.9 presents the cumulative number of fish from leakage and episodic losses at the 5-, 10- and 25-year time points of the simulations. Like with the full production alternative, the results for the short-term simulations differ from the 90-year simulations. Presented are the actual maximum and minimum values from the 1000 simulations. As such, the reported maximum values and upper tails in the box-and-whisker plots in this section reflect individual data points rather than the median of the maximum or minimum values, for example, of all 1000 simulations. Again, this distinction is important if trying to compare results between the 90-year and short-term simulations.

For each year, 2,687 fish escape from leakage due to the constant assumed leak rate. If an episodic event occurs in a year, somewhere between 48,000 and 98,000 fish escape (loss of half to full single cage of fish). The number of cumulative escaped fish in the wild increases as the episodic escape frequency increases, but the minimum numbers of escaped fish in population are relatively stable within time points as they represent the annual leakage and the number of fish surviving from leakage from previous years. Results for each of the time points are presented below.

Table 7-9. The cumulative number of escaped fish in the population in years 5, 10 and 25 resulting from leakage and episodic losses at half production (2,500 mt) under Scenario I.

Model scenario:	Cumulative number escaped fish in population				
Half production at 2,500 mt	Median	25%	75%	Min.	Max.
Number of Cultured Fish in Year 5					
Leakage + Episodic (5% annual likelihood)	4855	4697	5167	4100	111439
Leakage + Episodic (7.5% annual likelihood)	5198	4774	35900	4219	179800
Leakage + Episodic (12.5% annual likelihood)	5134	4783	34580	4134	164398
Number of Cultured Fish in Year 10					
Leakage + Episodic (5% annual likelihood)	6108	5737	16507	4905	131582
Leakage + Episodic (7.5% annual likelihood)	20089	6388	41900	4901	176229
Leakage + Episodic (12.5% annual likelihood)	17695	6242	39161	4992	152349
Number of Cultured Fish in Year 25					
Leakage + Episodic (5% annual likelihood)	6906	6154	16562	5059	117176
Leakage + Episodic (7.5% annual likelihood)	20351	9154	43473	5155	187421
Leakage + Episodic (12.5% annual likelihood)	21374	9339	43023	5367	145994

In year five, simulations revealed that the predicted cumulative median number of escaped fish in the population ranged between 4,855 fish (at the 5% likelihood) and 5,134 (at the 12.5% likelihood) (Table 7.9). Simulations with the worst outcomes indicated that a maximum between 111,439 (at the 5% likelihood) and 164,398 (at the 12.5% likelihood) escaped fish may accumulate in the wild population. Again, as noted previously, the results are highly skewed with 75% of the simulations far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 5,167 escaped fish (at the 5% likelihood) and 34,580 escaped fish (at the 12.5% likelihood) accumulating in the population after five years of half production, which represents less than 5% and 21% of the maximum values, respectively.

The percentage of escaped fish as a proportion of population biomass and spawning abundance after five years of production is shown in Table 7.10. The composition of escapees in the wild population is highest at the low end of the wild female biomass range, with a median of 0.1% (at all frequencies of annual episodic escape) cultured fish in the population biomass and in the spawning abundance. At the 5% annual episodic escape likelihood, 75% of simulations did not exceed 0.1% cultured fish in the population biomass and in the spawning abundance across the modeled wild population size range. These percentages increased at the higher 12.5% annual episodic escape frequency, however, even at this higher frequency, 75% of simulations did not exceed 0.3% and 0.6% escaped fish in the population biomass and spawning abundance, respectively.

Table 7-10. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from Scenario I leakage and episodic escape events under the half production alternative in Year 5 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Half production at 2,500 mt		**Median**	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.1%	0.0%	2.2%	0.1%	0.1%	0.1%	0.1%	3.2%
	10,000 to 12,000	0.1%	0.0%	0.1%	0.0%	1.5%	0.1%	0.1%	0.1%	0.0%	2.5%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	1.8%	0.1%	0.1%	0.1%	0.0%	2.5%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	1.2%	0.1%	0.1%	0.1%	0.0%	1.6%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	1.5%	0.1%	0.0%	0.1%	0.0%	1.9%
Leakage + Episodic (7.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.4%	0.0%	2.6%	0.1%	0.1%	0.6%	0.1%	3.0%
	10,000 to 12,000	0.1%	0.0%	0.4%	0.0%	2.2%	0.1%	0.1%	0.6%	0.0%	2.8%
	12,000 to 14,000	0.0%	0.0%	0.4%	0.0%	2.1%	0.1%	0.1%	0.5%	0.0%	2.5%
	14,000 to 16,000	0.0%	0.0%	0.3%	0.0%	1.9%	0.1%	0.1%	0.4%	0.0%	2.9%
	16,000 to 18,000	0.0%	0.0%	0.2%	0.0%	1.3%	0.1%	0.0%	0.4%	0.0%	1.6%
Leakage + Episodic (12.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.3%	0.0%	2.4%	0.1%	0.1%	0.6%	0.1%	3.4%
	10,000 to 12,000	0.1%	0.0%	0.5%	0.0%	2.5%	0.1%	0.1%	0.6%	0.1%	3.1%
	12,000 to 14,000	0.0%	0.0%	0.3%	0.0%	1.7%	0.1%	0.1%	0.5%	0.0%	2.4%
	14,000 to 16,000	0.0%	0.0%	0.3%	0.0%	1.6%	0.1%	0.1%	0.4%	0.0%	2.1%
	16,000 to 18,000	0.0%	0.0%	0.3%	0.0%	1.9%	0.1%	0.0%	0.4%	0.0%	1.8%

These results are displayed graphically in Figure 7.11 (population biomass) and Figure 7.12 (spawning abundance) in Year 5. As mentioned previously, the upper and lower whiskers in the figures reflects the greatest (single) impact detected across all simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range. The black line in the scatterplots reflects the median values across the population size range and the density of the smaller values below the median is undetectable.

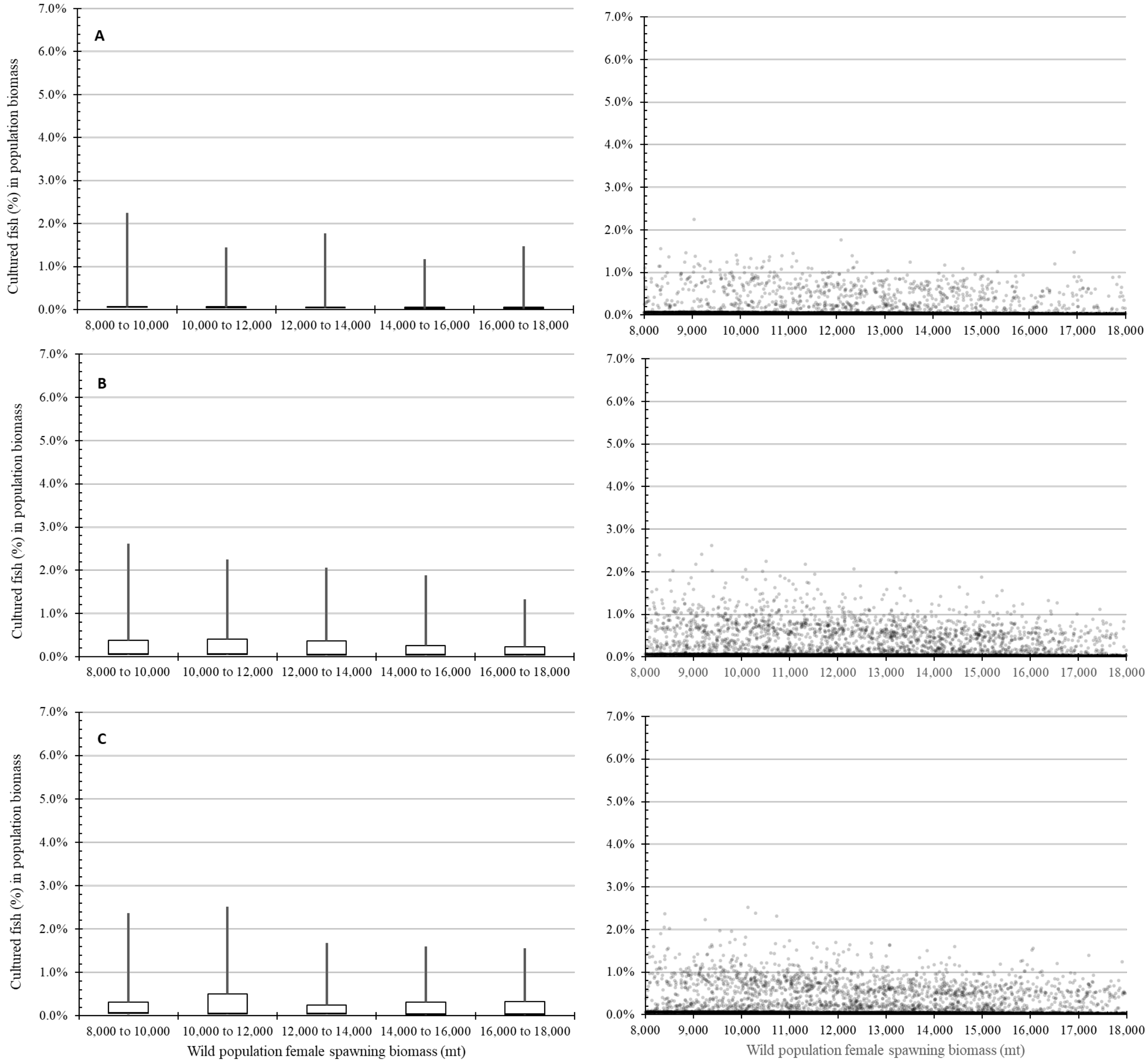


Figure 7.11. The percentage of cultured fish at half production (2,500 mt) in the population biomass in Year 5 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

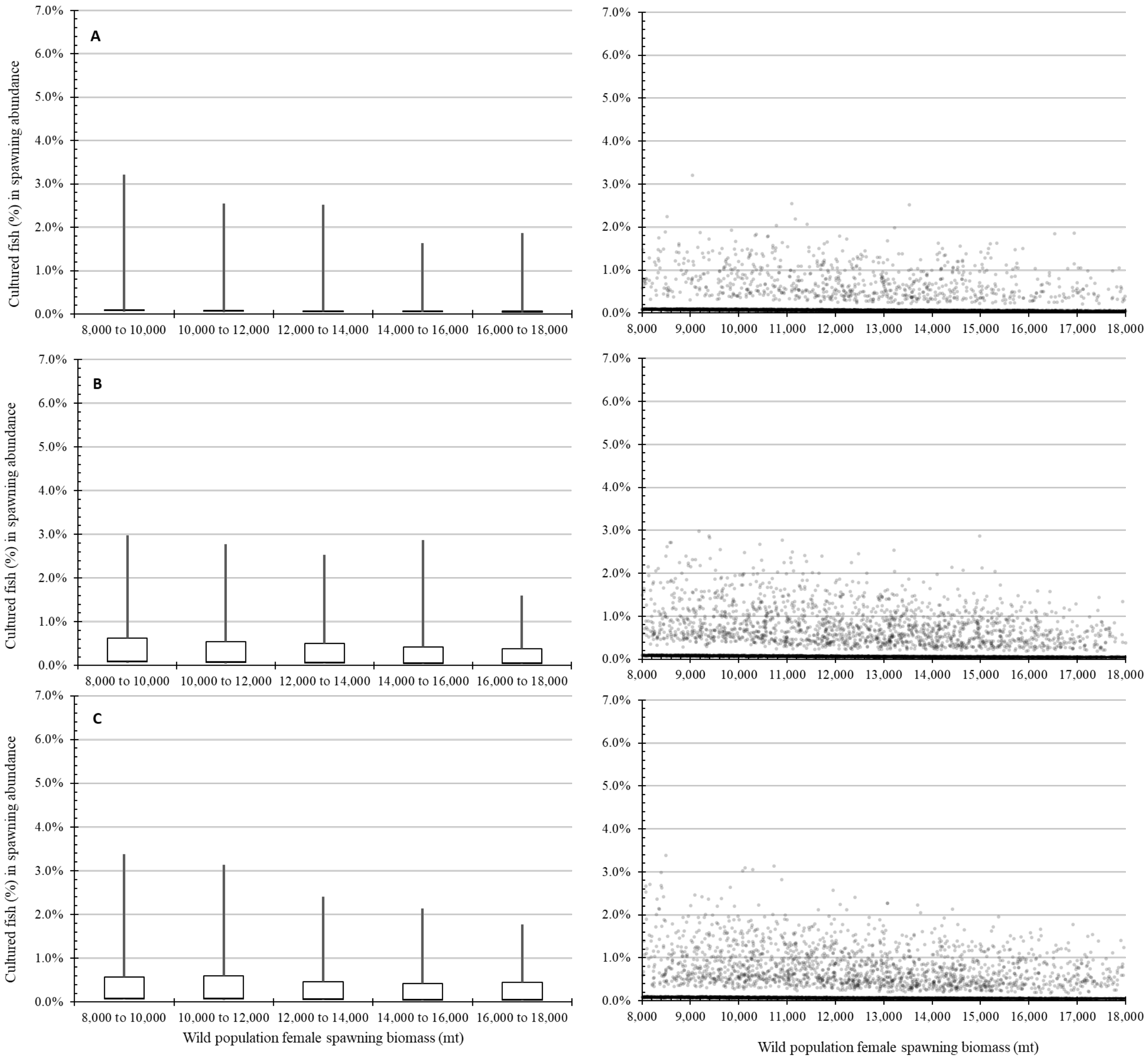


Figure 7.12. The percentage of cultured fish at half production (2,500 mt) in the population spawning abundance in Year 5 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

In Year 10, simulations revealed that the predicted cumulative median number of escaped fish in the population ranged between 6,108 fish (at the 5% likelihood) and 17,695 fish (at the 12.5% likelihood) (Table 7.9). However, due to the stochastic nature of the simulations, for year 10, the 7.5% annual episodic frequency had the highest cumulative median number of escaped fish (20,089 fish). Simulations with the worst outcomes indicated that a maximum of 131,582 (at the 5% likelihood), 176,229 (at the 7.5% likelihood) and 152,349 (at the 12.5% likelihood) escaped fish may accumulate in the wild population. Again, the results are highly skewed with 75% of the simulations far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 16,507 escaped fish (at the 5% likelihood), 41,900 (at the 7.5% likelihood) and 39,161 escaped fish (at the 12.5% likelihood) accumulating in the population after ten years of half production. These are 13%, 24%, and 26% of the maximum values across the three annual episodic frequencies.

The percentage of escaped fish as a proportion of population biomass and spawning abundance after ten years of production is shown in Table 7.11. Again, the composition of escapees is highest at the wild female biomass range of 8,000 to 10,000 mt, with a median between 0.1% (at the 5% likelihood) and 0.4% (at the 12.5% likelihood) cultured fish in the population biomass and the spawning abundance. At the 5% likelihood, 75% of simulations did not exceed 0.4% cultured fish in the population biomass or spawning abundance across the modeled wild population size range. At the 12.5% likelihood, 75% of simulations did not exceed 0.9% and 0.8% escaped fish in the population biomass and spawning abundance, respectively, across the modeled wild population size range.

Table 7-11. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under the half production alternative in Year 10 of the simulation.

Model Scenario:		**Percentage of population biomass that are cultured fish**					**Percentage of population spawning abundance (males and females) that are cultured fish**				
Half production (2,500 mt)		**Median**	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.4%	0.1%	2.4%	0.1%	0.1%	0.4%	0.1%	2.6%
	10,000 to 12,000	0.1%	0.1%	0.3%	0.1%	1.8%	0.1%	0.1%	0.3%	0.1%	2.1%
	12,000 to 14,000	0.1%	0.1%	0.3%	0.1%	1.5%	0.1%	0.1%	0.3%	0.1%	2.3%
	14,000 to 16,000	0.1%	0.1%	0.3%	0.1%	1.4%	0.1%	0.1%	0.2%	0.1%	1.5%
	16,000 to 18,000	0.1%	0.1%	0.3%	0.1%	1.3%	0.1%	0.1%	0.2%	0.1%	1.1%
Leakage + Episodic (7.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.4%	0.1%	0.9%	0.1%	3.1%	0.4%	0.1%	0.9%	0.1%	3.5%
	10,000 to 12,000	0.4%	0.1%	0.8%	0.1%	2.7%	0.4%	0.1%	0.7%	0.1%	3.5%
	12,000 to 14,000	0.3%	0.1%	0.7%	0.1%	2.6%	0.3%	0.1%	0.6%	0.1%	2.9%
	14,000 to 16,000	0.3%	0.1%	0.6%	0.1%	2.5%	0.3%	0.1%	0.6%	0.1%	3.1%
	16,000 to 18,000	0.3%	0.1%	0.5%	0.1%	1.6%	0.3%	0.1%	0.5%	0.1%	2.0%
Leakage + Episodic (12.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.4%	0.1%	0.9%	0.1%	2.9%	0.4%	0.1%	0.8%	0.1%	3.1%
	10,000 to 12,000	0.4%	0.1%	0.7%	0.1%	2.8%	0.3%	0.1%	0.7%	0.1%	2.8%
	12,000 to 14,000	0.3%	0.1%	0.6%	0.1%	2.0%	0.3%	0.1%	0.6%	0.1%	2.9%
	14,000 to 16,000	0.3%	0.1%	0.6%	0.1%	1.8%	0.3%	0.1%	0.6%	0.1%	1.9%
	16,000 to 18,000	0.3%	0.1%	0.6%	0.1%	1.7%	0.3%	0.1%	0.5%	0.1%	2.2%

The results after 10 years of production are displayed graphically in Figure 7.13 (population biomass) and Figure 7.14 (spawning abundance). As mentioned previously, the upper whisker in the figures reflects the greatest (single) impact detected during the simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range.

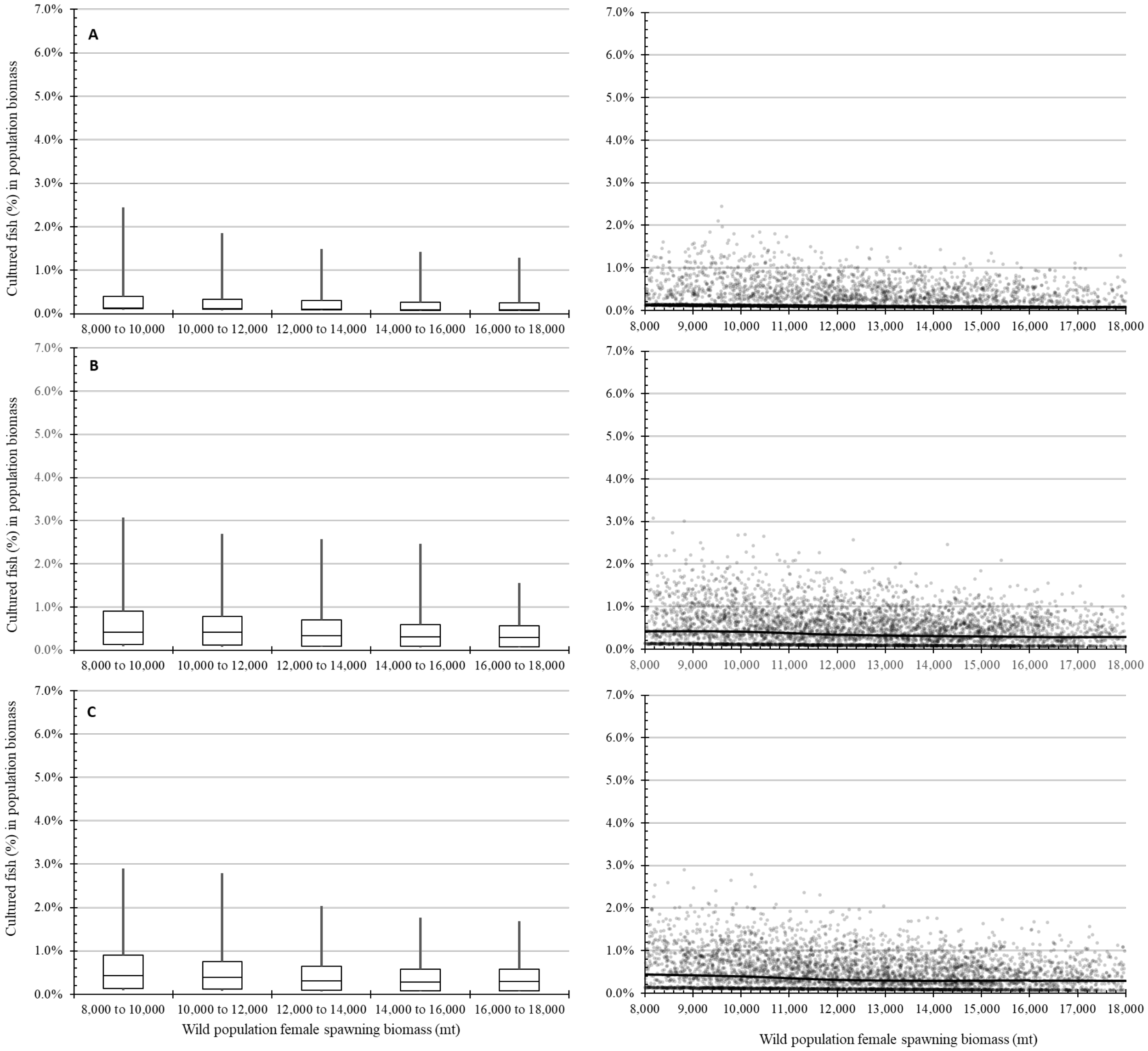


Figure 7.13. The percentage of cultured fish at half production (2,500 mt) in the population biomass in Year 10 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

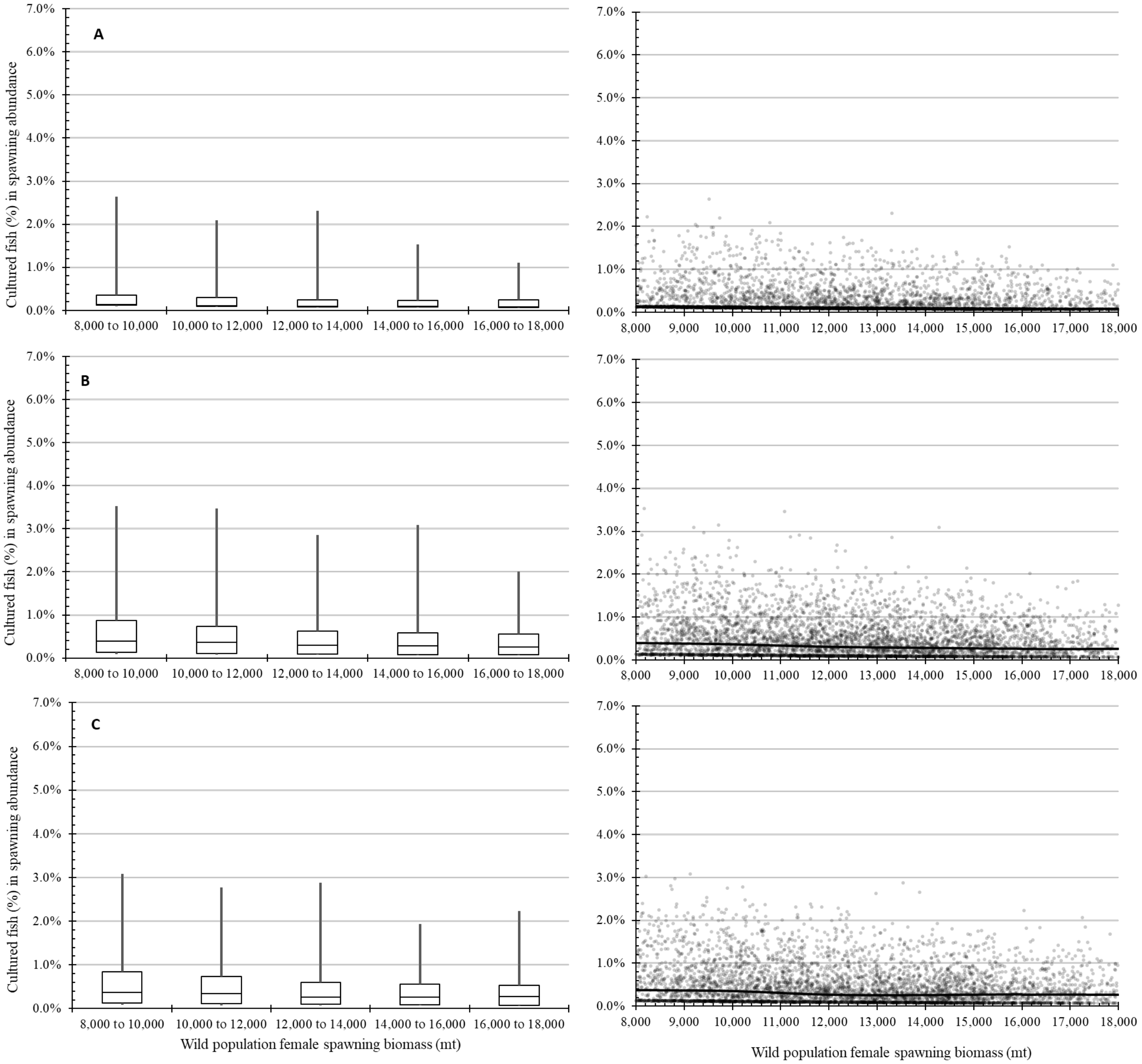


Figure 7.14. The percentage of cultured fish at half production (2,500 mt) in the population spawning abundance in Year 10 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

In Year 25, simulations revealed that the predicted cumulative median number of escaped fish in the population ranged between 6,906 fish (at the 5% event probability) and 21,374 fish (at the 12.5% event probability) (Table 7.9). Simulations with the worst outcomes indicated that a maximum between 117,176 (at the 5% likelihood) and 187,421 (at the 7.5% likelihood, which had the highest maximum in year 25) escaped fish may accumulate in the wild population. Again, the results are highly skewed with 75% of the simulations far below those maximum amounts. Results indicated that 75% of simulations led to fewer than 16,562 escaped fish (at the 5% likelihood), 43,473 escaped fish (at the 7.5% likelihood), and 43,023 escaped fish (at the 12.5% likelihood) accumulating in the population after 25 years of half production.

The percentage of escaped fish as a proportion of population biomass and spawning abundance after 25 years of half production is shown in Table 7.12. Again, the composition of escapees is highest at the female biomass range of 8,000 to 10,000 mt, with the median of escaped fish in the population biomass ranging between 0.2% (at the 5% likelihood), and 0.6% (at the 12.5% likelihood), and between 0.2% (at the 5% likelihood) and 0.4% (at the 12.5% likelihood) in the spawning abundance. At the 12.5% episodic escape frequency, 75% of simulations did not exceed 1.0% cultured fish in the population biomass, and 0.9% in the spawning abundance across the modeled wild population size range.

Table 7-12. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from aquaculture leakage and episodic escape events under the half production alternative in Year 25 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Half production (2,500 mt)		**Median**	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.2%	0.2%	0.5%	0.1%	2.1%	0.2%	0.1%	0.4%	0.1%	2.5%
	10,000 to 12,000	0.2%	0.1%	0.4%	0.1%	1.7%	0.1%	0.1%	0.3%	0.1%	2.4%
	12,000 to 14,000	0.2%	0.1%	0.4%	0.1%	1.7%	0.1%	0.1%	0.3%	0.1%	2.4%
	14,000 to 16,000	0.1%	0.1%	0.3%	0.1%	2.1%	0.1%	0.1%	0.2%	0.1%	2.0%
	16,000 to 18,000	0.1%	0.1%	0.3%	0.1%	1.9%	0.1%	0.1%	0.2%	0.1%	2.1%
Leakage + Episodic (7.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.3%	1.0%	0.1%	3.2%	0.4%	0.2%	0.9%	0.1%	3.4%
	10,000 to 12,000	0.5%	0.2%	0.9%	0.1%	2.9%	0.4%	0.2%	0.7%	0.1%	3.3%
	12,000 to 14,000	0.4%	0.2%	0.7%	0.1%	2.4%	0.3%	0.2%	0.6%	0.1%	2.6%
	14,000 to 16,000	0.4%	0.2%	0.7%	0.1%	2.3%	0.3%	0.1%	0.6%	0.1%	2.8%
	16,000 to 18,000	0.4%	0.2%	0.6%	0.1%	1.8%	0.3%	0.1%	0.5%	0.1%	2.2%
Leakage + Episodic (12.5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.6%	0.3%	1.0%	0.1%	3.1%	0.4%	0.2%	0.9%	0.1%	3.6%
	10,000 to 12,000	0.5%	0.3%	0.9%	0.1%	2.7%	0.4%	0.2%	0.7%	0.1%	3.3%
	12,000 to 14,000	0.4%	0.2%	0.8%	0.1%	2.5%	0.3%	0.1%	0.6%	0.1%	2.6%
	14,000 to 16,000	0.4%	0.2%	0.7%	0.1%	2.0%	0.3%	0.1%	0.6%	0.1%	2.5%
	16,000 to 18,000	0.4%	0.2%	0.7%	0.1%	1.9%	0.3%	0.1%	0.6%	0.1%	2.3%

The results after 25 years of production are displayed graphically in Figure 7.15 (population biomass) and Figure 7.16 (spawning abundance). As mentioned previously, the upper whisker in the figures reflects the greatest (single) impact detected during the simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range.

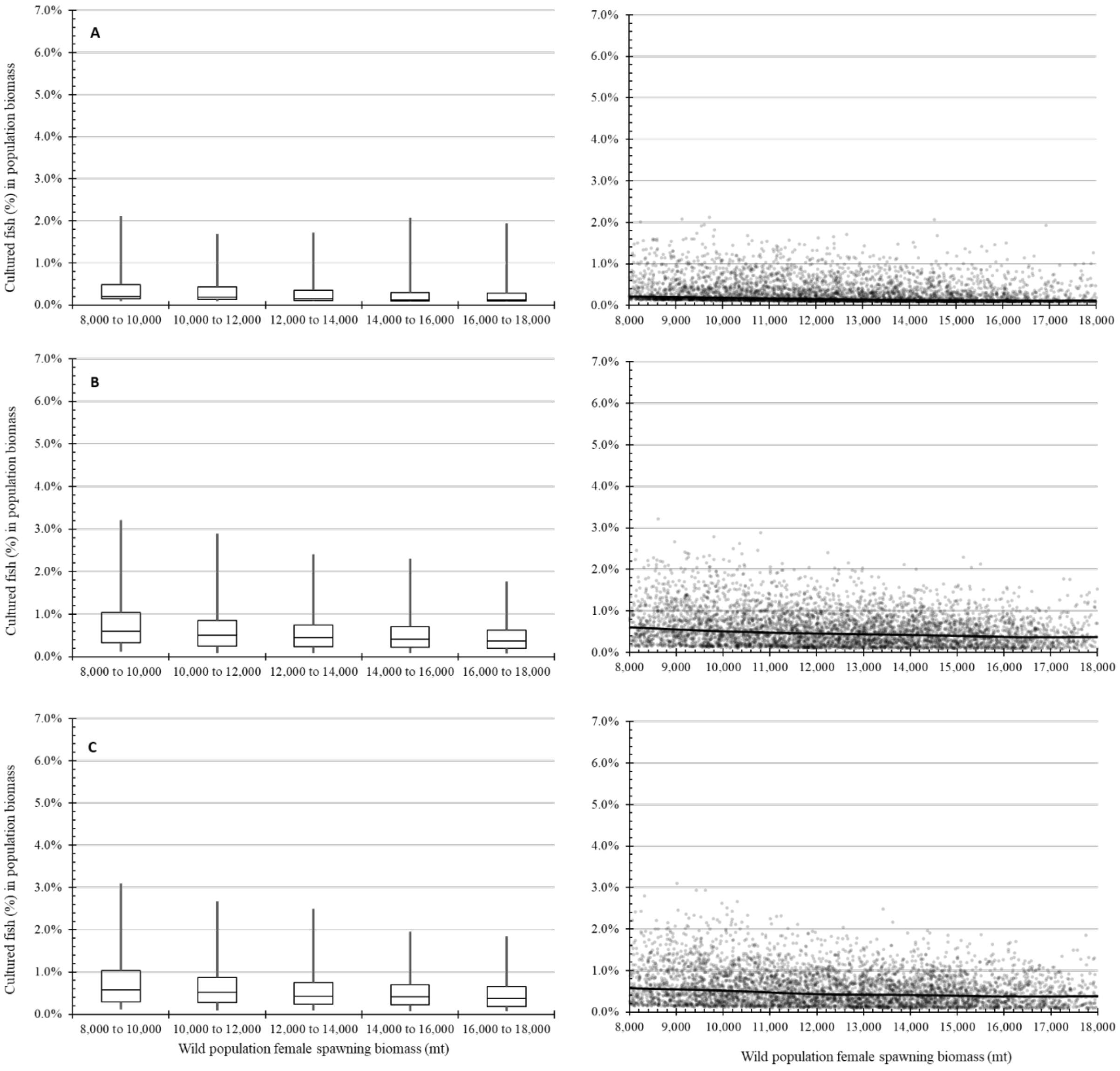


Figure 7.15. The percentage of cultured fish at half production (2,500 mt) in the population biomass in Year 25 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

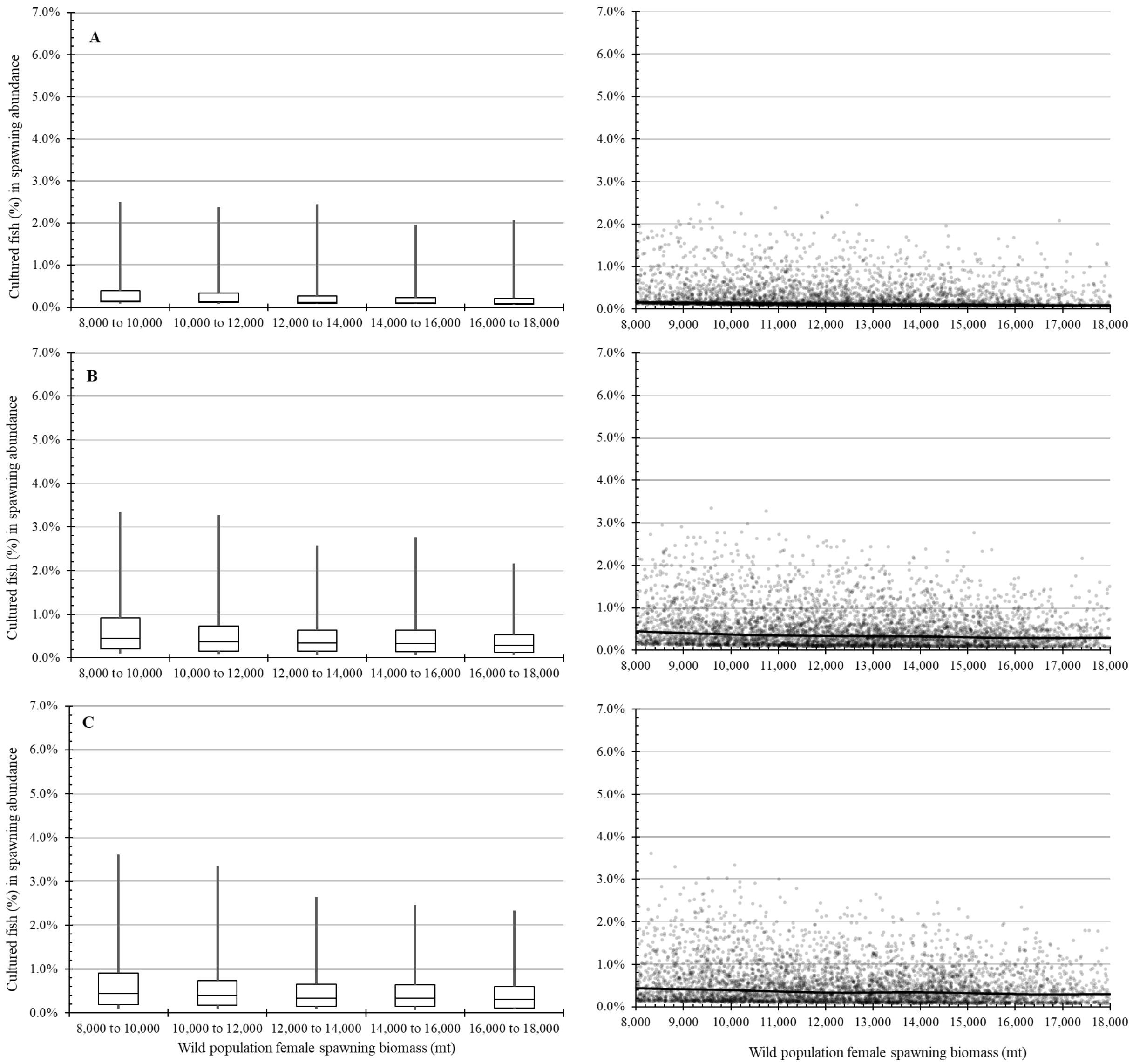


Figure 7.16. The percentage of cultured fish at half production (2,500 mt) in the population spawning abundance in Year 25 resulting from leakage and episodic escapes. Episodic events were modeled at 5% (A), 7.5% (B), and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the values for each iteration and the solid line is the median value over the range in female spawning biomass (in metric tons).

7.1.3 Impact Results

In any given year, under the leakage/cage-failure escape scenarios for the full-scale production alternative, 5,173 fish are predicted to escape due to leakage, and if a cage failure occurs during that year (episodic event), somewhere between 49,000 and 98,000 fish may escape during that cage loss. For the half-scale production alternative, 2,687 fish are predicted to escape due to leakage (from fewer cages), and between 49,000 and 98,000 fish may again escape from a cage loss if one occurs during that year. While cage loss events are less frequent under the half-scale production alternative, the magnitude of loss remains unchanged. These escape numbers are consistent between the 90-year and short-term (5-, 10, and 25-year) simulations, however the cumulative number of escaped fish in the mixed population will vary based on the duration of time modeled, as described above.

7.1.3.1 Fitness Impacts on the Wild Conspecific Population

Based on the model simulations over the 90-year period, the predicted maximum loss of fitness showed a slight reduction in value from the optimum value of 1.0. In over 1,000 simulations (Figure 7.17), the maximum predicted relative fitness loss was approximately 0.0019 in the mixed population compared to the original wild population (relative fitness of 0.998 versus 1.000) (Figure 7.17C on left), which occurred at full-scale production, at the highest frequency of episodic escape events (25% annual likelihood), and at the lower end of the modeled wild population biomass range. Even at the highest escape frequency, for the smallest wild population size range modeled (8,000 - 10,000 mt female spawning biomass), 95% of simulations predicted a relative fitness loss of less than 0.00132 at full-scale production in the mixed population (or alternatively, that the mixed population retained 0.9987 of the relative fitness compared to the original wild population). Fitness loss was even smaller for the two lower cage escape frequencies, with only a few simulations exceeding a maximum relative fitness loss greater than 0.0010 at the 15% annual cage loss frequency, and 0.0005 at the 10% annual cage loss frequency.

At half-scale production over the 90-year period, the maximum predicted loss of relative fitness in the mixed population was 0.00056 at the highest cage escape frequency (12.5%) and at the lower range of modeled population sizes (8,000 – 10,000 mt female spawning biomass). At the highest cage loss frequency, 95% of the simulations predicted a relative loss of fitness of less than 0.00048 in the mixed population (or alternatively, that the mixed population retained 0.9995 of its relative fitness) compared to the original wild population. Impacts were even more minimal at the lower cage loss frequencies.

From the short-term simulations at full-scale production (Figure 7.18), the maximum relative fitness loss was 0.00036 in the mixed population, which occurred at the highest cage loss frequency (25%), at the longest time-interval (25 years), and for the smallest range of wild population sizes (8,000 – 10,000 mt female spawning biomass). For the same cage loss frequency, time interval, and modeled population size range, 95% of the simulations predicted relative fitness losses that did not exceed 0.00019 in the mixed population compared to the original wild population. At half-scale production (Figure 7.19), with the highest cage loss frequency (12.5%), the longest time-interval (25 years), and the smallest range of modeled population sizes (8,000 – 10,000 mt female spawning biomass), the maximum relative fitness loss was 0.00024 in the mixed population, but 95% of simulations predicted relative fitness losses that did not exceed 0.00008 in the mixed population compared to the original wild population.

For all simulations, the greatest fitness losses were predicted for the lower end of the modeled wild population size range (i.e., between 8,000 – 10,000 mt female spawning biomass). Conversely, fitness impacts were lower for the shorter time-intervals (e.g., 5-year and 10-year simulations) and for the lower cage loss frequencies.

Across these simulations, fitness losses were slight, due to the use of F1 fingerlings from wild-caught broodstock. This result is expected because of the use of F1 fingerlings in the program, because escaped fish would not differ substantially in fitness from wild juveniles and there would be minimal opportunity for domestication. Although the predicted loss of fitness is extremely small, the fitness model assumes a single trait is under selection in the culture environment as expressed in the culture environmental optimum, and over multiple generations this would result in a slight shift in the mean trait value of the combined admixed population of cultured and wild California Yellowtail when cultured fish escape and breed with the wild population. The slightly greater loss of relative fitness reported for the 90-year results compared to the short-term results reflects a cumulative effect over multiple generations of escaped fish and compounded by a slight shift in mean trait value in fish from the wild population collected for broodstock.

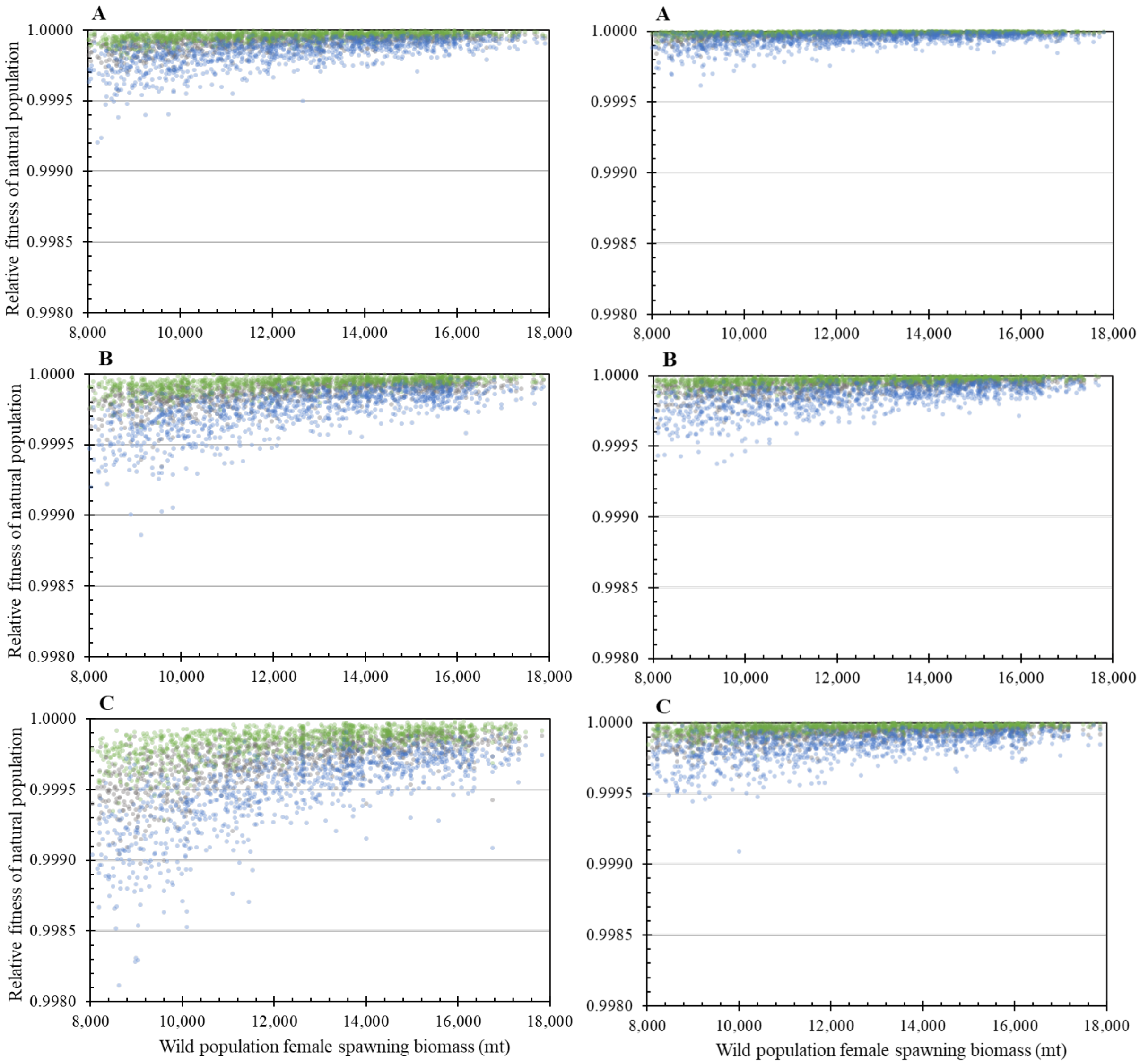


Figure 7.17. Relative fitness effects in years 10 to 100 under the full production (5,000 mt) alternative on the left with episodic events modeled at 10% (A), 15% (B), and 25% (C) likelihood of occurrence in a year. On the right, relative fitness effects in years 10 to 100 for the half production (2,500 mt) alternative with episodic events modeled at 5% (A), 7.5% (B) and 12.5% (C) likelihood of occurrence in a year. The scatterplots show the greatest (blue), median (gray), and least (green) loss in fitness for each iteration over the 90-year period.

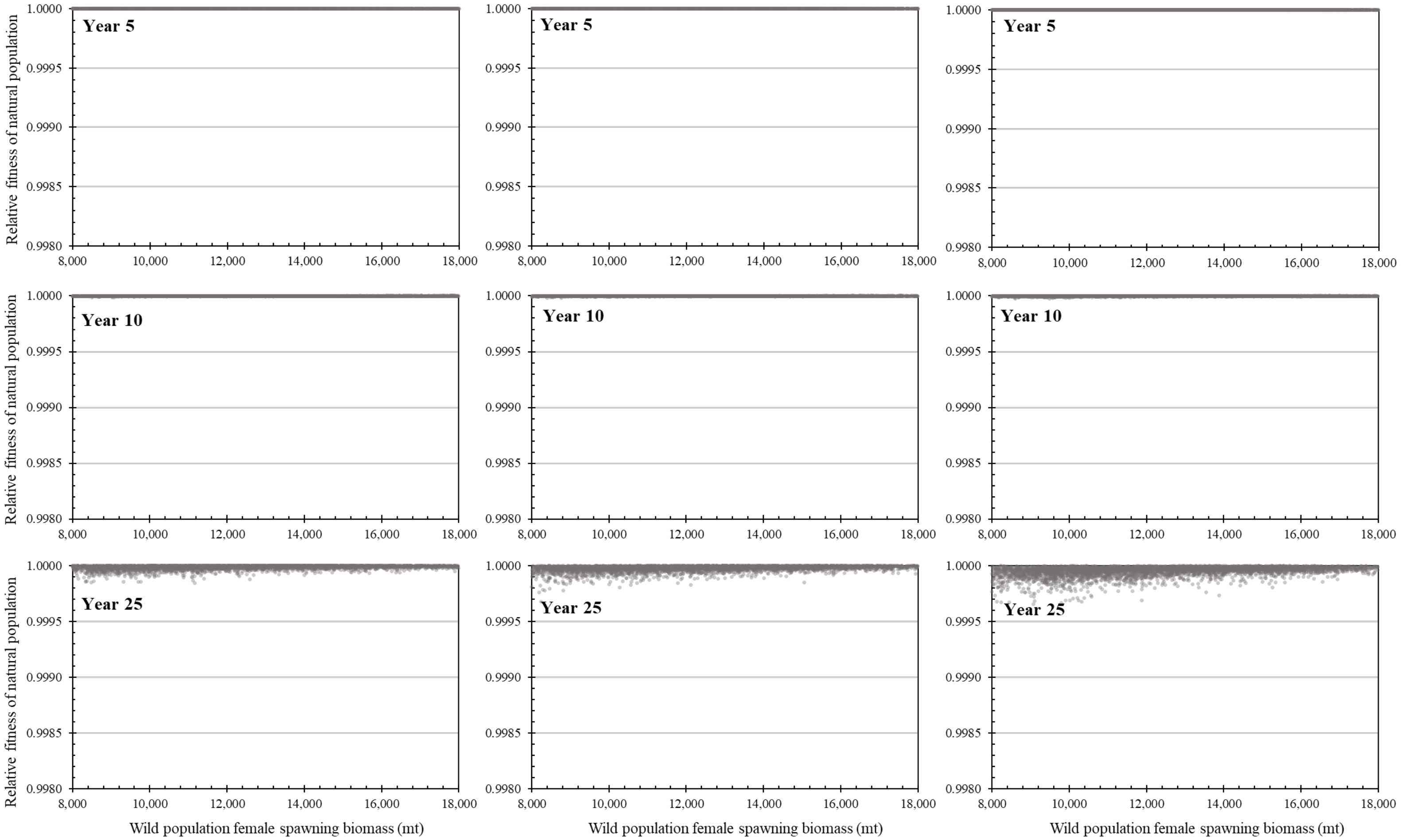


Figure 7.18. Short-term relative fitness effects under the full production (5,000 mt) alternative in Year 5, Year 10, and Year 25. Episodic events were modeled at 10% (left), 15% (middle), and 25% (right) likelihood of occurrence in a year.

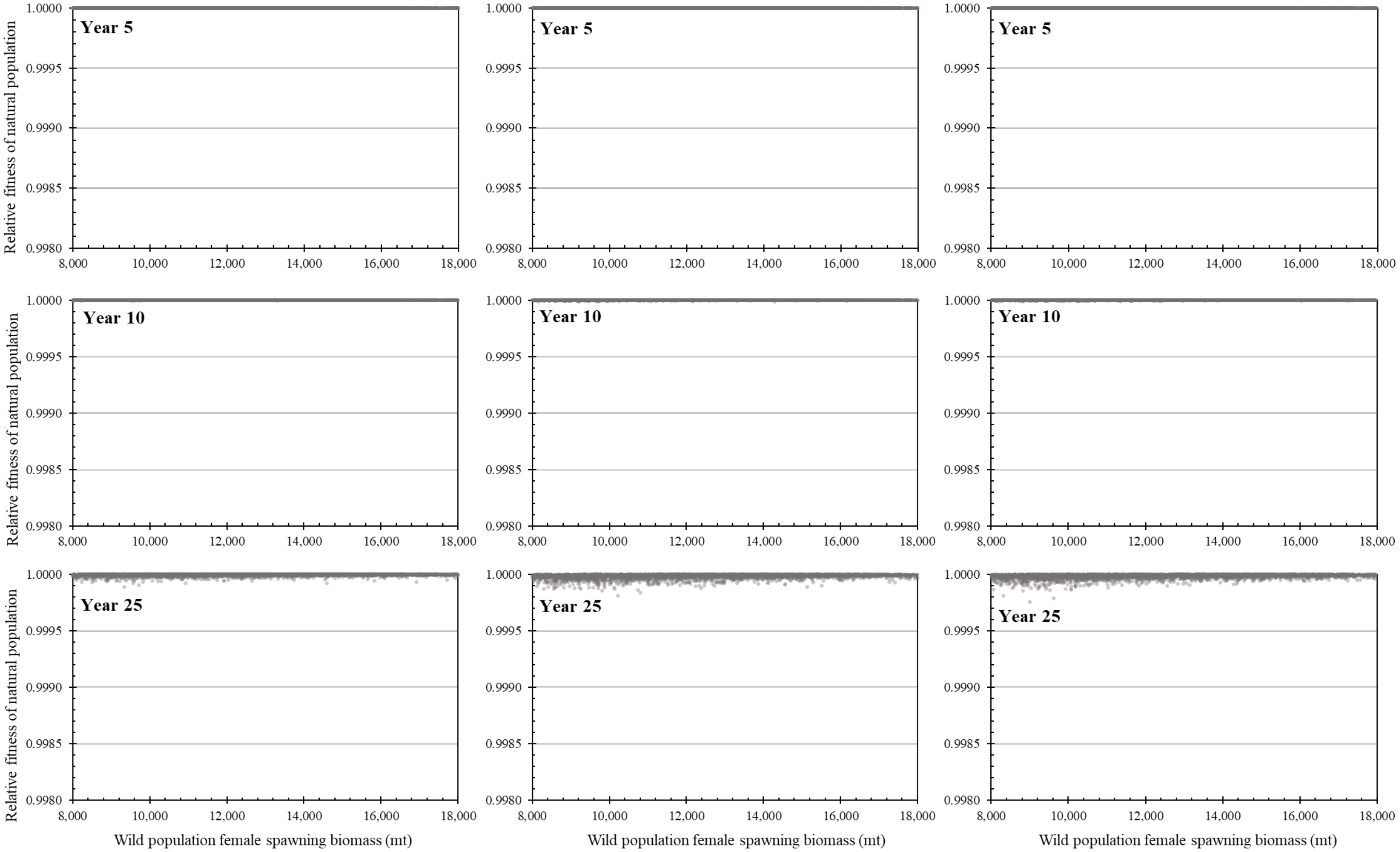


Figure 7.19. Short-term relative fitness effects under the half production (2,500 mt) alternative in Year 5, Year 10, and Year 25. Episodic events were modeled at 5% (left), 7.5% (middle), and 12.5% (right) likelihood of occurrence in a year.

7.1.3.2 Genetic Diversity Impacts on the Wild Conspecific Population

The potential for reduction in N_e is presented in Figure 7.20 with 10% likelihood of cage failure under the full production alternative and 5% likelihood of cage failure under the half production alternative. Results with 15% (full production) and 7.5% (half production) likelihood are presented in Figure 7.21 and 25% (full production) and 12.5% (half production) likelihood in Figure 7.22. Presented in each figure are results for the low and high population size (female spawning biomass) used in the previous tables and figures and the median value. For example, the proportion of cultured fish in the spawning biomass at the upper range represents the lower population abundance.

At the lowest cage failure frequency (Figure 7.20), in year 5 of the simulation, few cage failures had occurred, but by year 25, there were a handful of simulations that resulted in a relatively high proportion of cultured fish in the wild population under the full production alternative. Under the half production alternative, a similar pattern was not found at the lower cage failure frequency. For both the full- and half-scale production alternative, impacts grow with increasing cage failure frequency, nevertheless in all three cage failure scenarios, the results do not indicate a substantial loss of genetic diversity when comparing N_{eT} against the general rule-of-thumb that N_e greater than 5,000 fish is sufficient to avoid deleterious effects of small N_e. It is important to note that across all cage failure frequencies, the cultured fish spawning with wild California Yellowtail in year 25 were from multiple years of cultured fish escaping and thus the calculated N_{eT} may be a low estimate, as parents of these fish would include wild broodstock collected over multiple years (i.e., have a higher N_{eC} than calculated in the modified Ryman-Laikre model). However, Waples et al. (2012) also recommended that proportional reductions in N_{eW} (i.e., N_{eT}/N_{eW}) be considered in large marine populations and values less than 0.1 may have Ryman-Laikre effects. Proportional reductions in N_{eW} at the highest likelihood of cage failure are approaching a level where potential Ryman-Laikre effects may occur in the mixed population (Figure 7.22).

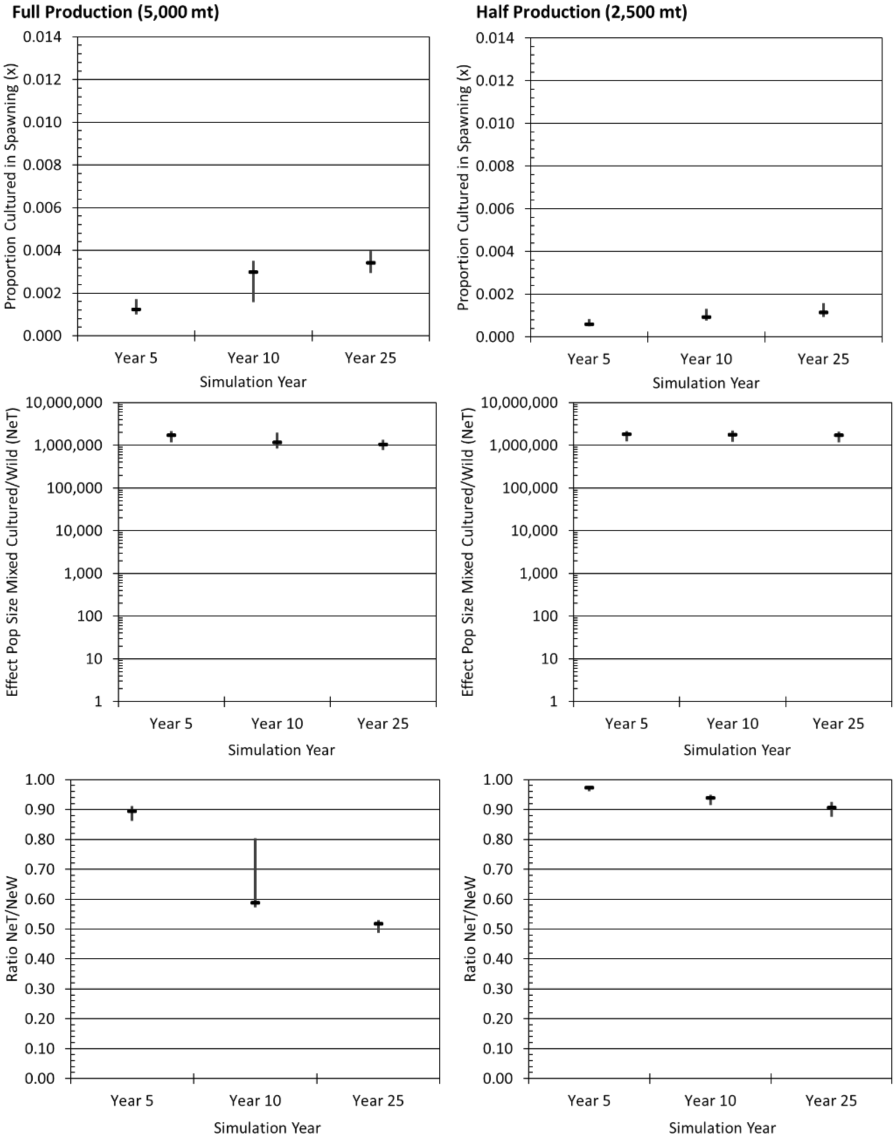


Figure 7.20. Short-term potential reduction in effective population size with Scenario I assumptions under the full production (5,000 mt) alternative (left) and half production (2,500 mt) alternative (right) in Year 5, Year 10, and Year 25. Episodic events were modeled at 10% likelihood of occurrence in a year under full production and 5% likelihood under half production.

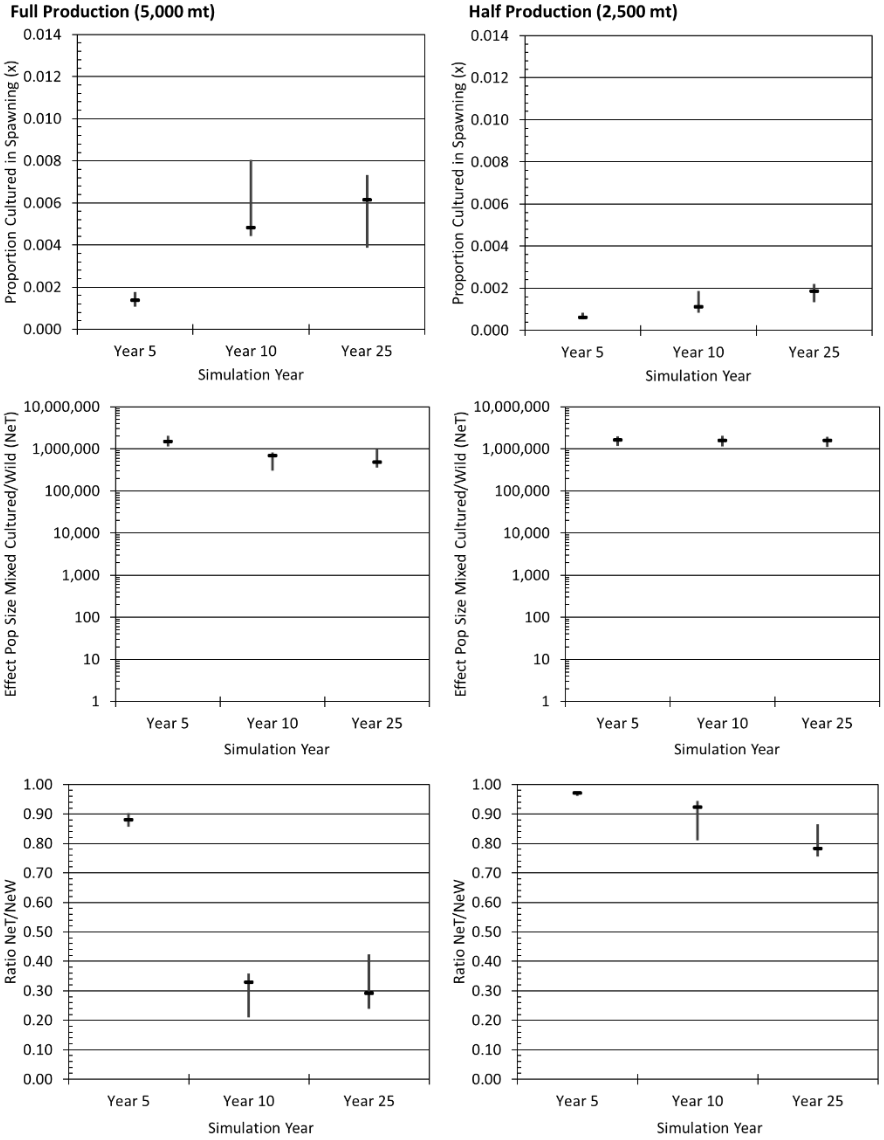


Figure 7.21. Short-term potential reduction in effective population size with Scenario I assumptions under the full production (5,000 mt) alternative (left) and half production (2,500 mt) alternative (right) in Year 5, Year 10, and Year 25. Episodic events were modeled at 15% likelihood of occurrence in a year under full production and 7.5% likelihood under half production.

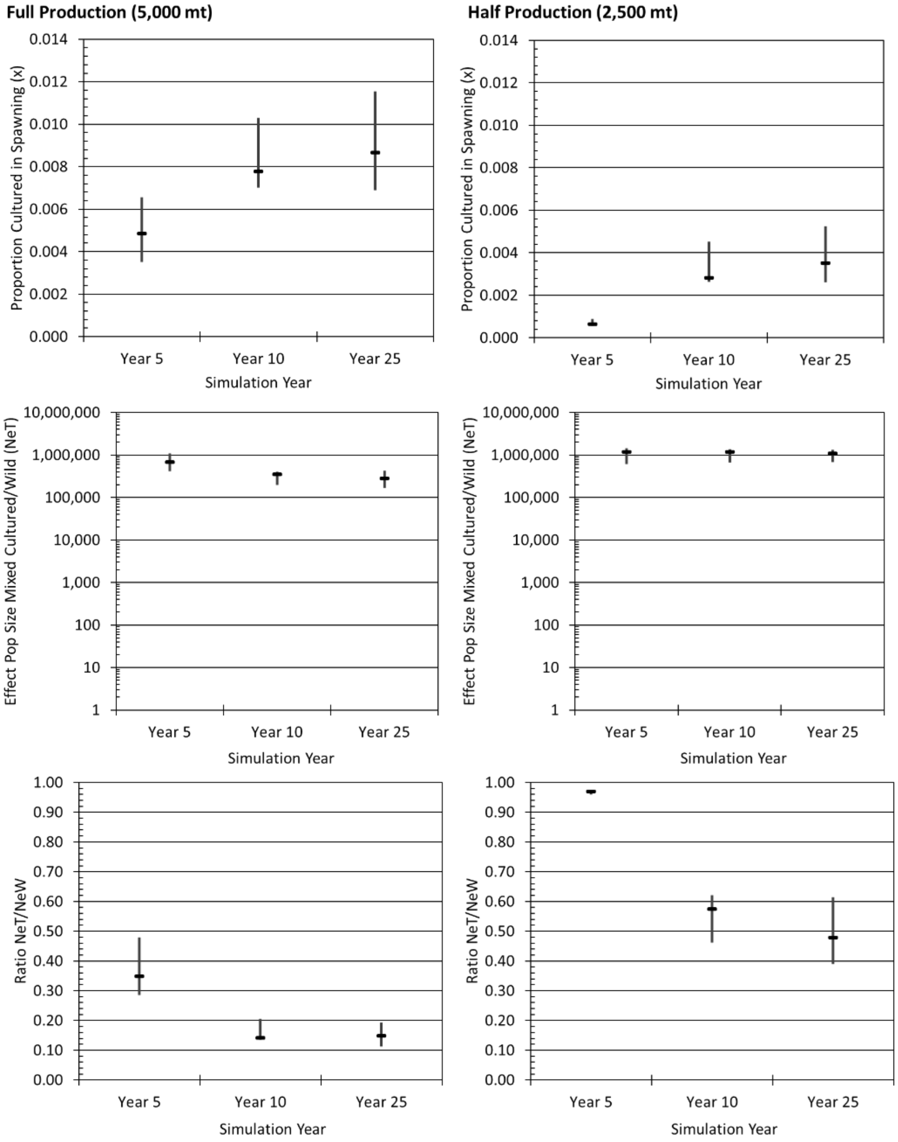


Figure 7.22. Short-term potential reduction in effective population size with Scenario I assumptions under the full production (5,000 mt) alternative (left) and half production (2,500 mt) alternative (right) in Year 5, Year 10, and Year 25. Episodic events were modeled at 25% likelihood of occurrence in a year under full production and 12.5% likelihood under half production.

7.2 Large Scale Escape Event: Scenario II

The impacts from the large-scale escape event scenario are distinct from impacts predicted by leakage and episodic escape scenarios and are therefore modeled separately as Scenario II. A large-scale escape event was modeled as a single occurrence as our analysis assumes a stop to operations following a catastrophic loss of this scale. How long before operations may be restarted after a large-scale event is unknown. Our analysis considered this a onetime event within the 25-year time frame of our analysis. The large-scale escape simulations reflect a remote case scenario; however, the analysis is performed as a due diligence evaluation to predict potential effects on the wild population under this scenario. For full production, the large-scale escape assumes the loss of all fish from two grids (28 pens), with no recapture of escaped fish. At half production, all fish are assumed to escape from one grid (14 pens), again with no recapture of escaped fish.

The size of fish at the time of escape affects the outcomes from escape events due to varying size-specific survival rates and differing amounts of time from escape to sexual maturity. To capture the range of outcomes, impacts were assessed by modeling fish at three points in time over the production cycle that reflect when fish are skewed towards a greater number of smaller fish on station, a greater number of larger fish on station, and a more even distribution of fish sizes on station (hereafter referred to as small-size skewed, large-size skewed, and evenly-sized fish distribution, respectively).

7.2.1 Full Production Alternative

Under Scenario II at full production, between 2,028,338 (large-size skewed fish distribution) and 2,731,522 (small-size skewed fish distribution) may escape from the 28 pens following a large-scale escape event (Table 7.13). Size-specific mortality is applied to the number of fish escaping to predict the number of fish that may enter the population following the initial escape. The number entering ranges from 1,436,755 (large-size skewed fish distribution) to 1,742,429 (small-size skewed fish distribution).

The number of cultured fish in the wild population was simulated for periods of time following the initial escape event; the first two periods reflect 5-year increments, while the last two periods reflect 10-year increments (Table 7.13). The range in the number of cultured fish during each period represents the beginning and ending years of that period (e.g., during the one to five years post-escape period for the evenly-sized fish distribution, 1,055,492 cultured fish were estimated to be in the population one year after the escape, while 305,151 were estimated to be in the population five years after the escape). The number of cultured fish in the population decreases over time following the escape event, and at five years post-escape, less than 15% of the escaped cultured fish are expected to remain in the wild population, at ten years post-escape less than 3.2%, and at twenty years post-escape less than 0.07% of the escaped fish remain in the population regardless of the initial size-distribution (based on the highest percentage from the three fish size distributions for each period).

Table 7-13. Number fish escaping, number entering population, and number surviving in the population post escape with a large-scale escape event (Scenario II) under the full production (5,000 mt) alternative.

Model Scenario: Full Production, Large-scale escape event	Number of fish escaping	Number of fish entering population (includes size-specific mortality)	Number of cultured fish in population - Median	Number of cultured fish in population - Range during period	
Large-scale evenly-sized fish distribution					
Initial escape	2189863	1441088			
1 to 5 years post-escape			569657	1055492	305151
6 to 10 years post-escape			121251	224910	64647
11 to 20 years post-escape			11793	47368	1196
21 to 30 years post-escape			0	878	0
Large-scale small-size skewed fish distribution					
Initial escape	2731522	1742429			
1 to 5 years post-escape			693750	1277144	371146
6 to 10 years post-escape			146555	272325	79116
11 to 20 years post-escape			14183	57728	1790
21 to 30 years post-escape			0	1301	0
Large-scale large-size skewed fish distribution					
Initial escape	2028338	1436755			
1 to 5 years post-escape			563293	1049657	301583
6 to 10 years post-escape			119865	221833	63755
11 to 20 years post-escape			11802	46722	599
21 to 30 years post-escape			0	440	0

Table 7-14 (evenly sized fish distribution), Table 7.15 (small-size skewed fish distribution), and Table 7.16 (large-size skewed fish distribution) present the percentages of escaped fish as a proportion of the population biomass and spawning abundance over the four periods following a large-scale escape event at full production.

For the evenly sized fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 11.6% and 7.4%, and between 17.6% and 11.0% in the spawning abundance from the smallest to largest modeled wild population sizes (Table 7.14). In the first five years, maximum values of evenly sized cultured fish in the population biomass ranged between 12.1% and 7.7%, and in the spawning abundance between 18.7% and 11.6%, again across the female biomass range. Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of six to ten years post-escape (8.1% to 5.1% and 4.5% to 2.8%, respectively), 11 to 20 years (1.4% to 0.9% and 0.4% to 0.3%, respectively), and by the 21-to-30-year period, all percentages were 0.0%.

Table 7-14. The percentage cultured fish in population biomass and spawning abundance (male and female) under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario II) and evenly sized fish escaping.

Model scenario		Small-size skewed fish distribution - Percentage of population biomass that are cultured fish			Small-size skewed fish distribution - Percentage of population spawning abundance that are cultured fish		
Full production at 5,000 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	11.6%	12.1%	8.1%	17.6%	18.7%	10.7%
	10,000 to 12,000	10.1%	10.5%	6.9%	15.2%	16.1%	9.1%
	12,000 to 14,000	8.9%	9.3%	6.0%	13.2%	14.0%	7.9%
	14,000 to 16,000	7.9%	8.3%	5.2%	11.6%	12.3%	6.9%
	16,000 to 18,000	7.4%	7.7%	4.8%	11.0%	11.6%	6.5%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	8.1%	10.7%	5.5%	4.5%	8.1%	2.5%
	10,000 to 12,000	6.9%	9.3%	4.7%	3.8%	6.9%	2.1%
	12,000 to 14,000	6.0%	8.1%	4.0%	3.2%	5.9%	1.8%
	14,000 to 16,000	5.4%	7.2%	3.6%	2.8%	5.2%	1.6%
	16,000 to 18,000	5.1%	6.8%	3.5%	2.8%	4.9%	1.5%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	1.4%	4.4%	0.3%	0.4%	1.8%	0.1%
	10,000 to 12,000	1.2%	3.7%	0.3%	0.4%	1.5%	0.1%
	12,000 to 14,000	1.0%	3.2%	0.2%	0.3%	1.3%	0.1%
	14,000 to 16,000	0.9%	2.8%	0.2%	0.3%	1.2%	0.1%
	16,000 to 18,000	0.9%	2.8%	0.2%	0.3%	1.1%	0.1%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%

For the small-size skewed fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 12.8% and 8.3%, and in the spawning abundance between 18.3% and 11.6% from the smallest to largest modeled wild population sizes (Table 7-15). In the first five years, maximum values of small-size skewed cultured fish in the population biomass ranged between 13.3% and 8.7%, and in the spawning abundance between 20.5% and 13.0%, again across the female biomass range. Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of six to ten years post-escape (9.4% to 6.0% and 5.4% to 3.3%, respectively), 11 to 20 years (1.7% to 1.0% and 0.6% to 0.3%, respectively), and by the 21-to-30-year period, all percentages were 0.0%.

Table 7-15. The percentage cultured fish in population biomass and spawning abundance under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario II) and small-size skewed fish escaping.

Model scenario		Small-size skewed fish distribution - Percentage of population biomass that are cultured fish			Small-size skewed fish distribution - Percentage of population spawning abundance that are cultured fish		
Full production at 5,000 mt		Median	Range during period		Median	Range during period	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	12.8%	13.3%	8.2%	18.3%	20.5%	12.7%
	10,000 to 12,000	11.0%	11.5%	7.1%	15.8%	17.7%	10.8%
	12,000 to 14,000	9.7%	10.2%	6.1%	13.8%	15.5%	9.3%
	14,000 to 16,000	8.9%	9.3%	5.6%	12.4%	13.9%	8.3%
	16,000 to 18,000	8.3%	8.7%	5.1%	11.6%	13.0%	7.9%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	9.4%	12.1%	6.4%	5.4%	9.6%	3.0%
	10,000 to 12,000	8.0%	10.4%	5.5%	4.6%	8.1%	2.5%
	12,000 to 14,000	7.0%	9.2%	4.7%	3.9%	7.0%	2.1%
	14,000 to 16,000	6.3%	8.3%	4.2%	3.4%	6.2%	1.9%
	16,000 to 18,000	6.0%	7.8%	4.0%	3.3%	5.9%	1.8%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	1.7%	5.2%	0.4%	0.6%	2.2%	0.1%
	10,000 to 12,000	1.4%	4.4%	0.3%	0.5%	1.8%	0.1%
	12,000 to 14,000	1.2%	3.8%	0.3%	0.4%	1.6%	0.1%
	14,000 to 16,000	1.1%	3.4%	0.3%	0.4%	1.4%	0.1%
	16,000 to 18,000	1.0%	3.2%	0.3%	0.3%	1.3%	0.1%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%
	10,000 to 12,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%

For the large-size skewed fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 13.0% and 8.5%, and in the spawning abundance between 17.8% and 11.3% from the smallest to largest modeled wild population sizes (Table 7-16). In the first five years, maximum values of large sized escaped cultured fish in the population biomass ranged between 13.7% to 9.1%, and between 23.2% and 15.0% of the spawning abundance, again across the female biomass range. Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of six to ten years post-escape (8.5% to 5.4% and 4.4 to 2.7%, respectively), 11 to 20 years (1.4% to 0.8% and 0.5% to 0.3%, respectively), and again by the 21-to-30-year period, all percentages were 0.0%.

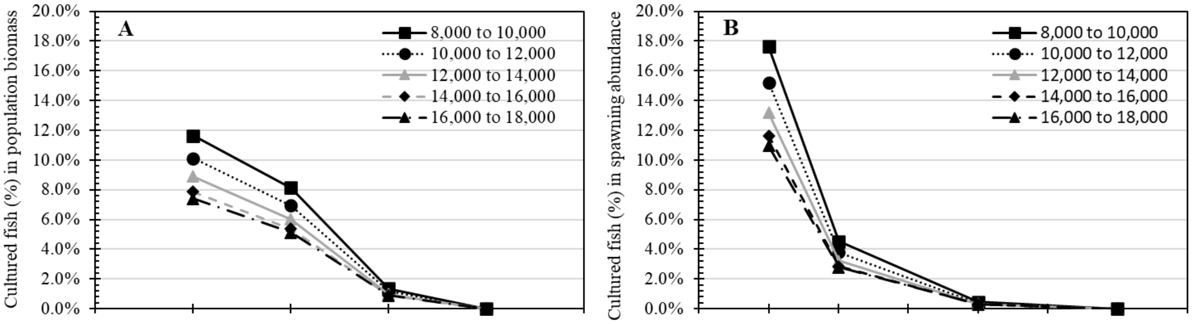
Table 7-16. The percentage cultured fish in population biomass and spawning abundance under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario II) and large-size skewed fish escaping.

Model scenario		Large-size skewed fish distribution - Percentage of population biomass that are cultured fish			Large-size skewed fish distribution - Percentage of population spawning abundance that are cultured fish		
Full production at 5,000 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	13.0%	13.7%	11.0%	17.8%	23.2%	10.6%
	10,000 to 12,000	11.6%	12.3%	9.8%	15.5%	20.5%	9.1%
	12,000 to 14,000	10.1%	10.8%	8.5%	13.3%	17.8%	7.8%
	14,000 to 16,000	9.1%	9.6%	7.6%	11.9%	15.9%	6.9%
	16,000 to 18,000	8.5%	9.1%	7.1%	11.3%	15.0%	6.6%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	8.5%	11.5%	5.6%	4.4%	8.0%	2.4%
	10,000 to 12,000	7.3%	10.1%	4.9%	3.8%	6.8%	2.1%
	12,000 to 14,000	6.4%	8.8%	4.2%	3.2%	5.8%	1.8%
	14,000 to 16,000	5.6%	7.8%	3.7%	2.8%	5.1%	1.5%
	16,000 to 18,000	5.4%	7.5%	3.5%	2.7%	4.9%	1.5%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	1.4%	4.4%	0.3%	0.5%	1.8%	0.1%
	10,000 to 12,000	1.2%	3.9%	0.2%	0.4%	1.5%	0.1%
	12,000 to 14,000	1.0%	3.3%	0.2%	0.3%	1.3%	0.1%
	14,000 to 16,000	0.9%	2.9%	0.2%	0.3%	1.1%	0.1%
	16,000 to 18,000	0.8%	2.7%	0.2%	0.3%	1.1%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

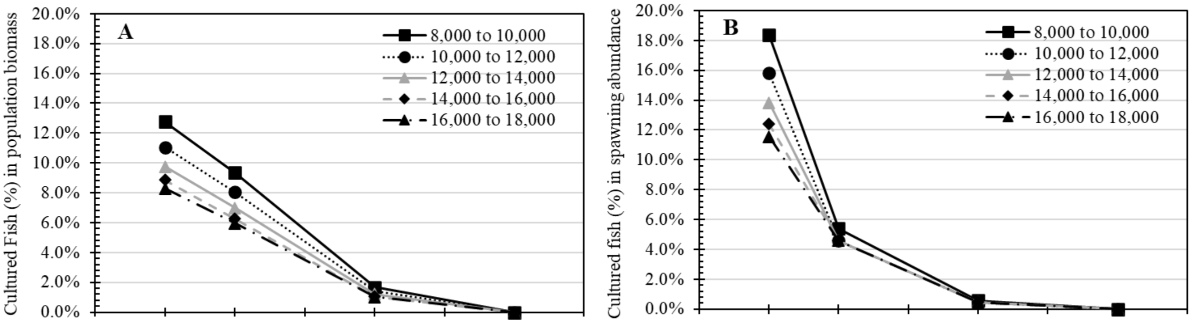
In Figure 7.23, it is apparent that the percentage of escaped fish initially make up a much larger proportion of the spawning abundance compared to the population biomass. However, in the later time periods, it appears that this proportion also declines more rapidly in the spawning abundance than in the population biomass. This is due to the difference in the population biomass (weight-based) and spawning abundance (number-based) metrics. The escaped fish reach sexual maturity within 1-2 years after escape (within the initial 5-year time period) and are counted in the spawning abundance, however, over time, mortality is also reducing the total number of cultured fish within the spawning abundance. At the same time, those surviving escaped fish are also increasing in size, so the decreasing proportion of escaped fish in the population biomass is partially offset by their growth and is not reduced at the same rate as the spawning abundance.

The modeled range of the female spawning biomass (in metric tons) is also shown for each period. Cultured fish from a large-scale escape event make up a substantial portion of both the population biomass and spawning abundance for the lower wild population estimates.

Even-sized fish distribution



Small-skewed size fish distribution



Large-skewed size fish distribution

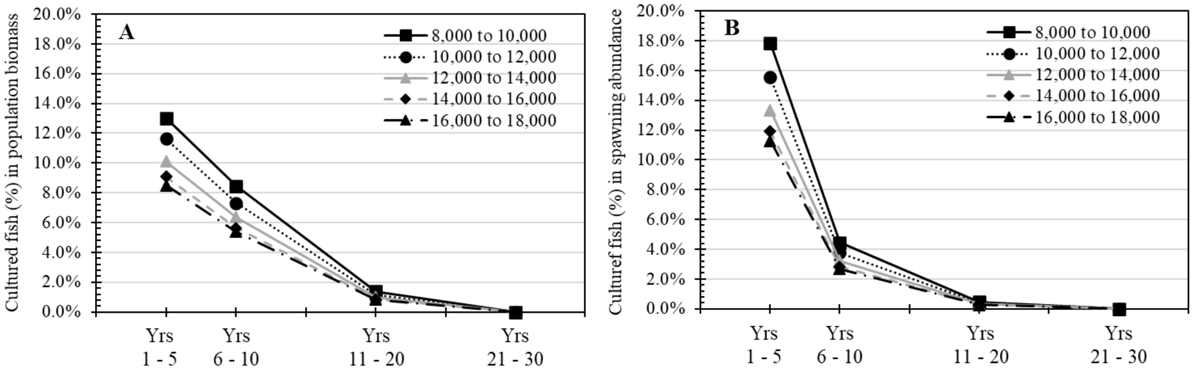


Figure 7.23. The percentage of cultured fish at full-scale production (5,000 mt) in the population biomass (left) and spawning abundance (right) following a large-scale escape (Scenario II). Shown are percentages over the range of female spawning biomass (in metric tons) by period.

7.2.2 Half Production Alternative

Under Scenario II at half production, between 1,014,170 (large sized skewed fish distribution) and 1,365,761 (small sized skewed fish distribution) may escape from the 14 pens (one grid) following a large-scale escape event (Table 7.17). Size-specific mortality is applied to the number of fish escaping to predict the number of fish that may enter the population following the initial escape; this ranges from 718,378 (large-size skewed fish distribution) to 871,214 fish (small sized skewed fish distribution).

The number of cultured fish in the wild population was simulated for periods of time following the initial escape event; the first two periods reflect 5-year increments, while the last two periods reflect 10-year increments. The range in the number of cultured fish during each period (Table 7.17) represents the beginning and ending years of that period (e.g., during the one to five years post-escape period for the evenly-sized fish distribution, 526,344 cultured fish were estimated in the population one year after the escape, while 153,161were estimated in the population five years after the escape). As with the full-scale alternative, the number of cultured fish in the population decreases over time from the escape event, and at five years post-escape, 15%, or fewer, of the escaped cultured fish are expected to remain in the wild population, at ten years post-escape less than 3.2%, and at twenty years post-escape less than 0.07% of the escaped fish remain in the population regardless of the initial size-distribution (based on the highest percentage from the three fish size distributions for each period).

Table 7-17. Number fish escaping, number entering population, and number surviving in the population post escape with large scale escape (Scenario II) under the half production (2,500 mt) alternative.

Model Scenario: Half Production, Large-scale escape event	Number of fish escaping	Number of fish entering population (includes size-specific mortality)	Number of cultured fish in population-Median	Number of cultured fish in population- Range during period	
Large-scale evenly sized fish distribution					
Initial escape	1094933	720545			
1 to 5 years post-escape			285316	526344	153161
6 to 10 years post-escape			60776	112414	32672
11 to 20 years post-escape			6039	23888	616
21 to 30 years post-escape			0	451	0
Large-scale small-size skewed fish distribution					
Initial escape	1365761	871214			
1 to 5 years post-escape			346718	637810	185928
6 to 10 years post-escape			73380	135793	39352
11 to 20 years post-escape			7228	28773	890
21 to 30 years post-escape			0	650	0
Large-scale large-size skewed fish distribution					
Initial escape	1014170	718378			
1 to 5 years post-escape			283617	525436	152185
6 to 10 years post-escape			60466	111916	32361
11 to 20 years post-escape			5948	23718	302
21 to 30 years post-escape			0	221	0

Table 7-18 (evenly sized fish distribution), Table 7.19 (small sized skewed fish distribution), and Table 7.20 (large sized skewed fish distribution) present the percentages of escaped fish as a proportion of the population biomass and spawning abundance over the four periods following a large-scale escape event at half production.

For the evenly sized fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 6.6% and 4.0%, and in the spawning abundance between 9.7% and 5.8% from the smallest to largest modeled wild population sizes (Table 7.18 and Table 7-14). In the first five years, maximum values of evenly sized cultured fish in the population biomass ranged between 6.9% and 4.2%, and in the spawning abundance between 10.3% and 6.2%, again across the female biomass range. Median percentages of cultured fish in the population biomass and spawning abundance decreased during the periods of six to ten years post-escape (4.4 to 2.7% and 2.3 to 1.4%, respectively), 11 to 20 years (0.7 to 0.4% and 0.2 to 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0%.

Table 7-18. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half production (2,500 mt) alternative with a large-scale escape event (Scenario II) and evenly sized fish escaping.

Model scenario		Evenly sized fish distribution-Percentage of population biomass that are cultured fish			Evenly sized fish distribution-Percentage of population spawning abundance that are cultured fish		
Half production at 2,500 mt		Median	Range during period		Median	Range during period	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	6.6%	6.9%	4.3%	9.7%	10.3%	5.6%
	10,000 to 12,000	5.6%	5.9%	3.7%	8.2%	8.8%	4.8%
	12,000 to 14,000	4.8%	5.1%	3.2%	7.1%	7.5%	4.1%
	14,000 to 16,000	4.3%	4.5%	2.8%	6.3%	6.7%	3.6%
	16,000 to 18,000	4.0%	4.2%	2.6%	5.8%	6.2%	3.4%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	4.4%	6.0%	2.9%	2.3%	4.2%	1.2%
	10,000 to 12,000	3.8%	5.2%	2.5%	1.9%	3.6%	1.1%
	12,000 to 14,000	3.2%	4.4%	2.1%	1.7%	3.0%	0.9%
	14,000 to 16,000	2.9%	3.9%	1.9%	1.5%	2.7%	0.8%
	16,000 to 18,000	2.7%	3.7%	1.8%	1.4%	2.5%	0.8%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.7%	2.3%	0.2%	0.2%	0.9%	0.1%
	10,000 to 12,000	0.6%	2.0%	0.1%	0.2%	0.8%	0.0%
	12,000 to 14,000	0.5%	1.7%	0.1%	0.2%	0.7%	0.0%
	14,000 to 16,000	0.4%	1.5%	0.1%	0.1%	0.6%	0.0%
	16,000 to 18,000	0.4%	1.4%	0.1%	0.1%	0.6%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

For the small sized skewed fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 7.3% and 4.6%, and in the spawning abundance between 10.1% and 6.3% from the smallest to largest modeled wild population sizes (Table 7.19). In the first five years, maximum values of small sized skewed cultured fish in the population biomass ranged between 7.7% and 4.8%, and in the spawning abundance between 11.4% and 7.1%, again across the female biomass range. Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to10 years post-escape (5.1% to 3.2% and 2.7% to 1.7%, respectively), 11 to 20 years (0.8% to 0.5% and 0.3% to 0.2%, respectively), and by the 21-to-30-year period, all percentages were 0.0%.

Table 7-19. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half production (2,500 mt) alternative with a large-scale escape event (Scenario II) and small-size skewed fish escaping.

Model scenario		Small-size skewed fish distribution- Percentage of population biomass that are cultured fish			Small-size skewed fish distribution- Percentage of population spawning abundance that are cultured fish		
Half production at 2,500 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	7.3%	7.7%	4.5%	10.1%	11.4%	6.8%
	10,000 to 12,000	6.3%	6.6%	3.8%	8.6%	9.7%	5.8%
	12,000 to 14,000	5.5%	5.8%	3.4%	7.5%	8.5%	4.9%
	14,000 to 16,000	4.9%	5.1%	2.9%	6.6%	7.5%	4.3%
	16,000 to 18,000	4.6%	4.8%	2.8%	6.3%	7.1%	4.1%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	5.1%	6.8%	3.4%	2.7%	5.0%	1.5%
	10,000 to 12,000	4.4%	5.9%	3.0%	2.4%	4.3%	1.3%
	12,000 to 14,000	3.8%	5.2%	2.5%	2.0%	3.7%	1.1%
	14,000 to 16,000	3.4%	4.6%	2.2%	1.8%	3.2%	1.0%
	16,000 to 18,000	3.2%	4.2%	2.1%	1.7%	3.0%	0.9%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.8%	2.7%	0.2%	0.3%	1.1%	0.1%
	10,000 to 12,000	0.7%	2.3%	0.2%	0.2%	0.9%	0.1%
	12,000 to 14,000	0.6%	2.0%	0.2%	0.2%	0.8%	0.0%
	14,000 to 16,000	0.5%	1.8%	0.1%	0.2%	0.7%	0.0%
	16,000 to 18,000	0.5%	1.6%	0.1%	0.2%	0.7%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

For the large sized skewed fish distribution, in the first five years the median percentage of cultured fish in the population biomass ranged between 7.6% and 4.8%, and in the spawning abundance between 9.8% and 6.0% from the smallest to largest modeled wild population sizes (Table 7.20). In the first five years, maximum values of large sized skewed cultured fish in the population biomass ranged between 8.1% and 5.1%, and in the spawning abundance between 13.2% and 8.3%, again across the female biomass range. Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (4.6% to 2.8% and 2.3% to 1.4%, respectively), 11 to 20 years (0.7% to 0.4% and 0.2% to 0.1%, respectively), and again by the 21-to-30-year period, all percentages were 0.0%.

Table 7-20. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half production (2,500 mt) alternative with a large-scale escape event (Scenario II) and large-size skewed fish escaping.

Model scenario		Large-size skewed fish distribution- Percentage of population biomass that are cultured fish			Large-size skewed fish distribution- Percentage of population spawning abundance that are cultured fish		
Half production at 2,500 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	7.6%	8.1%	6.3%	9.8%	13.2%	5.6%
	10,000 to 12,000	6.4%	6.9%	5.3%	8.3%	11.2%	4.8%
	12,000 to 14,000	5.7%	6.1%	4.7%	7.3%	9.9%	4.1%
	14,000 to 16,000	5.0%	5.3%	4.1%	6.3%	8.7%	3.6%
	16,000 to 18,000	4.8%	5.1%	3.9%	6.0%	8.3%	3.4%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	4.6%	6.5%	3.0%	2.3%	4.1%	1.2%
	10,000 to 12,000	4.0%	5.6%	2.6%	2.0%	3.6%	1.1%
	12,000 to 14,000	3.4%	4.8%	2.2%	1.7%	3.0%	0.9%
	14,000 to 16,000	3.0%	4.3%	1.9%	1.4%	2.6%	0.8%
	16,000 to 18,000	2.8%	4.0%	1.8%	1.4%	2.5%	0.7%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.7%	2.3%	0.1%	0.2%	0.9%	0.0%
	10,000 to 12,000	0.6%	2.0%	0.1%	0.2%	0.8%	0.0%
	12,000 to 14,000	0.5%	1.7%	0.1%	0.2%	0.7%	0.0%
	14,000 to 16,000	0.4%	1.5%	0.1%	0.1%	0.6%	0.0%
	16,000 to 18,000	0.4%	1.4%	0.1%	0.1%	0.5%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

In Figure 7.24, the difference between the percentage of cultured fish in the population biomass and spawning abundance is again apparent, with the cultured fish making up a larger percentage of the spawning abundance during the initial five-year period. Like the full production alternative, the decline of cultured fish in the spawning abundance over time is more rapid than for the population biomass. Again, this is due, in part, to the difference in the population biomass (weight-based) and spawning abundance (number-based) metrics. Variation in the modeled female spawning biomass range (in metric tons) is also shown for each period; cultured fish from a large-scale escape event make up a portion of both the population biomass and spawning abundance for the lower wild population estimates.

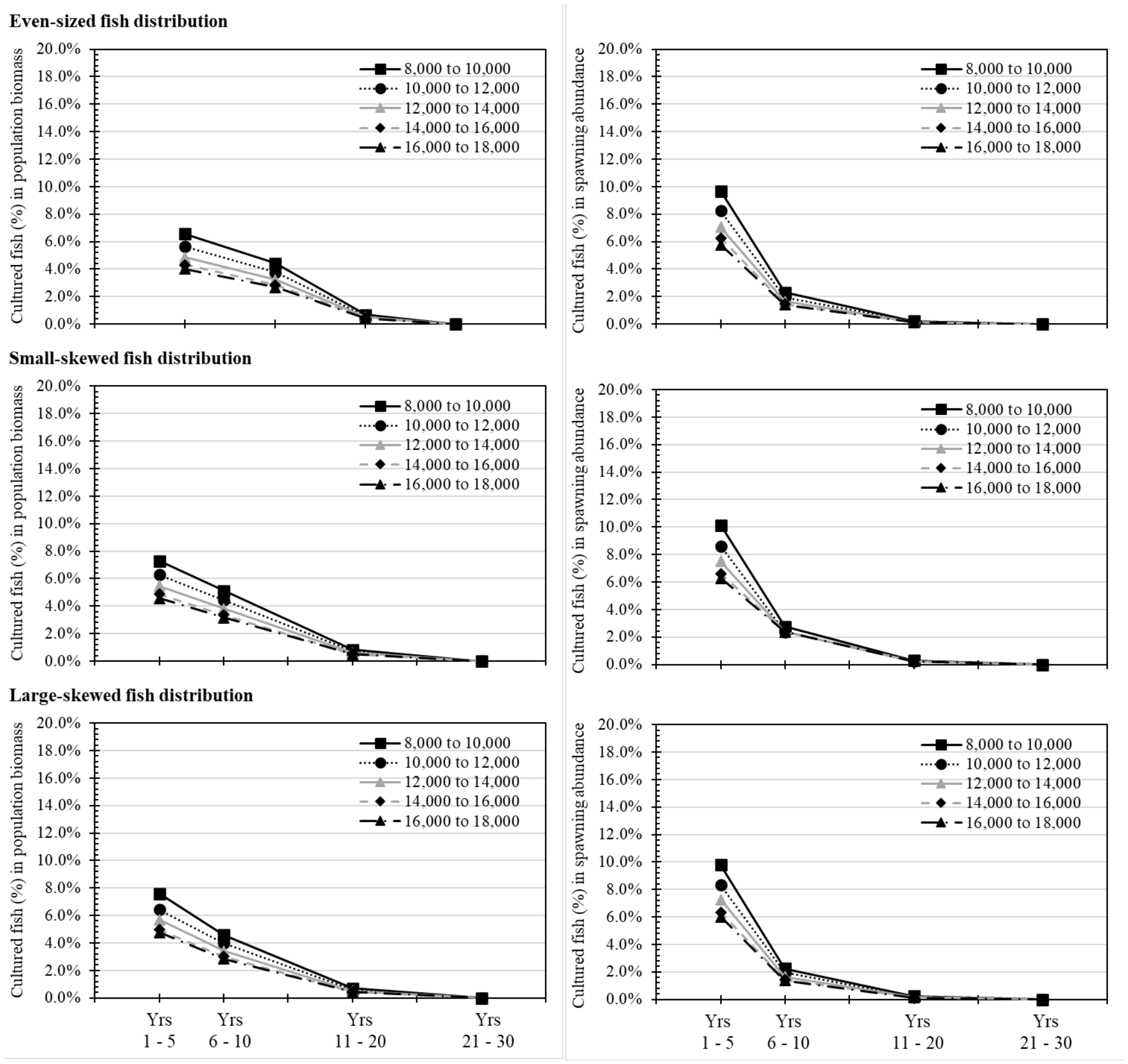


Figure 7.24. The percentage of cultured fish at half production (2,500 mt) in the population biomass (left) and spawning abundance (right) following a large-scale escape (Scenario II). Shown are percentages over the range of female spawning biomass (in metric tons) by period.

7.2.3 Impact Results

If the catastrophic scenario was to occur, between 2.2 and 2.7 million fish may escape from the cages, and after accounting for the initial size-specific mortality, between 1.43 and 1.74 million escaped fish may enter the population under the full-scale production alternative. Under the half-scale production alternative, between 1.1 and 1.4 million escaped fish may escape from the cages in this catastrophic scenario, with between 0.72 and 0.87 million fish entering the population. The number of fish potentially entering the ecosystem under this remote case scenario is why the impact from large-scale failures is included in the due diligence analysis and why it is modeled independently from the leakage and episodic cage failure scenarios.

7.2.3.1 Fitness Impacts on the Wild Conspecific Population

Following the large-scale loss event, relative fitness losses in the mixed population varied by the size distribution of the escaped fish, the size of the wild population, and the length of time following the escape event (Figure 7.25). However, the median relative loss of fitness did not exceed 0.0012 in these varied scenarios at full-scale production, and small responses in the relative fitness were reflected in the mixed population. Following the loss of fish at a time during the production cycle when the sizes of fish are evenly distributed (between small and large fish), the predicted relative fitness in the mixed population decreased from the initial period (approximately 0.9992 in Years 1-5) to the second period (approximately 0.9989 in Years 6-10), in the smallest modeled population range (8,000 – 10,000 mt female spawning biomass). This decline in relative fitness is due to the growth, sexual maturation, and increasing fecundity of the surviving smaller fish from the escape event. The relative fitness improved in subsequent time periods, and no fitness losses were detected by the last period (Years 21-30). For the larger modeled population sizes under the even-sized fish distribution, relative fitness losses were nearly undetectable (or at the original wild population fitness).

In the large-scale event scenario with the small-skewed fish distribution (meaning a greater number of smaller fish on station when the escape event occurred), the predicted median relative fitness again decreased from the initial period (0.9992 for the 8,000 – 10,000 mt female spawning biomass, and 0.9994 for the 10,000 – 12,000 mt female spawning biomass for Years 1-5) to the second period (approximately 0.9990 for both the 8,000 – 10,000 mt and 10,000 - 12,000 mt female spawning biomass in Years 6-10) (Figure 7.25). Again, this is due to the surviving small fish growing in size, becoming sexually mature, and increasing in fecundity over time in the mixed population. Following the second time period, the relative fitness losses lessened in subsequent intervals. Relative fitness in the smallest modeled size-range improved the most slowly, but fitness losses were no longer detected by the last time period (Years 21-30). For the larger population sizes, no relative fitness losses were detected.

For the large-skewed fish distribution scenario, the relative fitness in the smallest modeled population range (8,000 – 10,000 mt) was steady at 0.9990 for the first two time periods (Years 1-5 and 6-10) but improved to 0.9997 in Years 11-20 with no relative fitness loss detected in the mixed population by Years 21-30 (Figure 7.25). For the modeled population size range of

10,000-12,000 mt female spawning biomass, the relative fitness was approximately 0.9996 in the initial period (Years 1-5), but in subsequent time periods no relative fitness losses were detected. Under the large-skewed fish distribution scenario for the larger modeled population ranges, relative fitness losses were not detected.

For the large-scale escape scenarios in the half-scale production scenario, no relative fitness losses were detected across the modeled population size range or for the three size-distributions of fish at the time of escape (Figure 7.25).

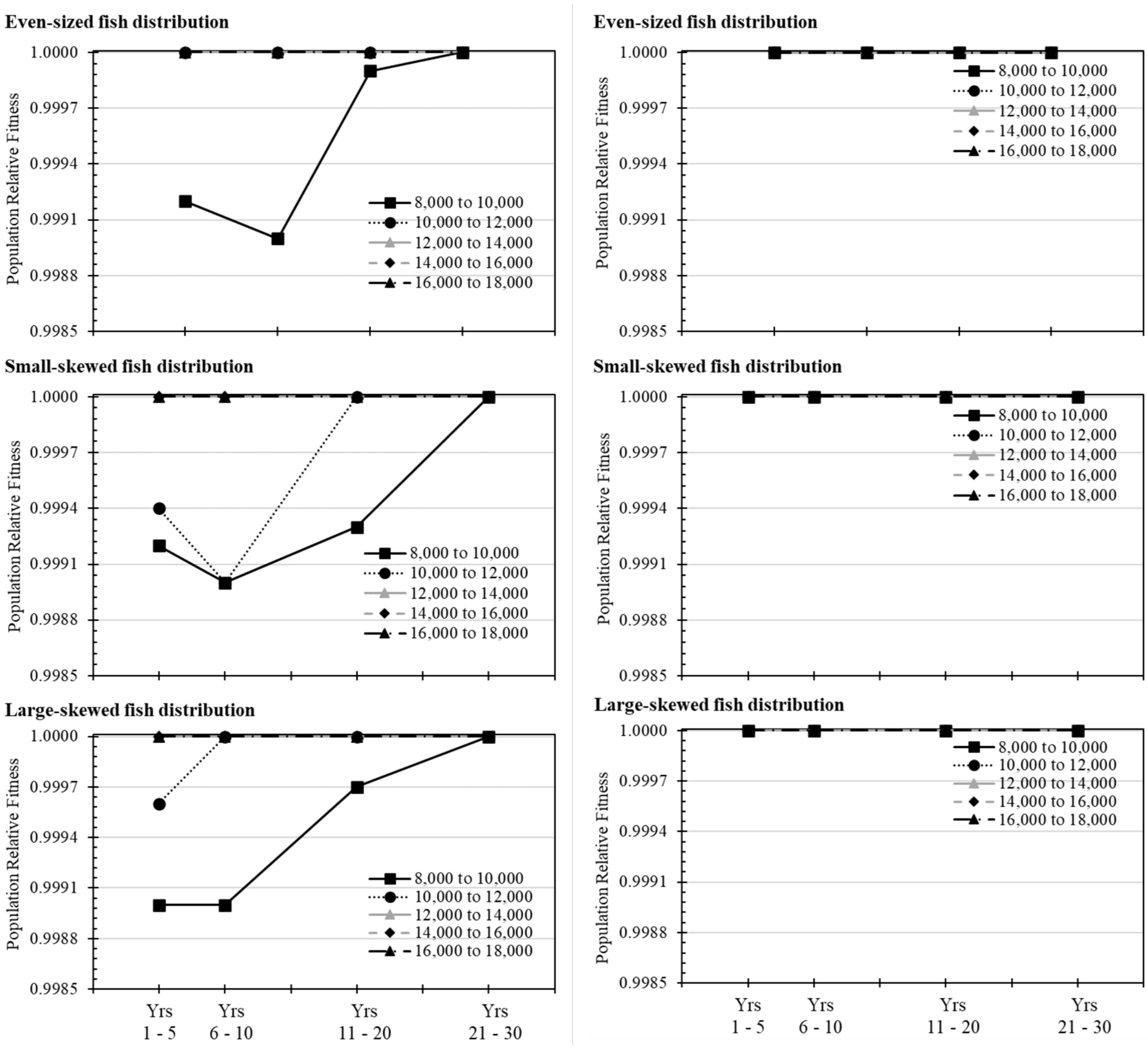


Figure 7.25. Relative fitness effects following a large-scale escape event (Scenario II) with full production (5,000 mt) on the left and half production (2,500 mt) on the right. Shown are relative fitness values over the range of female spawning biomass (in metric tons) by period.

7.2.3.2 Genetic Diversity Impacts on the Wild Conspecific Population

The potential for reduction in N_e is presented in Figure 7.26 following a large-scale escape event in brood years following the event. Like the cage failure analysis, presented are results for the low and high population sizes (female spawning biomass), used in the previous tables and figures, and the median value. For example, the proportion cultured in spawning at the upper range represents the lower population abundance in the first year where cultured fish are entering the breeding population. All simulations assume the large size skewed distribution of escaped fish for simplicity. Results did not vary substantially for the other size categories.

These simulations represent a single escape of a substantial number of cultured fish. In the four years immediately following the escape, the proportion of cultured fish in the admixed population exceeds 0.10, and the estimated N_{eT} in those years is less than the general rule-of-thumb of 5,000 effective spawners under the full production alternative. The calculated proportional decrease in N_e (N_{eT}/N_{eW}) is substantial (<<0.10) in multiple years. Potential Ryman-Laikre effects under the half production alternative are not as severe, but also suggest a potential reduction in N_e.

The concept and estimation of N_e and what it portends for the maintenance or loss of genetic diversity are among the most important and also most challenging concepts to model for a population (Waples 2022). These challenges similarly exist for this assessment. What is unknown is the mitigating effect of this large-scale loss occurring as a one-time event and the ongoing spawning contributions of multiple previous cohorts that were not subject to a Ryman-Laikre effect. In addition, the distribution of the escaped fish may not be uniform across the entire population, and as a result, the analyses may overestimate impacts on N_e. However, if a large-scale event were to occur following several years of smaller cage failures, those cohorts may also have a reduced genetic diversity as discussed in Section 7.1, *Leakage and Episodic Failure: Scenario I*. Consequently, in evaluating these results, it may be more important to consider the relative reduction of N_e and the timeframe for recovery rather than specific estimates of N_e following the escape event.

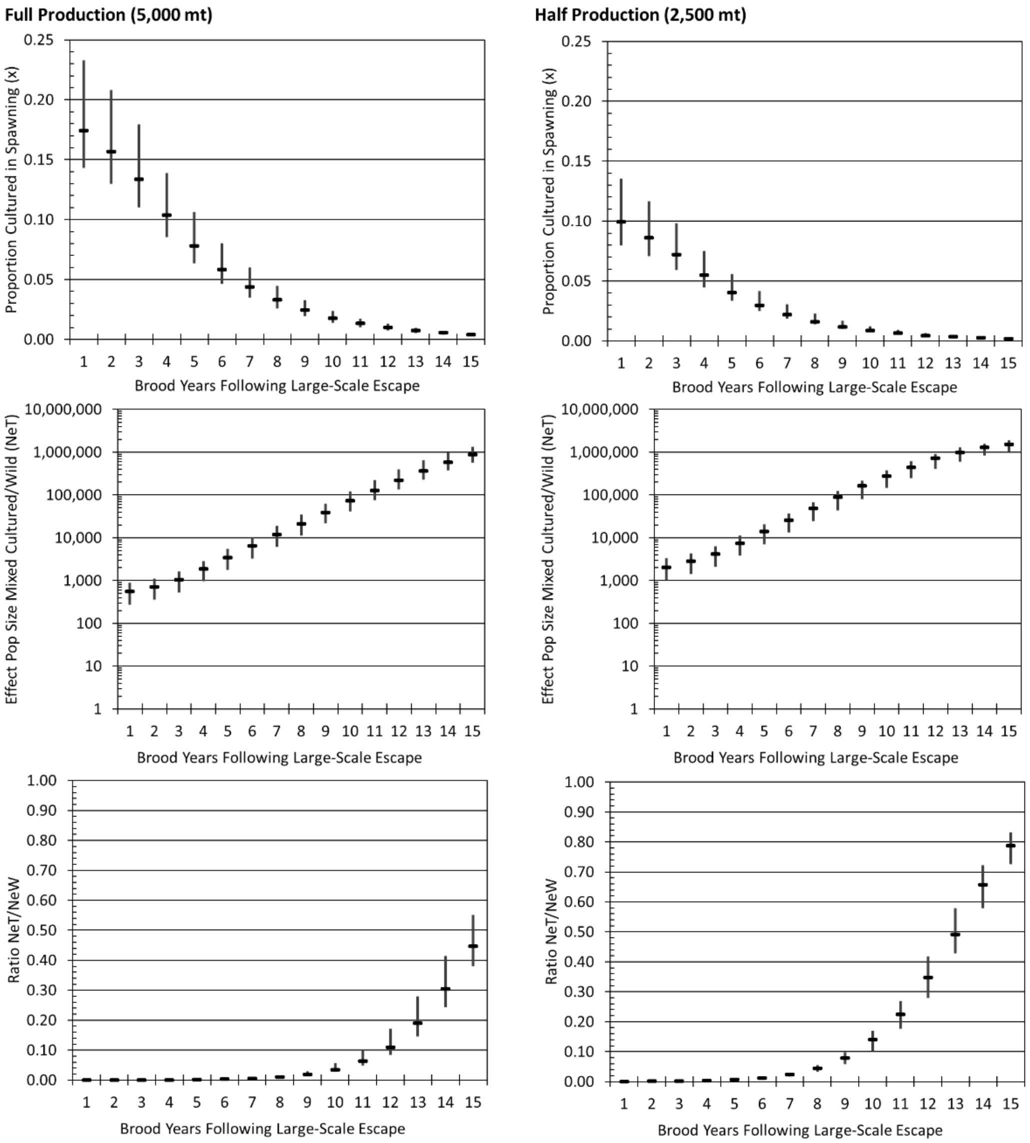


Figure 7.26. Potential reduction in effective population size (N_e) following a large-scale escape event (Scenario II) with full production (5,000 mt) on the left and half production (2,500 mt) on the right. Shown are proportion cultured in brood years following a large-scale escape (top) and potential reduction in effective population size (middle and bottom).

7.3 Scenarios III and IV

The preceding analyses examined scenarios for leakage and episodic escapes (Scenario I), and large-scale escape events (Scenario II). Scenarios III and IV include modest revisions to escape parameters representing the low range of episodic escape frequency (one cage failure every 10 years; 10% annual likelihood of an episodic escape), an expectation that fast response and containment measures would ensure a cage failure would only result in a quarter to half of the fish escaping from a cage, and an assumption that escaped cultured fish would survive at half the rate of wild California Yellowtail because of behavioral differences of escaped cultured fish escape. Scenario IV is a large-scale scenario with the lower survival assumption similar to Scenario III and an expectation in a large-scale event that only 75% of the fish would escape, 25% of the fish would remain contained in cages or could be recovered before escaping. Scenarios III and IV were included to provide an assessment that may better reflect improved gear technologies, monitoring capabilities, and operational approaches consistent with planned operations such as POA.

7.3.1 Leakage and Episodic Cage Failure: Scenario III

Scenario III simulations for leakage and episodic escape scenarios utilized the lowest of the episodic escape frequencies, one event every 10 years for the full-scale production alternative (at the 10% likelihood), and 0.5 events every 10 years (at the 5% likelihood) for the half scale production alternative. The range of magnitude for the episodic losses were lessened to simulate that between one quarter to one half of the fish in a cage escape during an episodic event (or alternatively, that there is the recovery of 50 to 75% of fish following a cage failure) compared with between half and full cage being lost in Scenario I simulations. Scenario III also assumed escaped fish survive at 50% as well as wild fish of the same size.

7.3.1.1 90-Year Simulation Results

Like the analyses presented previously, for the Scenario III simulations, the 90-year simulation period (simulation years 10 to 100) was used to demonstrate longer-term impacts on the conspecific wild population due to escape events occurring from continuous operations within this time frame. For each year, 5,187 fish (at full production) and 2,6587 fish (at half production) escaped due to a constant assumed leakage rate; these values were unchanged from Scenario II. When, or if, an episodic event occurs, somewhere between 24,389 and 48,777 fish escaped (quarter to half the number of fish lost from a single cage).

The cumulative number of escaped fish in the population resulting from leakage and episodic losses is presented in Table 7.21 for both the full and half scale production alternatives. At full production, a median of 8,282 fish escaped, which was just under 40% of the median value from the full production Scenario I at the 10% annual episodic escape frequency. At half scale production, a median of 3,345 fish escaped, which was just under 47% of the median value from Scenario I at the 5% annual episodic escape frequency. Like the full and half scale productions alternatives in sections 7.1.1 and 7.1.2, maximum values represent simulations where Scenario I routine operational escapes occur (i.e., based on leakage and episodic escape) in terms of impacts (e.g., larger episodic events, but using the reduced magnitude, and only at the lowest episodic frequencies for the full and half scale production). With these changes, the medians of the maximum values for the Scenario III simulations under full (28,749 fish) and half scale production (20,884 fish) were only 28% and 27%, respectively, of the maximum values under Scenario I. Further, at full scale production, 75% of simulations fell at or below 13,120 cumulative escaped fish, which was 46% of the Scenario III maximum value (and just below 13% of the Scenario I maximum value at the same episodic frequency). For the half scale production, 75% of simulations fell at or below 5,680 cumulative escaped fish, which was 28% of the Scenario III maximum value (and just over 7% of the Scenario I maximum value at the same episodic frequency).

Table 7-21. The cumulative number of cultured fish in the population resulting from leakage and episodic losses from current year escapes and surviving fish from previous years under the full production and half production alternatives – years 10 – 100 simulation results.

Model Scenario:	Cumulative number escaped fish in population (Simulation years 10 – 90 summaries)				
	Median	25%	75%	Min.	Max.
Full production at 5,000 mt	8,282	6,471	13,120	5,593	28,749
Half production at 2,500 mt	3,345	3,064	5,680	2,744	20,884

In Table 7-22 and Figure 7.27, the percentages of escaped fish in the population biomass and spawning abundance are presented for the 90-year simulations for Scenario III across a range of wild female biomasses (8,000 to 18,000 metric tons). Like the previous Scenario I results, escaped fish made up the largest percentages of the biomass and abundances at the smallest ranges of wild female biomass. However, even the maximum values for the smallest modeled population did not exceed one percent for either the full or half scale production. Under Scenario III, 75% of the values fell at or below 0.3% for both the population biomass and spawning abundance across the modeled population range for full scale production, and at or below 0.25% (population biomass) and 0.1% (spawning abundance) for half scale production.

Individual simulation values, shown in the scatterplots in Figure 7.27 reveal the variation around median values. At the full-scale production level, a small number of the individual simulations ranged to just over one percent in the population biomass and spawning abundance at the low end of the wild female spawning biomass range. However, no individual simulation was at, or over, one percent at the half scale production level, regardless of wild population size. The individual maximum values from each iteration (blue points) and the median of the maximum values across the population size range (blue line) are easy to discern in the figures. Figure 7.27, however, the points around the median (gray points) and minimum (green points) in the population biomass and spawning abundance are not discernable due to their low values.

Table 7-22. The percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from leakage and episodic escape events (Scenario III) under full production (5,000 mt) and half production (2,500 mt) alternatives - years 10 – 100 simulation results.

Model Scenario:		**Percentage of population biomass that are cultured fish**					**Percentage of population spawning abundance (males and females) that are cultured fish**				
		Median	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Full Production at 5,000 mt Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.2%	0.2%	0.3%	0.1%	0.6%	0.2%	0.1%	0.3%	0.1%	0.7%
	10,000 to 12,000	0.2%	0.1%	0.3%	0.1%	0.5%	0.2%	0.1%	0.2%	0.1%	0.6%
	12,000 to 14,000	0.2%	0.1%	0.2%	0.1%	0.4%	0.1%	0.1%	0.2%	0.1%	0.5%
	14,000 to 16,000	0.1%	0.1%	0.2%	0.1%	0.4%	0.1%	0.1%	0.2%	0.1%	0.4%
	16,000 to 18,000	0.1%	0.1%	0.2%	0.1%	0.3%	0.1%	0.1%	0.2%	0.1%	0.4%
Half Production at 2,500 mt Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.2%	0.1%	0.4%	0.1%	0.1%	0.1%	0.1%	0.5%
	10,000 to 12,000	0.1%	0.1%	0.1%	0.1%	0.3%	0.1%	0.1%	0.1%	0.1%	0.5%
	12,000 to 14,000	0.1%	0.1%	0.1%	0.0%	0.3%	0.1%	0.0%	0.1%	0.0%	0.4%
	14,000 to 16,000	0.1%	0.0%	0.1%	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%	0.3%
	16,000 to 18,000	0.1%	0.0%	0.1%	0.0%	0.2%	0.0%	0.0%	0.1%	0.0%	0.3%

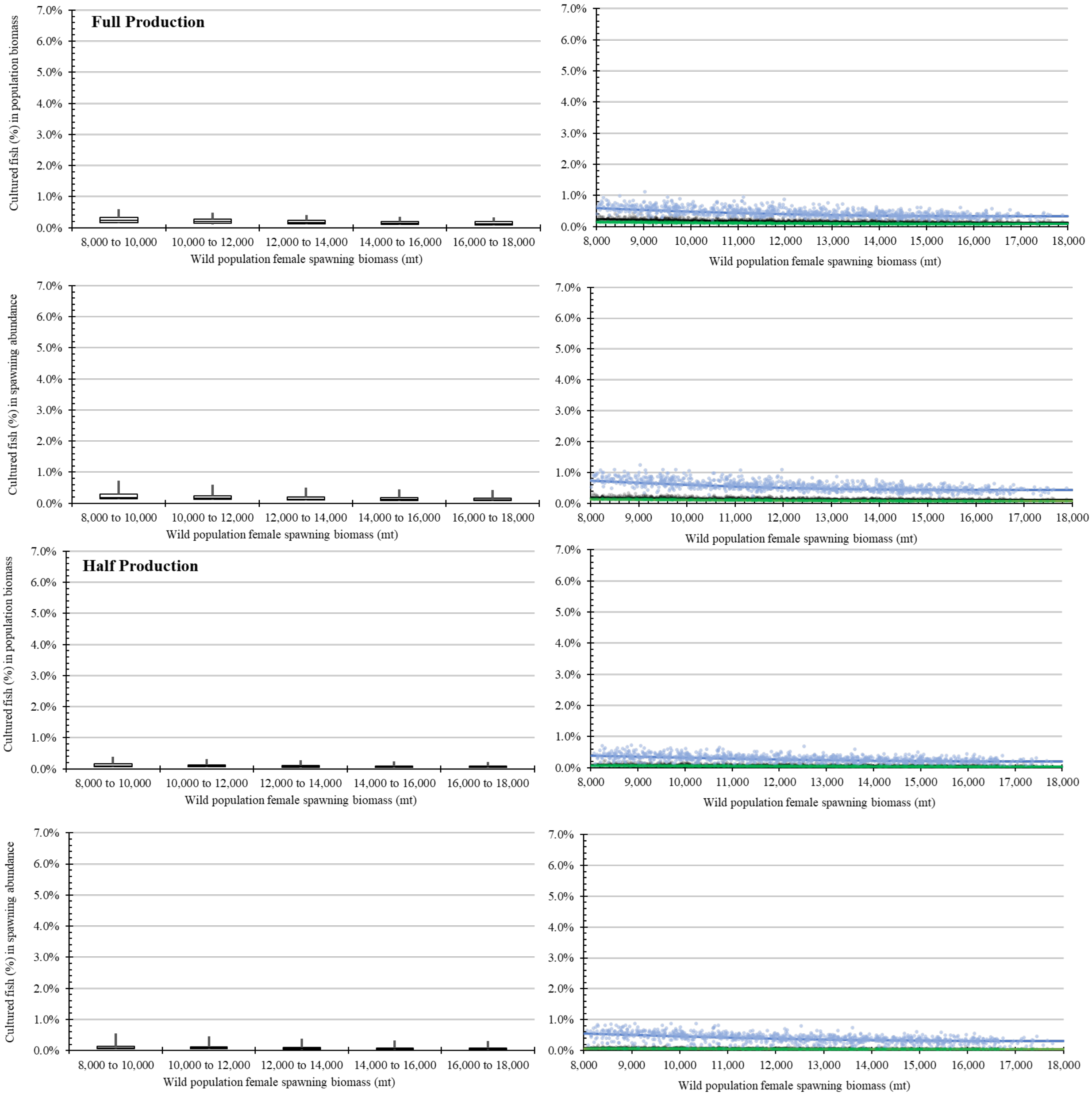


Figure 7.27. The percentage of cultured fish at full-scale production (5,000 mt) (top) and half-scale production (2,500 mt) (bottom) alternatives in the population biomass and spawning abundance resulting from leakage and episodic escapes with Scenario III assumptions. Episodic events were modeled at 10% (for full production) and 5% (for half production) likelihood of occurrence in a year. The scatterplots show the maximum (blue), median (gray), and minimum (green) values for each iteration and solid lines represent the respective median values over the range in female spawning biomass (in metric tons).

7.3.1.2 Short-term Simulation Results

Using Scenario III assumptions, model simulations were conducted for 5, 10, and 25 years for the full and half production alternatives. Results are again based on the lowest episodic escape frequencies – one event every 10 years at full production and 0.5 events every 10 years at half-production (or 10% and 5% likelihoods of an episodic escape event in a year, respectively). Table 7-23 presents the cumulative number of escaped fish from leakage and episodic losses at the 5-, 10-, and 25-year points of the simulations for both production level alternatives. Like the previously reported short-term results, these results differ from the 90-year simulations. Presented are the actual maximum and minimum values from the 1000 simulations. As such, the reported maximum values and upper tails in the box-and-whisker plots in this section reflect individual data points rather than the median of the maximum value from the 1000 simulations. Again, this distinction is important if trying to compare results between the 90-year and short-term simulations.

Using Scenario III assumptions for the full production alternative, the cumulative median number of cultured fish surviving in the population ranged from 5,008 (Year 5), 7,861 (Year 10) to 8,449 (Year 25) (Table 7.23); these values are 50% (or less) of the median values at the same episodic frequency under Scenario I assumption, for comparison. The Scenario III cumulative maximum values ranged as high as 45,450 fish (Year 5); however, these maximum values were a fraction of the Scenario I maximum values (between 26 and 30% of the Scenario I maximums over the three time points). Results indicated that 75% of the simulations led to fewer than 11,212 escaped fish (at Year 5), 12,785 escaped fish (at Year 10), and 13,380 escaped fish (at Year 25) in the population, which represented less than 25%, 29%, and 34% of the Scenario III maximum values, respectively.

In Scenario III under the half production alternative, the cumulative median number of fish in the population ranged between 2,429 (Year 5), 3,055 (Year 10) and 3,340 (Year 25) (Table 7.23); again, these values are 50% (or less) of the median values at the same episodic frequency under Scenario I assumption. Scenario III cumulative maximum numbers of cultured fish in the population ranged as high as 37,166 (Year 10), but in comparison, were 28% (or less) of the Scenario I maximum values. In 75% of the simulations, fewer than 2,581 (Year 5), 5,494 (Year 10), and 5,921 escaped fish (Year 25) accumulated in the population, representing less than 8.5%, 15%, and 19% of the Scenario III maximum values, respectively.

Because the episodic frequencies are the same in these comparisons, differences in numbers of escaped fish are due to the smaller magnitude of episodic losses (i.e., 50% lower potential number of escaped fish from an episodic event) and by applying a survival penalty to cultured fish compared to wild counterparts (i.e., they survive only 50% as well as wild counterparts of the same size). Because of these changes, considerably fewer fish are predicted to escape, survive, and accumulate into the wild population because of these modest assumptions.

Table 7-23. The cumulative number of escaped fish in the population in years 5, 10 and 25 resulting from leakage and episodic losses at full production and half production under Scenario III.

Model Scenario:	Cumulative number escaped fish in population				
	Median	25%	75%	Min.	Max.
Full production at 5,000 mt Leakage + Episodic (10% annual likelihood)					
Number of Cultured Fish in Year 5	5,008	4,746	11,212	4,061	45,650
Number of Cultured Fish in Year 10	7,861	5,964	12,785	4,958	44,739
Number of Cultured Fish in Year 25	8,449	6,438	13,380	5,117	39,626
Half production at 2,500 mt Leakage + Episodic (5% annual likelihood)					
Number of Cultured Fish in Year 5	2,429	2,347	2,581	2,114	30,699
Number of Cultured Fish in Year 10	3,055	2,872	5,494	2,359	37,166
Number of Cultured Fish in Year 25	3,340	3,056	5,921	2,516	31,327

The percentage of escaped fish as a proportion of population biomass and spawning abundance at the three time points in production are shown in Table 7.24 for Scenario III under the full-scale production alternative. The composition of escapees in the wild population is highest at the low end of the wild female biomass range, with a median at that lowest population range of 0.1% (Year 5), 0.2% (Year 10), and 0.2% (Year 25) cultured fish in both the population biomass and in the spawning abundance. Maximum percentages of cultured fish across the modeled population range varied between 0.6% and 0.4% (population biomass) and 0.8% and 0.6% (spawning abundance) in Year 5, between 0.8% and 0.4% (population biomass) and 1.0% and 0.5% (spawning abundance) in Year 10, and between 0.9% and 0.5% (population biomass) and 1.0% and 0.6% (spawning abundance) in Year 25. In Year 5, in 75% of simulations cultured fish did not exceed 0.1% in the population biomass and 0.2% in the spawning abundance across the modeled wild population size range, in Years 10 and 25 this value increased slightly, and 75% of simulations did not exceed 0.3% for either the population biomass or spawning abundance at full scale production.

These results are displayed graphically in Figure 7.28 (population biomass) and Figure 7.29 (spawning abundance) for the full-scale production alternative. As mentioned previously, the upper and lower whiskers in the figures reflects the greatest (single) impact detected across all simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range. The black line in the scatterplots reflects the median values across the population size range and the density of the smaller values below the median is undetectable.

Table 7-24. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from Scenario III leakage and episodic escape events under the full production (5,000 mt) alternative in year 5, 10 and 25 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Full production at 5,000 mt		**Median**	**25%**	**75%**	**Min.**	**Max.**	**Median**	**25%**	**75%**	**Min.**	**Max.**
Year 5 of Simulation Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.1%	0.0%	0.6%	0.1%	0.1%	0.2%	0.1%	0.8%
	10,000 to 12,000	0.1%	0.0%	0.1%	0.0%	0.6%	0.1%	0.1%	0.2%	0.1%	0.9%
	12,000 to 14,000	0.0%	0.0%	0.1%	0.0%	0.5%	0.1%	0.1%	0.1%	0.0%	0.6%
	14,000 to 16,000	0.0%	0.0%	0.1%	0.0%	0.4%	0.1%	0.1%	0.1%	0.0%	0.5%
	16,000 to 18,000	0.0%	0.0%	0.1%	0.0%	0.4%	0.1%	0.0%	0.1%	0.0%	0.6%
Year 10 of Simulation Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.2%	0.1%	0.3%	0.1%	0.8%	0.2%	0.1%	0.3%	0.1%	1.0%
	10,000 to 12,000	0.1%	0.1%	0.2%	0.1%	0.8%	0.1%	0.1%	0.2%	0.1%	0.9%
	12,000 to 14,000	0.1%	0.1%	0.2%	0.1%	0.6%	0.1%	0.1%	0.2%	0.1%	0.6%
	14,000 to 16,000	0.1%	0.1%	0.2%	0.1%	0.5%	0.1%	0.1%	0.2%	0.1%	0.6%
	16,000 to 18,000	0.1%	0.1%	0.2%	0.1%	0.4%	0.1%	0.1%	0.2%	0.1%	0.5%
Year 25 of Simulation Leakage + Episodic (10% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.2%	0.2%	0.3%	0.1%	0.9%	0.2%	0.1%	0.3%	0.1%	1.0%
	10,000 to 12,000	0.2%	0.1%	0.3%	0.1%	0.7%	0.2%	0.1%	0.3%	0.1%	0.8%
	12,000 to 14,000	0.2%	0.1%	0.2%	0.1%	0.6%	0.1%	0.1%	0.2%	0.1%	0.8%
	14,000 to 16,000	0.2%	0.1%	0.2%	0.1%	0.5%	0.1%	0.1%	0.2%	0.1%	0.6%
	16,000 to 18,000	0.1%	0.1%	0.2%	0.1%	0.5%	0.1%	0.1%	0.2%	0.1%	0.6%

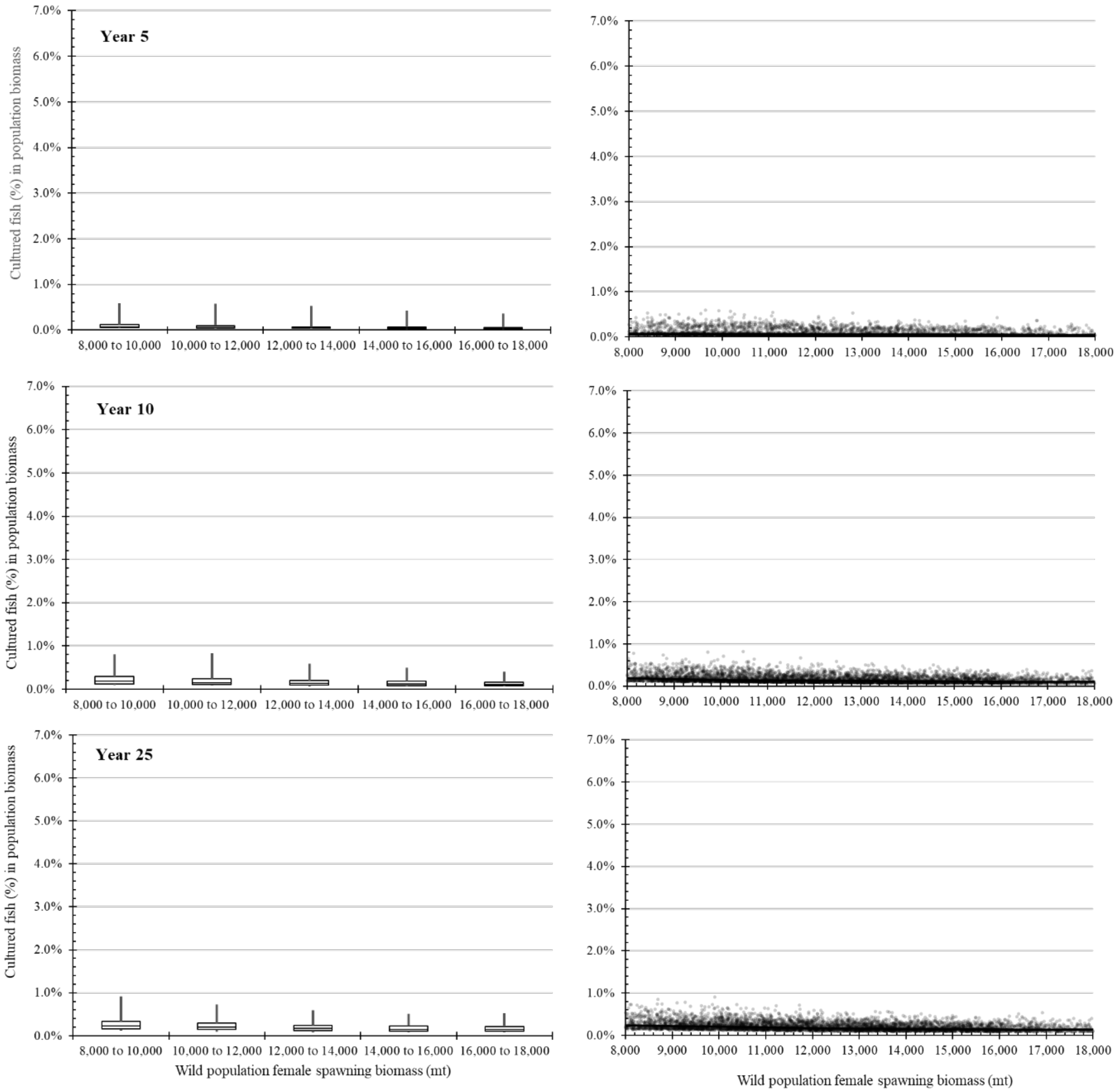


Figure 7.28. The percentage of cultured fish at full-scale production (5,000 mt) in the population biomass in Year 5, 10, and 25 with Scenario III assumptions.

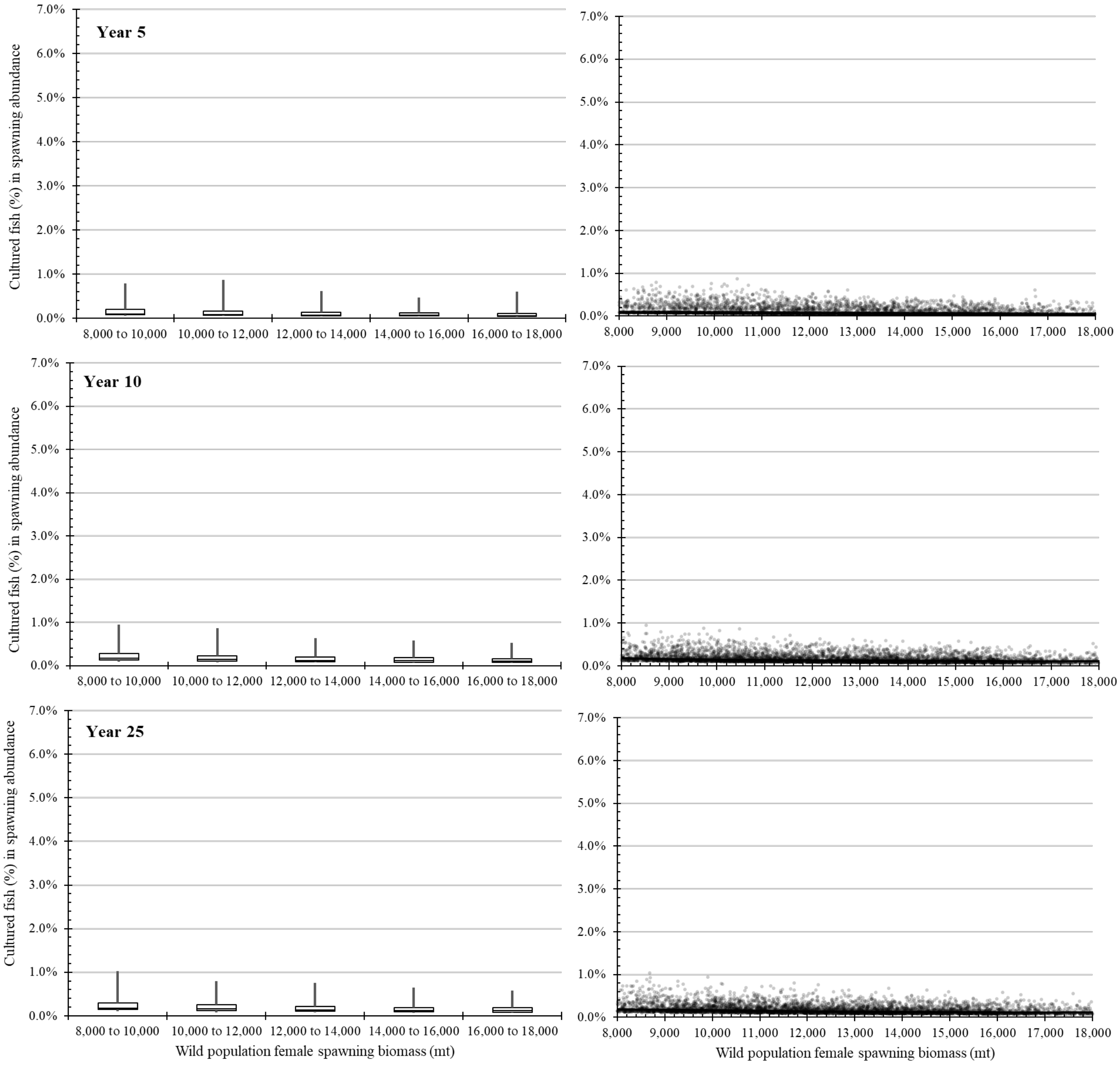


Figure 7.29. The percentage of cultured fish at full-scale production (5,000 mt) in the population spawning abundance in Year 5, 10, and 25 with Scenario III assumptions.

The percentage of escaped fish as a proportion of population biomass and spawning abundance at the three time points in production is shown in Table 7-25 for Scenario III under the half scale production alternative. As with the previous results, the composition of escapees in the wild population is highest at the low end of the wild female biomass range, with a median at that lowest population range of 0.0% (Year 5), 0.1% (Year 10), and 0.1% (Year 25) cultured fish in both the population biomass and in the spawning abundance. Maximum percentages of cultured fish across the modeled population range varied between 0.5% and 0.3% (population biomass) and 0.7% and 0.3% (spawning abundance) in Year 5, between 0.7% and 0.4% (population biomass) and 0.9% and 0.4% (spawning abundance) in Year 10, and between 0.5% and 0.4% (population biomass) and 0.7% and 0.4% (spawning abundance) in Year 25. In Year 5, in 75% of the simulations, cultured fish were less than 0.1% in the population biomass or spawning abundance across the modeled wild population size range, in Year 10 this value increased to 0.1% for both the biomass and abundance, and in Year 25, 75% of simulations did not exceed 0.2% for the population biomass or 0.1% for the spawning abundance at half scale production.

These results are displayed graphically in Figure 7.26 (population biomass) and Figure 7.27 (spawning abundance) for the half scale production alternative. As mentioned previously, the upper and lower whiskers in the figures reflect the greatest (single) impact detected across all simulations (for that portion of the modeled population size range), and the scatterplot reveals the variation in individual simulations across the modeled population size range. The black line in the scatterplots reflects the median values across the population size range, and again, the density of the smaller values below the median is undetectable.

Table 7-25. Percentage of escaped fish in the population biomass and spawning abundance (male and female fish) resulting from Scenario III leakage and episodic escape events under the half production (2,500 mt) alternative in year 5, 10 and 25 of the simulation.

Model Scenario:		Percentage of population biomass that are cultured fish					Percentage of population spawning abundance (males and females) that are cultured fish				
Half production at 2,500 mt		Median	25%	75%	Min.	Max.	Median	25%	75%	Min.	Max.
Year 5 of Simulation Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.7%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.8%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.5%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.5%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.3%
Year 10 of Simulation Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.1%	0.0%	0.7%	0.1%	0.1%	0.1%	0.0%	0.9%
	10,000 to 12,000	0.1%	0.0%	0.1%	0.0%	0.5%	0.1%	0.1%	0.1%	0.0%	0.6%
	12,000 to 14,000	0.0%	0.0%	0.1%	0.0%	0.4%	0.0%	0.0%	0.1%	0.0%	0.5%
	14,000 to 16,000	0.0%	0.0%	0.1%	0.0%	0.4%	0.0%	0.0%	0.1%	0.0%	0.4%
	16,000 to 18,000	0.0%	0.0%	0.1%	0.0%	0.4%	0.0%	0.0%	0.1%	0.0%	0.4%
Year 25 of Simulation Leakage + Episodic (5% annual likelihood)											
Female Biomass Range (mt)	8,000 to 10,000	0.1%	0.1%	0.2%	0.1%	0.5%	0.1%	0.1%	0.1%	0.0%	0.7%
	10,000 to 12,000	0.1%	0.1%	0.1%	0.0%	0.7%	0.1%	0.1%	0.1%	0.0%	0.7%
	12,000 to 14,000	0.1%	0.1%	0.1%	0.0%	0.6%	0.1%	0.0%	0.1%	0.0%	0.6%
	14,000 to 16,000	0.1%	0.0%	0.1%	0.0%	0.3%	0.0%	0.0%	0.1%	0.0%	0.5%
	16,000 to 18,000	0.1%	0.0%	0.1%	0.0%	0.4%	0.0%	0.0%	0.1%	0.0%	0.4%

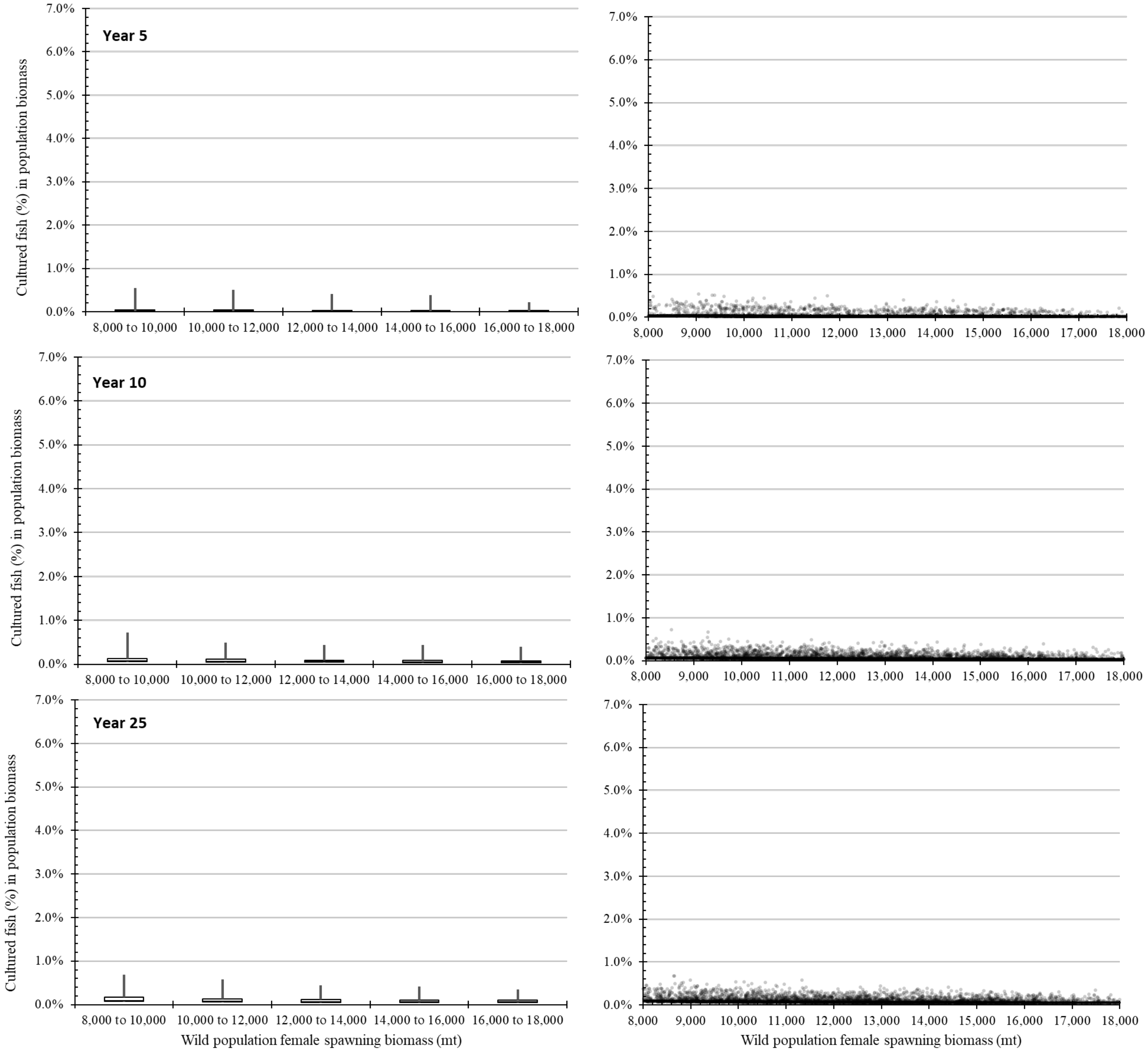


Figure 7.30. The percentage of cultured fish at half-scale production (2,500 mt) in the population biomass in Year 5, 10, and 25 with Scenario III assumptions.

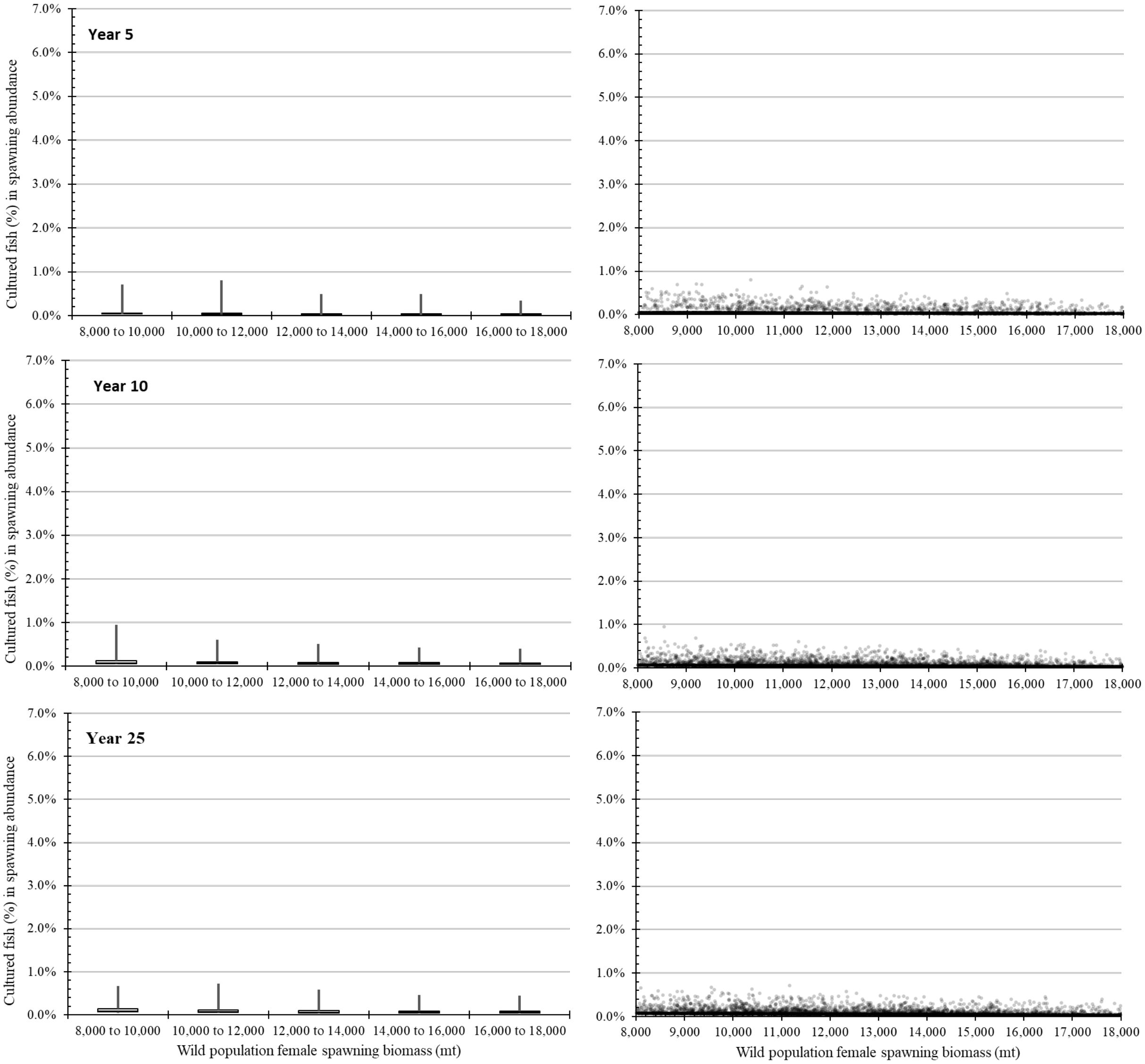


Figure 7.31. The percentage of cultured fish at half-scale production (2,500 mt) in the population spawning abundance in Year 5, 10, and 25 with Scenario III assumptions.

7.3.2 Large Scale Escape Event: Scenario IV

The impacts from the large-scale escape event scenarios are distinct from impacts predicted by leakage and episodic escape scenarios and are therefore modeled separately. They are also modeled as a single occurrence as our analysis assumes a stop to operations following a catastrophic loss of this scale. Even Scenario IV assumptions for a large-scale escape simulation, by its definition, is still a rare and catastrophic event from an operational standpoint.

At full production, Scenario IV still assumes the loss of fish from two grids (28 pens), however, in this scenario 25% of the fish are recovered (or alternatively, only 75% of fish from the 28 pens survive to escape due to some being retained or killed in a structural failure of this magnitude). Similarly, at half scale production, fish are assumed to escape from one grid (14 pens), but again with the recapture of 25% of the escaped fish. Like the leakage and episodic Scenario III, in Scenario III for the large-scale events, escaped cultured fish are assumed to survive half as well as wild fish of the same size.

Impacts were again assessed by modeling fish at three points in time over the production cycle that reflect when fish are skewed towards a greater number of smaller fish on station, a greater number of larger fish on station, and a more even distribution of fish sizes on station (hereafter referred to as small-size skewed, large-size skewed, and evenly-sized fish distribution, respectively).

7.3.2.1 Full Production Alternative

Under Scenario IV with the full production alternative, between 1,521,254 (large-size skewed fish distribution) and 2,048,642 (small-size skewed fish distribution) may escape from the 28 pens following a large-scale event (Table 7.26), compared to between 2.03 and 2.73 million fish in Scenario II. Both size-specific mortality and the additional culture-based differential survival was applied to the number of fish escaping to predict the number of fish that may enter the population following the initial escape. The number of cultured fish surviving to enter the population ranged from 538,783 (large-size skewed fish distribution) to 653,410 (small-size skewed fish distribution); these numbers were much lower (over 62% lower) compared to the Scenario II (when approximately 1.44 to 1.74 million fish were predicted to enter the population).

The number of cultured fish in the wild population was simulated for periods of time following the initial escape event; the first two periods reflect 5-year increments, while the last two periods reflect 10-year increments (Table 7.26). The range in the number of cultured fish during each period represents the beginning and ending years of that period. The number of cultured fish in the population decreases over time from the escape event, and at five years post-escape, less than 7.6% (compared to 15% under Scenario II) of the escaped cultured fish are expected to remain in the wild population, at ten years post-escape less than 1.6% (compared to 3.2% under Scenario II), and at twenty years post-escape less than 0.04% (compared to 0.07% under Scenario II) of the escaped fish remain in the population regardless of the initial size-distribution (based on the highest percentage from the three fish size distributions for each period).

Table 7-26. Number fish escaping, number entering population, and number surviving in the population post escape with a large-scale escape event (Scenario IV) under the full production (5,000 mt) alternative.

Model Scenario: Full Production, Large-scale escape event	Number of fish escaping	Number of fish entering population (includes size-specific mortality)	Number of cultured fish in population-Median	Number of cultured fish in population-Range during period	
Large-scale evenly sized fish distribution					
Initial escape	1642397	540408			
1 to 5 years post-escape			214192	394852	114954
6 to 10 years post-escape			45494	84458	24351
11 to 20 years post-escape			4480	17847	457
21 to 30 years post-escape			0	334	0
Large-scale small sized skewed fish distribution					
Initial escape	2048642	653410			
1 to 5 years post-escape			259324	477453	138489
6 to 10 years post-escape			54594	102139	29338
11 to 20 years post-escape			5387	21510	674
21 to 30 years post-escape			0	491	0
Large-scale large sized skewed fish distribution					
Initial escape	1521254	538783			
1 to 5 years post-escape			212152	394648	114127
6 to 10 years post-escape			44973	83868	24172
11 to 20 years post-escape			4463	17706	228
21 to 30 years post-escape			0	167	0

Table 7.27 (evenly sized fish distribution), Table 7.28 (small sized skewed fish distribution), and Table 7.29 (large sized skewed fish distribution) present the percentages of escaped fish as a proportion of the population biomass and spawning abundance over the four periods following a large-scale escape event at full production.

For the evenly sized fish distribution, in the first five years following an escape event, the median percent of cultured fish in the population biomass ranged between 5.1% and 3.1%, and in the spawning abundance between 7.5% and 4.4% from the smallest to largest modeled wild population sizes (Table 7.27). These results are approximately half (or less than half) of the Scenario II large-scale simulations (11.6% - 7.4% and 17.6% - 11.0% for the biomass and abundance, respectively). In the first five years, the maximum values of evenly sized cultured fish in the population biomass ranged between 5.4% and 3.2%, (compared to 12.1% and 7.7% under Scenario II), and in the spawning abundance between 8.0% and 4.7%, (compared to 18.7% and 11.6% under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (3.4% to 2.0% and 1.8% to 1.1%, respectively), 11 to 20 years (0.5% to 0.3% percent and 0.2% to 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-27. The percentage cultured fish in population biomass and spawning abundance (male and female) under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario IV) and evenly sized fish escaping.

Model scenario:		Evenly sized fish distribution- Percentage of population biomass that are cultured fish			Evenly sized fish distribution- Percentage of population spawning abundance that are cultured fish		
Full production at 5,000 mt		Median	Range during period		Median	Range during period	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	5.1%	5.4%	3.4%	7.5%	8.0%	4.3%
	10,000 to 12,000	4.3%	4.5%	2.8%	6.3%	6.7%	3.6%
	12,000 to 14,000	3.8%	4.0%	2.5%	5.4%	5.8%	3.1%
	14,000 to 16,000	3.3%	3.4%	2.1%	4.7%	5.0%	2.7%
	16,000 to 18,000	3.1%	3.2%	1.9%	4.4%	4.7%	2.5%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	3.4%	4.7%	2.2%	1.8%	3.2%	0.9%
	10,000 to 12,000	2.9%	3.9%	1.9%	1.5%	2.7%	0.8%
	12,000 to 14,000	2.4%	3.4%	1.6%	1.2%	2.3%	0.7%
	14,000 to 16,000	2.2%	3.0%	1.4%	1.1%	2.0%	0.6%
	16,000 to 18,000	2.0%	2.8%	1.4%	1.1%	1.9%	0.6%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.5%	1.8%	0.1%	0.2%	0.7%	0.0%
	10,000 to 12,000	0.4%	1.5%	0.1%	0.1%	0.6%	0.0%
	12,000 to 14,000	0.4%	1.3%	0.1%	0.1%	0.5%	0.0%
	14,000 to 16,000	0.3%	1.1%	0.1%	0.1%	0.4%	0.0%
	16,000 to 18,000	0.3%	1.1%	0.1%	0.1%	0.4%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

For the small sized skewed fish distribution, in the first five years following an escape event the median percent of cultured fish in the population biomass ranged between 5.7% and 3.5%, and in the spawning abundance between 7.7% and 4.8% from the smallest to largest modeled wild population sizes (Table 7.28). These results are approximately half (or less than half) of the Scenario II large-scale simulations (12.8% – 8.3% and 13.3% – 8.7% for biomass and abundance, respectively). In the first five years, the maximum values of small sized skewed cultured fish in the population biomass ranged between 6.0% and 3.7% (compared to 13.3 and 8.7% under Scenario II), and in spawning abundance between 8.9% and 5.4% (compared to 20.5% and 13.0%t under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (4.0% to 2.4% and 2.1% to 1.3%, respectively), 11 to 20 years (0.6% to 0.4% and 0.2% to 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-28. The percentage cultured fish in population biomass and spawning abundance (male and female) under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario IV) and small-size skewed fish escaping.

Model scenario:		**Small-size skewed fish distribution- Percentage of population biomass that are cultured fish**			**Small-size skewed fish distribution- Percentage of population spawning abundance that are cultured fish**		
Full production at 5,000 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	5.7%	6.0%	3.4%	7.7%	8.9%	5.2%
	10,000 to 12,000	4.8%	5.1%	2.9%	6.5%	7.5%	4.4%
	12,000 to 14,000	4.2%	4.4%	2.5%	5.6%	6.4%	3.7%
	14,000 to 16,000	3.7%	3.9%	2.2%	5.0%	5.7%	3.3%
	16,000 to 18,000	3.5%	3.7%	2.1%	4.8%	5.4%	3.1%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	4.0%	5.4%	2.6%	2.1%	3.8%	1.1%
	10,000 to 12,000	3.4%	4.5%	2.2%	1.8%	3.3%	1.0%
	12,000 to 14,000	2.9%	3.9%	1.9%	1.5%	2.7%	0.8%
	14,000 to 16,000	2.5%	3.4%	1.7%	1.3%	2.4%	0.7%
	16,000 to 18,000	2.4%	3.3%	1.6%	1.3%	2.3%	0.7%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.6%	2.1%	0.2%	0.2%	0.8%	0.0%
	10,000 to 12,000	0.5%	1.8%	0.1%	0.2%	0.7%	0.0%
	12,000 to 14,000	0.5%	1.5%	0.1%	0.1%	0.6%	0.0%
	14,000 to 16,000	0.4%	1.3%	0.1%	0.1%	0.5%	0.0%
	16,000 to 18,000	0.4%	1.3%	0.1%	0.1%	0.5%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

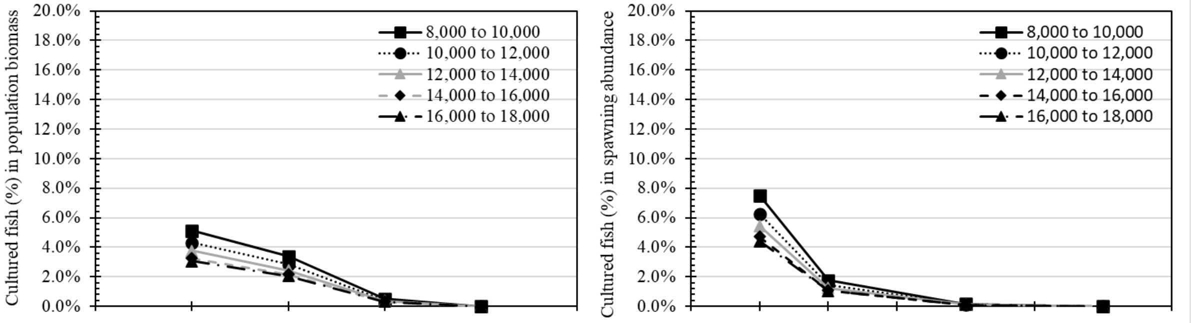
For the large sized skewed fish distribution, in the first five years following an escape event the median percent of cultured fish in the population biomass ranged between 5.8% and 3.6%, and in the spawning abundance between 7.5% and 4.6% from the smallest to largest modeled wild population sizes (Table 7.29). These results are approximately half (or less than half) of the Scenario II simulations (13.0% to 8.5% percent and 17.8% to 11.3% for biomass and abundance, respectively). In the first five years, the maximum values of large sized skewed cultured fish in the population biomass ranged between 6.2% and 3.9% (compared to 13.7% and 9.1% under Scenario II), and in spawning abundance between 10.1% and 6.3% percent (compared to 23.2% and 15.0% under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (3.5% to 2.1% and 1.7% to 1.0%, respectively), 11 to 20 years (0.5% to 0.3% and 0.2% to 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-29. The percentage cultured fish in population biomass and spawning abundance (male and female) under the full-scale production (5,000 mt) alternative with a large-scale escape event (Scenario IV) and large-size skewed fish escaping.

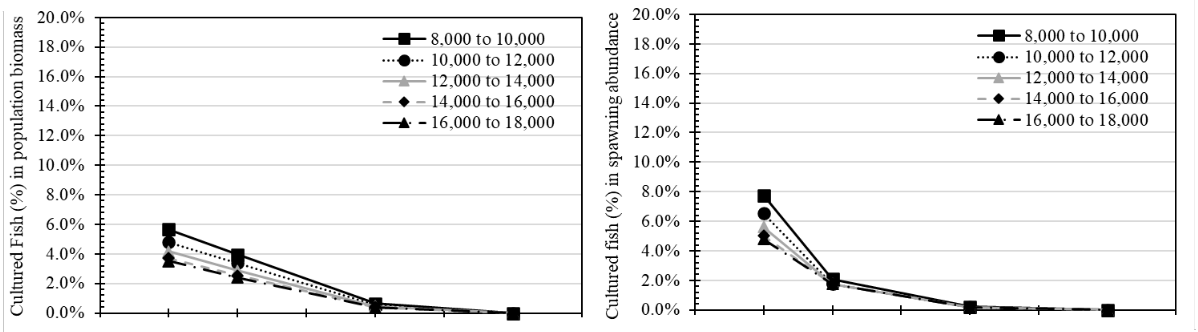
Model scenario:		Large sized skewed fish distribution- Percentage of population biomass that are cultured fish			Large sized skewed fish distribution- Percentage of population spawning abundance that are cultured fish		
Full production at 5,000 mt		Median	Range during period		Median	Range during period	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	5.8%	6.2%	4.8%	7.5%	10.1%	4.3%
	10,000 to 12,000	5.1%	5.4%	4.2%	6.4%	8.8%	3.6%
	12,000 to 14,000	4.4%	4.6%	3.6%	5.5%	7.6%	3.1%
	14,000 to 16,000	3.9%	4.1%	3.1%	4.8%	6.7%	2.7%
	16,000 to 18,000	3.6%	3.9%	3.0%	4.6%	6.3%	2.5%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	3.5%	5.0%	2.3%	1.7%	3.2%	0.9%
	10,000 to 12,000	3.0%	4.3%	1.9%	1.5%	2.7%	0.8%
	12,000 to 14,000	2.6%	3.7%	1.7%	1.2%	2.3%	0.7%
	14,000 to 16,000	2.3%	3.3%	1.5%	1.1%	2.0%	0.6%
	16,000 to 18,000	2.1%	3.1%	1.3%	1.0%	1.9%	0.5%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.5%	1.8%	0.1%	0.2%	0.7%	0.0%
	10,000 to 12,000	0.5%	1.5%	0.1%	0.1%	0.6%	0.0%
	12,000 to 14,000	0.4%	1.3%	0.1%	0.1%	0.5%	0.0%
	14,000 to 16,000	0.3%	1.1%	0.1%	0.1%	0.4%	0.0%
	16,000 to 18,000	0.3%	1.1%	0.1%	0.1%	0.4%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

In Figure 7.28, it is most immediately apparent how much lower the percentages of escaped fish in the biomass and abundance are in comparison with Scenario II simulations. Like above, the cultured fish made up a larger percentage of the spawning abundance during the initial 5-year period, but that proportion declines more rapidly than in the spawning abundance. This is again due to the difference in the weight-based (biomass) and number-based (metrics). Variation in the modeled female spawning biomass range (in metric tons) is also shown for each period, where cultured fish from a large-scale escape event made up a greater portion of both the population biomass and spawning abundance at the lower range of modeled wild population sizes.

Even-sized fish distribution



Small-skewed size fish distribution



Large-skewed size fish distribution

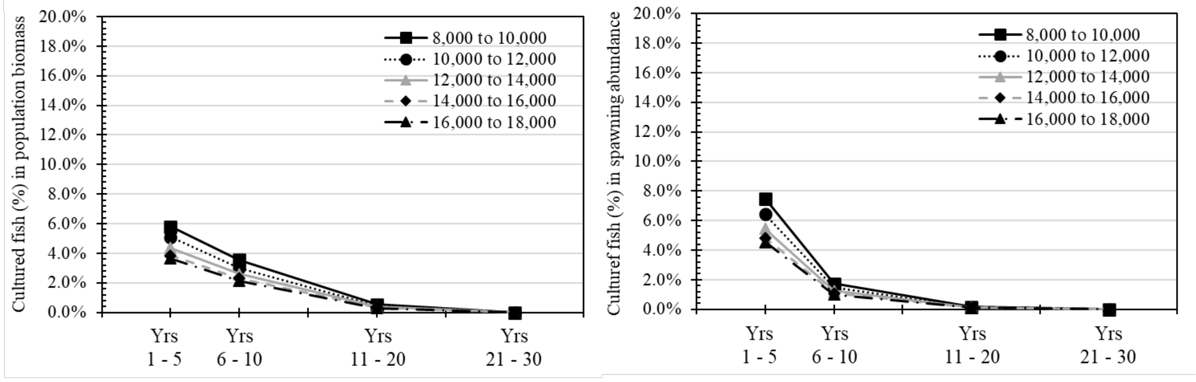


Figure 7.32. The percentage of cultured fish under the full production (5,000 mt) alternative in the population biomass (left) and spawning abundance (right) following a large-scale escape with Scenario IV assumptions. Shown are percentages over the range of female spawning biomass (in metric tons) by period.

7.3.2.2 Half production Alternative

Under Scenario IV simulations with the half production alternative, between 760,628 (large-size skewed fish distribution) and 1,024,321 (small-size skewed fish distribution) may escape from the 14 pens following a large-scale event (Table 7.30), compared to between 1.01 and 1.37 million fish in Scenario II. Both size-specific mortality and the additional culture-based differential survival were applied to the number of fish escaping to predict the number of fish that may enter the population following the initial escape. The number surviving to enter the population ranges from 269,392 (large sized skewed fish distribution) to 326,705 (small sized skewed fish distribution); these numbers are also over 62% lower compared to Scenario II simulations (718,378 to 871,214 fish entering the population).

The number of cultured fish in the wild population was simulated for periods of time following the initial escape event; the first two periods reflect 5-year increments, while the last two periods reflect 10-year increments (Table 7.30). The range in the number of cultured fish during each period represents the beginning and ending years of that period. The number of cultured fish in the population decreases over time from the escape event, and at five years post-escape, less than 7.5% (compared to 15% under Scenario II) of the escaped cultured fish are expected to remain in the wild population, at ten years post-escape less than 1.6% (compared to 3.2% under Scenario II), and at twenty years post-escape less than 0.04% (compared to 0.07% under Scenario II) of the escaped fish remain in the population regardless of the initial size-distribution (based on the highest percentage from the three fish size distributions for each period).

Table 7-30. Number fish escaping, number entering population, and number surviving in the population post escape with a large-scale escape event (Scenario IV) under the half production (2,5000 mt) alternative.

Model Scenario: Half Production, Large-scale escape event	Number of fish escaping	Number of fish entering population (includes size-specific mortality)	Number of cultured fish in population-Median	Number of cultured fish in population-Range during period	
Large-scale evenly sized fish distribution					
Initial escape	821200	270204			
1 to 5 years post-escape			106972	198407	57414
6 to 10 years post-escape			22657	42076	12136
11 to 20 years post-escape			2218	8876	226
21 to 30 years post-escape			0	165	0
Large-scale small sized skewed fish distribution					
Initial escape	1024321	326705			
1 to 5 years post-escape			129737	239038	69534
6 to 10 years post-escape			27526	50925	14812
11 to 20 years post-escape			2697	10763	334
21 to 30 years post-escape			0	244	0
Large-scale large sized skewed fish distribution					
Initial escape	760628	269392			
1 to 5 years post-escape			105970	197133	56991
6 to 10 years post-escape			22431	41545	12098
11 to 20 years post-escape			2212	8862	113
21 to 30 years post-escape			0	83	0

Table 7.31 (evenly sized fish distribution), Table 7.32 (small sized skewed fish distribution), and Table 7.33 (large sized skewed fish distribution) present the percentages of escaped fish as a proportion of the population biomass and spawning abundance over the four periods following a large-scale escape event at half production.

For the evenly sized fish distribution, in the first five years following an escape event the median percent of cultured fish in the population biomass ranged between 2.7% and 1.6% and in the spawning abundance between 3.9% and 2.3% from the smallest to largest modeled wild population sizes (Table 7.31). These results are less than half of Scenario II large-scale simulations (6.6% to 4.0% and 9.7% to 5.8% for biomass and abundance, respectively). In the first five years, the maximum values of evenly sized cultured fish in the population biomass ranged between 2.8% and 1.7% percent (compared to 6.9% and 4.2% under Scenario II), and in the spawning abundance between 4.1% and 2.4% (compared to 10.3% and 6.2% under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (1.8% to 1.0% and 0.9% to 0.5%, respectively), 11 to 20 years (0.3% to 0.2% and 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-31. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half-scale production (2,000 mt) alternative with a large-scale escape event (Scenario IV) and evenly sized fish escaping.

Model scenario:		Evenly sized fish distribution- Percentage of population biomass that are cultured fish			Evenly sized fish distribution- Percentage of population spawning abundance that are cultured fish		
Full production at 2,500 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	2.7%	2.8%	1.7%	3.9%	4.1%	2.2%
	10,000 to 12,000	2.3%	2.4%	1.5%	3.2%	3.5%	1.8%
	12,000 to 14,000	1.9%	2.0%	1.2%	2.8%	3.0%	1.6%
	14,000 to 16,000	1.7%	1.8%	1.1%	2.4%	2.6%	1.4%
	16,000 to 18,000	1.6%	1.7%	1.0%	2.3%	2.4%	1.3%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	1.8%	2.4%	1.1%	0.9%	1.6%	0.5%
	10,000 to 12,000	1.5%	2.0%	0.9%	0.7%	1.4%	0.4%
	12,000 to 14,000	1.2%	1.7%	0.8%	0.6%	1.2%	0.3%
	14,000 to 16,000	1.1%	1.5%	0.7%	0.6%	1.0%	0.3%
	16,000 to 18,000	1.0%	1.4%	0.7%	0.5%	1.0%	0.3%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.3%	0.9%	0.1%	0.1%	0.3%	0.0%
	10,000 to 12,000	0.2%	0.7%	0.1%	0.1%	0.3%	0.0%
	12,000 to 14,000	0.2%	0.6%	0.0%	0.1%	0.2%	0.0%
	14,000 to 16,000	0.2%	0.6%	0.0%	0.1%	0.2%	0.0%
	16,000 to 18,000	0.2%	0.5%	0.0%	0.1%	0.2%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

For the small sized skewed fish distribution, in the first five years following an escape event the median percent of cultured fish in the population biomass ranged between 3.0% and 1.8%, and in the spawning abundance between 4.1% and 2.4% from the smallest to largest modeled wild population sizes (Table 7.32). These results are approximately less than half of Scenario II large-scale simulations (7.3% to 4.6% and 10.1% to 6.3% for biomass and abundance, respectively). In the first five years, the maximum values of small sized skewed cultured fish in the population biomass ranged between 3.2% and 1.9% (compared to 7.7% and 4.8% under Scenario II) and in spawning abundance between 4.6% and 2.8% (compared to 11.4% and 7.1% under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (2.1% to 1.2% and 1.1% to 0.6%, respectively), 11 to 20 years (0.3% to 0.2% and 0.1%, respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-32. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half-scale production (2,000 mt) alternative with a large-scale escape event (Scenario IV) and small-size skewed fish escaping.

Model scenario:		Small sized skewed fish distribution- Percentage of population biomass that are cultured fish			Small sized skewed fish distribution- Percentage of population spawning abundance that are cultured fish		
Full production at 2,500 mt		Median	Range during period		Median	Range during period	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	3.0%	3.2%	1.8%	4.1%	4.6%	2.6%
	10,000 to 12,000	2.6%	2.7%	1.5%	3.4%	3.9%	2.2%
	12,000 to 14,000	2.2%	2.3%	1.3%	2.9%	3.3%	1.9%
	14,000 to 16,000	1.9%	2.0%	1.1%	2.5%	2.9%	1.6%
	16,000 to 18,000	1.8%	1.9%	1.1%	2.4%	2.8%	1.6%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	2.1%	2.8%	1.3%	1.1%	1.9%	0.6%
	10,000 to 12,000	1.7%	2.4%	1.1%	0.9%	1.6%	0.5%
	12,000 to 14,000	1.5%	2.0%	1.0%	0.8%	1.4%	0.4%
	14,000 to 16,000	1.3%	1.8%	0.8%	0.7%	1.2%	0.4%
	16,000 to 18,000	1.2%	1.7%	0.8%	0.6%	1.2%	0.3%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.3%	1.1%	0.1%	0.1%	0.4%	0.0%
	10,000 to 12,000	0.3%	0.9%	0.1%	0.1%	0.4%	0.0%
	12,000 to 14,000	0.2%	0.8%	0.1%	0.1%	0.3%	0.0%
	14,000 to 16,000	0.2%	0.7%	0.0%	0.1%	0.3%	0.0%
	16,000 to 18,000	0.2%	0.6%	0.0%	0.1%	0.2%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

For the large sized skewed fish distribution, in the first five years following an escape event the median percent of cultured fish in the population biomass ranged between 3.1% and 1.9%, and in the spawning abundance between 3.9% and 2.3% from the smallest to largest modeled wild population sizes (Table 7.33). These results are less than half of the Scenario II large-scale simulations (7.6% to 4.8% and 9.8% to 6.0% for biomass and abundance, respectively). In the first five years, the maximum values of large sized cultured fish in the population biomass ranged between 3.3% and 2.0% (compared to 8.1% and 5.1% under Scenario II), and in the spawning abundance between 5.3% and 3.2% (compared to 13.2% and 8.3% under Scenario II). Median percentages of cultured fish in both the population biomass and spawning abundance decreased during the periods of 6 to 10 years post-escape (1.8% to 1.1% and 0.9% to 0.5%, respectively), 11 to 20 years (0.3% to 0.2% and 0.1% respectively), and by the 21-to-30-year period, all percentages were 0.0 percent.

Table 7-33. The percentage cultured fish in population biomass and spawning abundance (male and female) under the half-scale production (2,000 mt) alternative with a large-scale escape event (Scenario IV) and large size skewed fish escaping.

Model scenario:		Large sized skewed fish distribution- Percentage of population biomass that are cultured fish			Large sized skewed fish distribution- Percentage of population spawning abundance that are cultured fish		
Full production at 2,500 mt		**Median**	**Range during period**		**Median**	**Range during period**	
Post-escape period: 1 to 5 years							
Female biomass range (mt)	8,000 to 10,000	3.1%	3.3%	2.5%	3.9%	5.3%	2.2%
	10,000 to 12,000	2.6%	2.8%	2.1%	3.3%	4.5%	1.8%
	12,000 to 14,000	2.2%	2.4%	1.8%	2.8%	3.8%	1.6%
	14,000 to 16,000	2.0%	2.2%	1.6%	2.5%	3.4%	1.4%
	16,000 to 18,000	1.9%	2.0%	1.5%	2.3%	3.2%	1.3%
Post-escape period: 6 to 10 years							
Female biomass range (mt)	8,000 to 10,000	1.8%	2.6%	1.2%	0.9%	1.6%	0.5%
	10,000 to 12,000	1.6%	2.2%	1.0%	0.7%	1.3%	0.4%
	12,000 to 14,000	1.3%	1.9%	0.8%	0.6%	1.1%	0.3%
	14,000 to 16,000	1.2%	1.7%	0.7%	0.5%	1.0%	0.3%
	16,000 to 18,000	1.1%	1.6%	0.7%	0.5%	0.9%	0.3%
Post-escape period: 11 to 20 years							
Female biomass range (mt)	8,000 to 10,000	0.3%	0.9%	0.1%	0.1%	0.3%	0.0%
	10,000 to 12,000	0.2%	0.8%	0.0%	0.1%	0.3%	0.0%
	12,000 to 14,000	0.2%	0.7%	0.0%	0.1%	0.2%	0.0%
	14,000 to 16,000	0.2%	0.6%	0.0%	0.1%	0.2%	0.0%
	16,000 to 18,000	0.2%	0.5%	0.0%	0.1%	0.2%	0.0%
Post-escape period: 21 to 30 years							
Female biomass range (mt)	8,000 to 10,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	10,000 to 12,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	12,000 to 14,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	14,000 to 16,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	16,000 to 18,000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

In Figure 7.29 it is again apparent how much lower the percentages of escaped fish in the biomass and abundance are in comparison with Scenario II large-scale scenarios for the half production alternative. As with the above figures, the cultured fish made up a larger percentage of the spawning abundance during the initial 5-year period, but that proportion declines more rapidly than in the spawning abundance, although the lower percentages make this more difficult to see than at full production. This is again due to the difference in the weight-based (biomass) and number-based (metrics). Variation in the modeled female spawning biomass range (in metric tons) is also shown for each period; where cultured fish from a large-scale escape event made up a greater portion of both the population biomass and spawning abundance at the lower range of modeled wild population sizes.

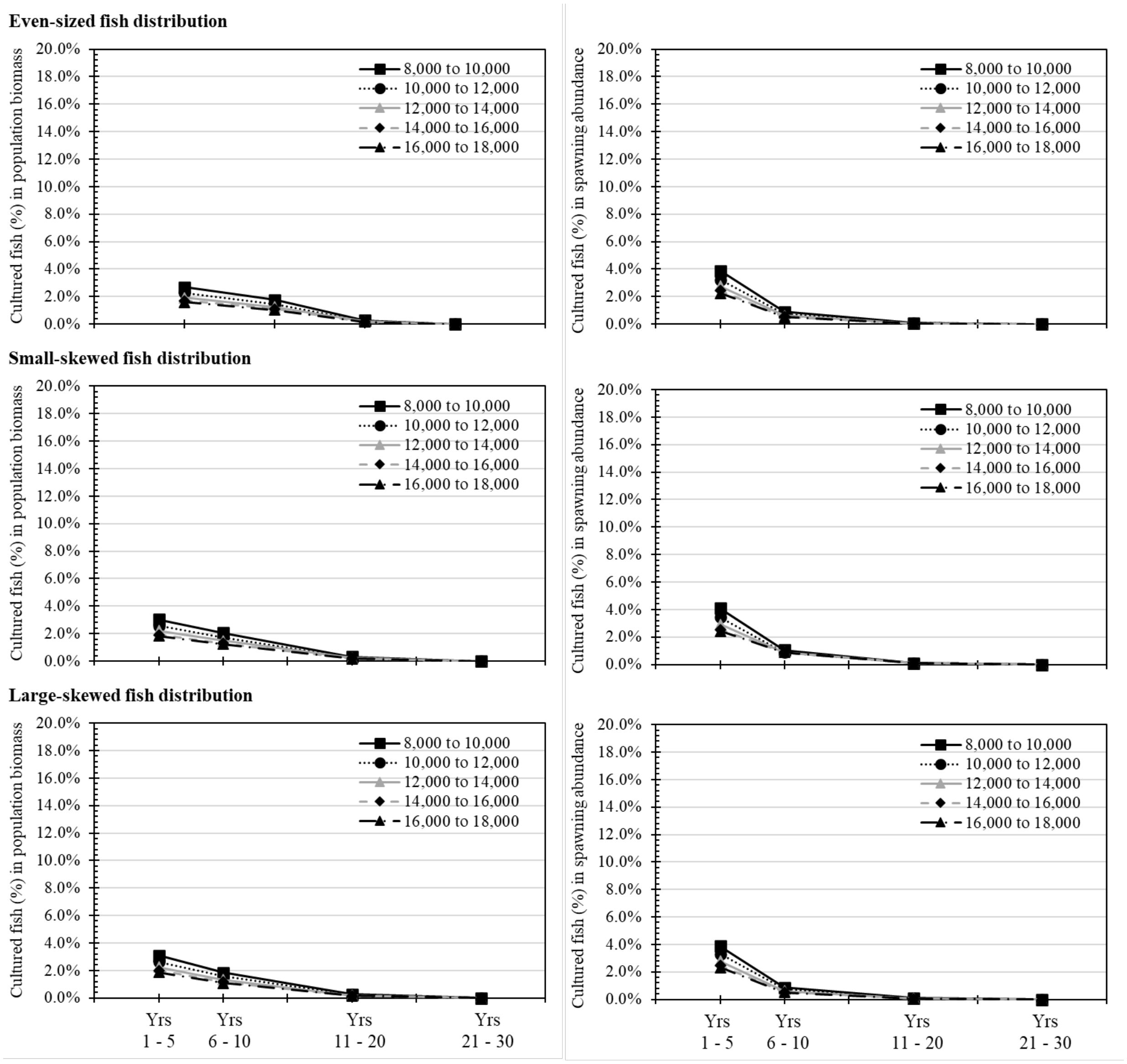


Figure 7.33. The percentage of cultured fish under half production (2,500 mt) alternative in the population biomass (left) and spawning abundance (right) following a large-scale escape with Scenario IV assumptions. Shown are percentages over the range of female spawning biomass (in metric tons) by period.

7.3.3 Impact Results

In any given year, under Scenario III leakage/cage-failure assumptions for the full-scale production alternative, 5,173 fish are predicted to escape due to leakage (this rate remains unchanged under Scenario III simulations compared to Scenario I), and if a cage failure occurs during that year, somewhere between 24,5000 and 49,000 fish may escape during that cage loss. Under Scenario III assumptions, only a quarter to half a cage is predicted to be lost during an episodic event (or alternatively, 50% to 75% of fish are expected to be recovered from the loss of a cage). While not reflected in the number of fish that may be expected on an annual basis, the lower assumed frequency of cage loss (10% under Scenario III) lowers the cumulative number of fish in the population predicted in the longer simulations (e.g., 25-years and 90-years). For the half-scale production alternative, 2,687 fish are predicted to escape due to leakage (from fewer cages), and between 24,500 and 49,000 fish may again escape from a cage loss if one occurs during that year. As above, these escape numbers are consistent between the 90-year and short-term (5-, 10, and 25-year) simulations, however the cumulative number of escaped fish in the mixed population is much lower due to the lower survival of the escaped fish (50% survival compared to wild conspecifics of the same size).

If a large-scale catastrophic escape was to occur under the Scenario IV assumptions for the full-scale production alternative, between 1.52 and 2.05 million fish may escape. This number is lower under Scenario IV due to the assumption that recovery of 25% of the escaped fish (or alternatively, that 25% of the fish were retained in the structure). With the lower assumed survival of the escaped fish (50% compared to similarly sized wild conspecifics), between 0.54 and 0.65 million escaped fish are predicted to enter the wild population. Under the half-scale production alternative with these Scenario IV assumptions, between 0.76 and 1.02 million fish may escape under a catastrophic scenario, but between 0.27 and 0.33 million escaped fish may enter the population.

7.3.3.1 Fitness Impacts on the Wild Conspecific Population

From Scenario III simulations, the predicted maximum loss of fitness over the 90-year period shows a very slight reduction for both the full- and half-scale production alternatives (Figure 7.30). In over 1,000 simulations, the maximum predicted relative fitness loss was approximately 0.00007 in the mixed population compared to the original wild population (relative fitness of 0.99993 versus 1.000) (Figure 7.34 top), which occurred at full-scale production, and at the lower end of the modeled wild population biomass range. At full-scale production and in the smallest modeled wild population size range (8,000 - 10,000 mt female spawning biomass), 95% of simulations predicted a relative fitness loss of less than 0.00005 in the mixed population. These fitness predictions are based on a cage loss frequency of 10% under the assumptions for Scenario III. At half-scale production, the maximum relative fitness impact was 0.00003 over the 90-year period at the smallest modeled population size range (8,000 – 10,000 mt), and 95% of the simulations did not exceed a relative fitness loss of 0.00002 at this population size range.

These fitness predictions are based on a cage loss frequency of 5% under the assumptions for Scenario III. Relative fitness losses at larger modeled population sizes were even smaller.

In Figure 7.35, relative fitness losses for the short-term simulations under Scenario III is presented. In the longest of the short-term simulations where greatest losses were detected (25 years), the maximum relative fitness losses were nearly undetectable (0.000001) in the mixed population for both the full- and half-scale production levels. For over 95% of the short-term simulations, under both the full- and half-scale production levels, and across the modeled population size range, no relative fitness loss was detected.

Results from Scenario IV large-scale escape simulations are shown in Figure 7.36. Again, across the modeled size ranges, for the three size-distributions of escaped fish, and for all time periods, the loss of relative fitness in the mixed population is nearly undetectable in both the full- and half-scale production alternatives.

The predicted losses in relative fitness are nearly undetectable for these scenarios again because of the use of wild caught broodstock, with minimal opportunity for domestication, but also partially due to Scenario III and IV assumptions. The fewer fish escaping (due to smaller modeled cage losses in the episodic events, or recapture in the large-scale events), the lower frequency of cage losses, and the 50% lower survival assumption on cultured fish compared to similarly sized wild conspecifics further reduces an already minimal loss of relative fitness in the mixed population compared to the original wild population.

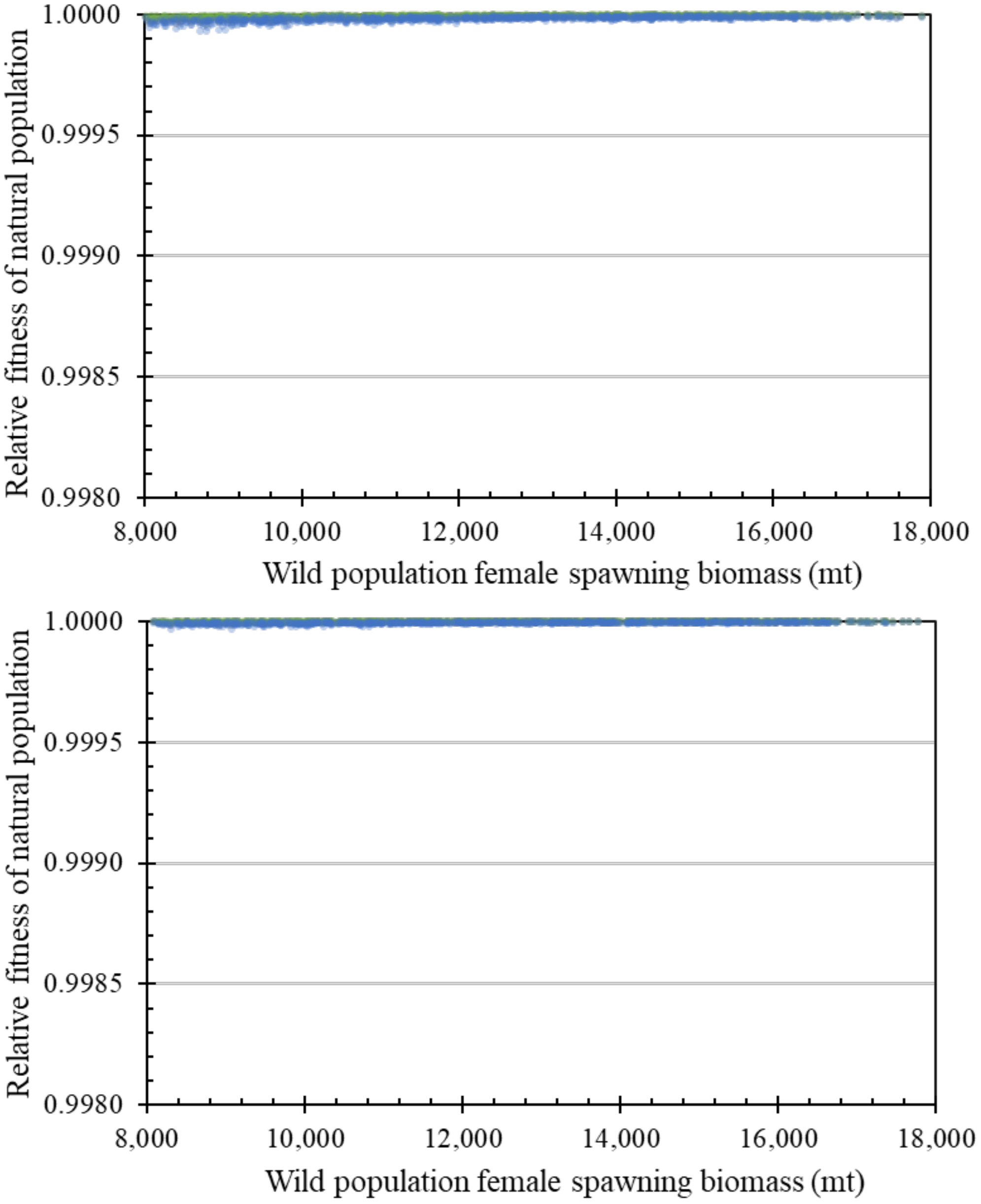


Figure 7.34. Relative fitness effects with Scenario III assumptions in years 10 to 90 under the full production (5,000 mt) alternative (top) at a modeled episodic event annual likelihood of 10%, and for the half production (2,500 mt) alternative (bottom) at a modeled episodic event annual likelihood of 5%. The scatterplots show the greatest loss (blue), median (gray), and least (green) loss in fitness for each iteration over the 90-year period.

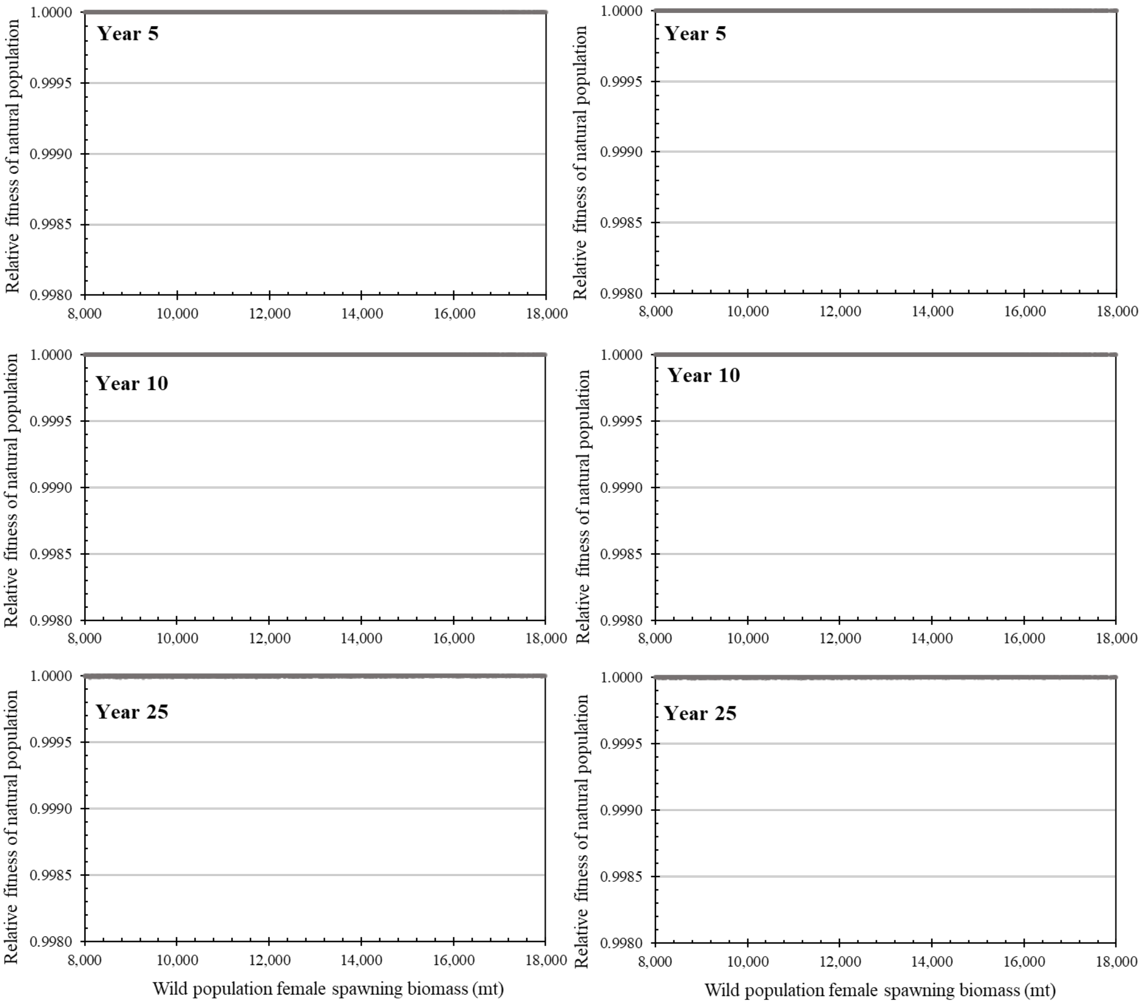


Figure 7.35. Short-term relative fitness effects with Scenario III assumptions under the full production (5,000 mt) alternative (left) and half production (2,500 mt) alternative (right). Shown are predictions in Year 5, Year 10, and Year 25. The modeled episodic event annual likelihoods were 10% under full production and 5% under half production.

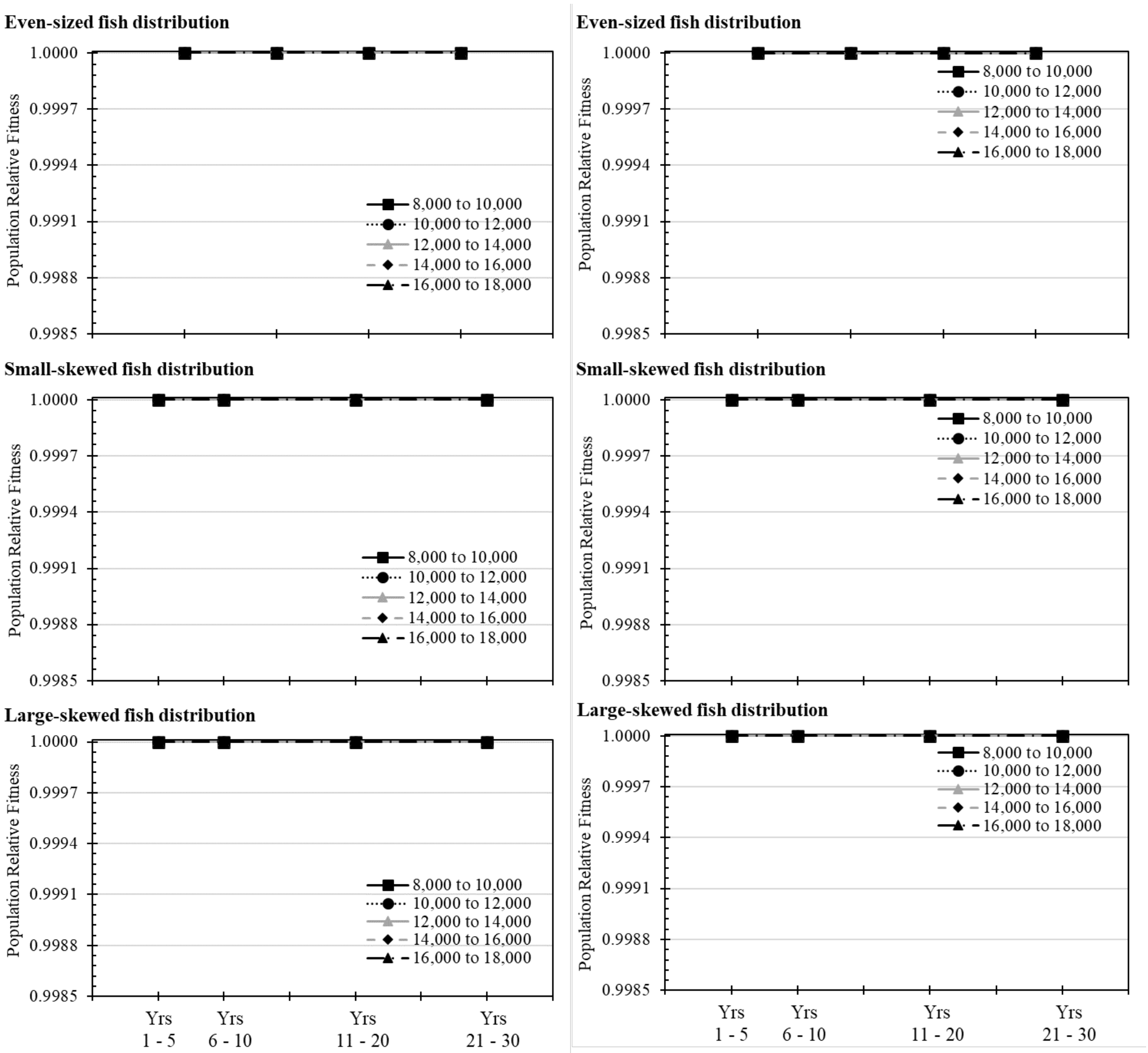


Figure 7.36. Relative fitness effects following a large-scale escape event under full production (5,000 mt) alternative (left) and half production (2,500 mt) alternative (right) with Scenario IV assumptions. Shown are relative fitness values over the range of female spawning biomass (in metric tons) by period.

7.3.3.2 Genetic Diversity Impacts on the Wild Conspecific Population

As with the Scenario I results, the potential for reduction in N_e following escapes due to leakage and cage failures is presented in Figure 7.37, with a 10% likelihood of cage failure under the full production alternative and a 5% likelihood under the half production alternative, per Scenario III assumptions. Potential impacts were again simulated after 5, 10, and 25 years of production. The predicted maximum reduction in N_e shows a slight reduction in both the full- and half-scale production alternatives, and the maximum predicted proportional effect on N_e (N_{eT}/N_{eW}) was 0.80. Across all simulations for the leakage and cage failures under Scenario III assumptions, the potential for Ryman-Laikre effects is insignificant.

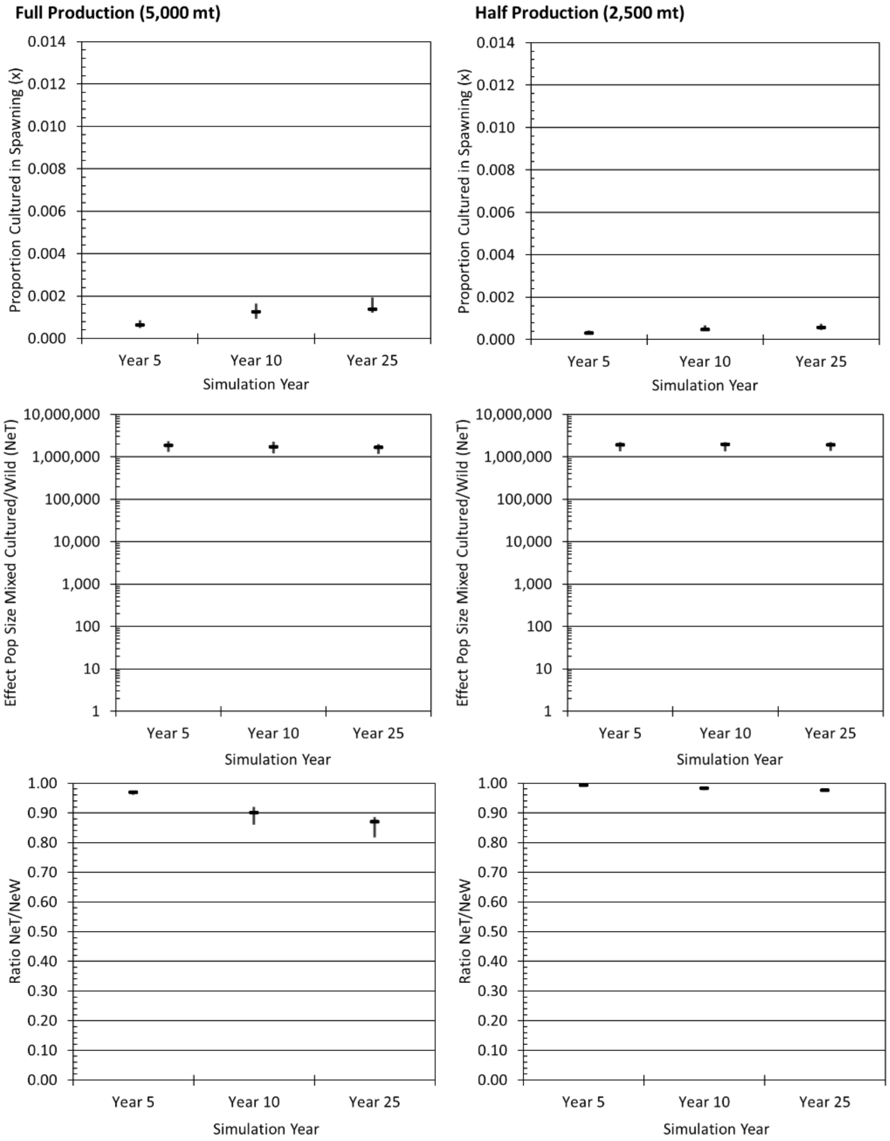


Figure 7.37. Short-term potential reduction in effective population size with Scenario III assumptions under the full production (5,000 mt) alternative (left) and half production alternative (right) in Year 5, Year 10, and Year 25. Episodic events were modeled at 5% likelihood of occurrence in a year.

A large-scale escape event with Scenario IV assumptions generally indicates lower potential for a Ryman-Laikre effect compared to the large-scale escape event discussed in the previous section. Estimated N_{eT} exceeded 5,000 fish in nearly all simulations (Figure 7.38). Only at the lowest population size is N_{eT} less than 5,000 fish. However, like the Scenario II analysis, the proportional decrease in N_e (N_{eT}/N_{eW}) is substantial in the admixed population in the years following a large-scale event.

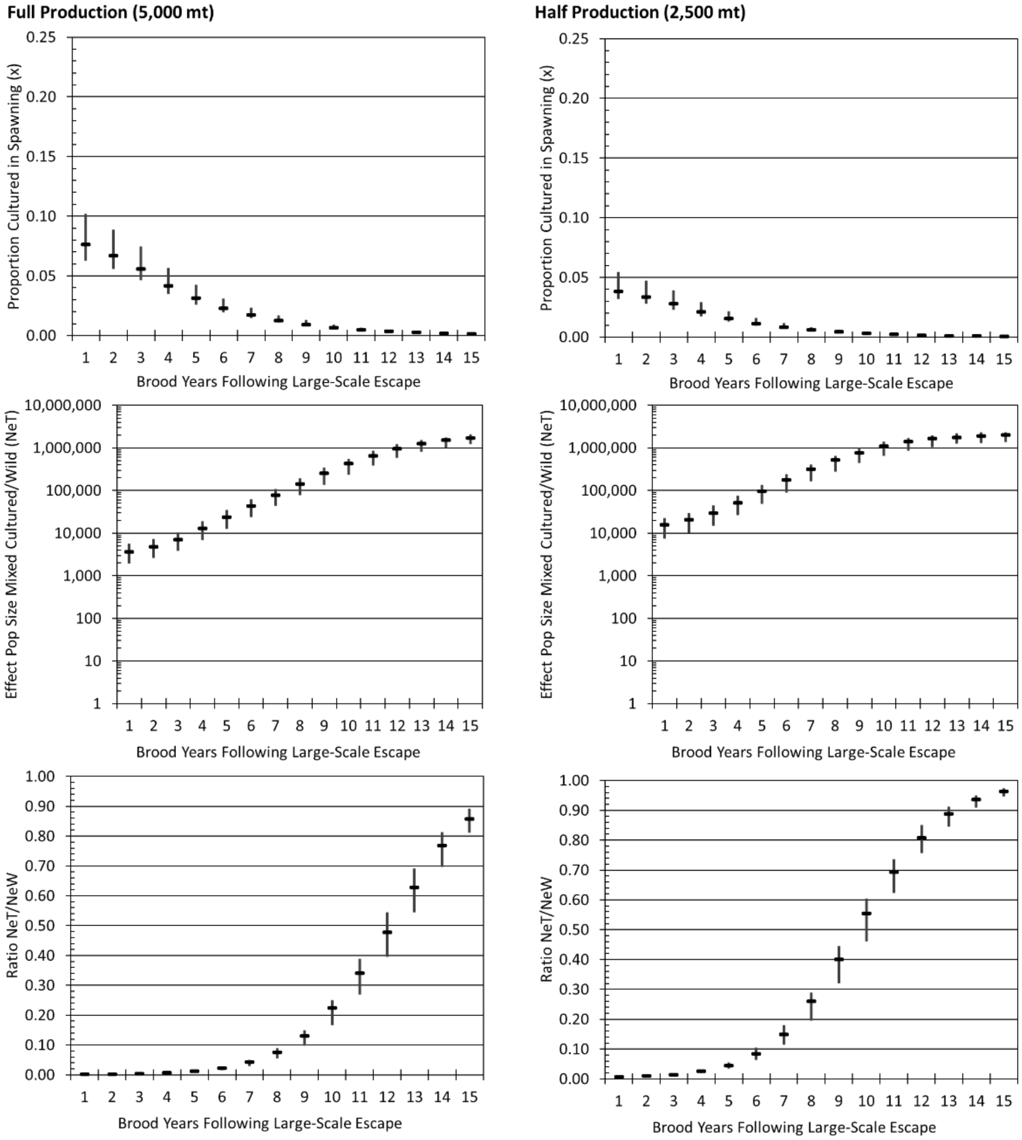


Figure 7.38. Potential reduction in effective population size (N_e) following a large-scale escape event with full production (5,000 mt) on the left and half production (2,500 mt) on the right with Scenario IV assumptions. Shown are proportion cultured in brood years following a large-scale escape (top) and potential reduction in effective population size (middle and bottom).

8.0 Conclusions

We used the OMEGA model to evaluate potential impacts from escaped California yellowtail on wild conspecifics. The potential impacts of cultured fish escaping into nature include genetic effects from introgression of cultured fish with the wild population of California Yellowtail leading to a loss of fitness, reduction in the effective population size and the subsequent loss of genetic diversity within the impacted population(s). Ecological effects from escaped fish on the wild population include-predation, competition or disease transfer to the wild population are other potential impacts that may be of concern. Our analysis focuses on the genetic impacts. We report the number of fish escaping from leakage, cage failure and large-scale failure to provide a measure for evaluation of potential ecological impacts from escaped fish.

Simulation results for the POA aquaculture project at full production with Scenario I assumptions suggest negligible effects on population fitness. Important factors in the proposed POA aquaculture program that greatly minimize the potential for loss of fitness in the wild population include: the use of local wild-origin fish in the captive breeding program, the absence of intentional selection for specific traits in breeding program, and the existence of a single population of California Yellowtail that appear abundant relative to the proposed POA aquaculture program. However, there is some uncertainty on this last part as a formal stock assessment has not been completed for the population. Historical catch data from Southern California and Baja Mexico suggest an abundant population. We simulated impacts using a ranges of assumptions and a range of wild population abundances to provide a buffer of uncertainty around our predictions of impacts. Unintentional selection during captive breeding (of F1 fish) was accounted for in the model following the first year of production, where the mixed population moved slightly away from wild fitness optimum and towards the cultured fitness optimum in subsequent years of the simulations. For both full- and half-scale production levels, the loss of genetic fitness in the wild population following escapes due to operational leakage and cage-failures, or a one-time large-scale loss, was negligible.

Based on simulations from leakage and cage failures at both full- and half-scale production, the effective size of the mixed population (N_{eT}) was sufficiently large enough (i.e., above 5,000 fish) to avoid deleterious effects of small N_e. However, the proportional reductions in effective population size (N_{eT}/N_{eW}) increase in magnitude with increasing length of time the farm is operating, with increasing cage failure frequencies, and with decreasing population size. At the highest frequency of cage failures, the values for the lower modeled population ranges begin to approach a level where the wild population may experience Ryman-Laikre effects.

However, we found a substantial potential for loss of within population genetic diversity following a large-scale escape event (Scenario II) under the full and half production alternatives. For several years immediately following the escape under full production, the proportion of cultured fish in the population exceeds 10% and the effective population size may not be large enough to avoid deleterious Ryman-Laikre effects and the subsequent loss of genetic diversity. Two components suggest a potential for loss of genetic diversity: 1) a high contribution of cultured escaped fish in the wild spawning population and 2) a very low number of California

Yellowtail used in the captive breeding program (although in practice within a reasonable size for a commercial breeding program). Although not assessed specially, unintentional differential survival of offspring from culture practices may further reduce the number of adults contributing to offspring transferred to cages.

The impact of escaped or released fish on effective population size (N_e) in a mixed population, the effect of N_e on the genetic diversity in that population, and the consequences of genetic diversity on adaptive potential for a species are important questions where there is great interest but also high levels of uncertainty. The recent realization that the ratio of N_e to total population size (N) may be orders of magnitude higher than previous estimates for many marine fish with high fecundity and high early mortality rates (Waples et al. 2018, Jones et al. 2019, Tringali and Lowerre-Barbierri 2023) is leading to a rethinking of how early-life stage strategies in fish are characterized (Tringali and Lowerre-Barbieri 2023), and shifting paradigms of recruitment dynamics theories for these species (Lowerre-Barbieri et al. 2017, Árnason et al. 2023).

With some low level of escapement on a regular basis, or possibly infrequent larger incursions of escaped fish into the wild population from episodic cage failures, the mixed population may be resilient to some reduction in N_e, especially for a species with intermediate generation lengths and high lifetime variance in reproductive success, such as CA Yellowtail. Resilience in a population is thought to arise from variable selective pressures acting across all life-stages in an ever-changing environment, from the egg and larval stages through spawning, reproductively mature fish, which helps shape the genetic diversity in the population (Lowerre-Barbieri et al. 2017, Tringali and Lowerre-Barbieri 2023).

Accidental release of fish from cages results in fish entering the population at a size where they skipped the selective forces acting (perhaps most strongly) on those earliest stages with the highest mortality (Tringali 2023). While this could give those escaped fish a greater advantage in contributing offspring to subsequent generations, and hence lowering N_e and genetic diversity in the mixed population, the larger and more fecund wild individuals may have the more important advantage of having survived that selective gauntlet which could lead to a greater lifetime reproductive success for those individuals, and provide an important buffer for the mixed population. However, the capacity of that buffer and the potential for the population to maintain its resiliency will vary over time (e.g., temporal stochasticity), environmental conditions (e.g., water temperatures impacting spawning events), and external pressures (e.g., fishing pressure, frequency of escapes).

Quantifying or trying to weigh the outcomes between these opposing impacts is not possible with the current state of knowledge. However, resilience of the population to withstand reductions in N_e and loss of genetic diversity will be only be improved by fewer escaped fish (e.g., operational designs and plans to minimize escape events), escaped fish with genetic backgrounds that capture a large portion of the existing genetic diversity in the region of the commercial operation (e.g., regional broodstock selection with a sufficient brood size and breeding design to maximize culture-based N_e), and/or generating fish that will not survive in the wild environment or produce offspring in subsequent generations (e.g., sterilization).

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