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# Modeling the Variable Effects of Using Wild and Cultured Broodstock on the Fitness Risk Due to Escaped Farmed Fish

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**Abstract**: Various negative ecological and genetic impacts may occur when farmed fish escape and mix with wild conspecifics. Genetic impacts result due to interbreeding between wild fish and escapees and may result in reduced genetic diversity within and among populations and a loss of fitness. Loss of genetic diversity and fitness compromise the adaptive potential of a mixed (wild plus cultured) population, making it potentially less able to respond to changes in environmental conditions (e.g. climate change).

Simplified, risk to wild population fitness due to interbreeding with escapees is a function of the number of escapees relative to wild census size, the genetic difference between escapees and wild fish, and the fitness of escapees in the wild relative to wild fish. The Offshore Mariculture Escapes Genetics Assessment (OMEGA) model simulates the magnitude of this risk. To illustrate OMEGA's application, we present results from evaluations of a planned pilot project for Almaco jack (*Seriola rivoliana*) in Hawaii and contrast them with those obtained from evaluation of a theoretical sablefish (*Anoplopoma fimbria*) aquaculture program originally used to verify the model. Escape scenarios for both species varied from low to high base leak rates, cage failure probabilities, and catastrophic cage failure probabilities. Whereas the high escapes scenario for sablefish resulted in a significant impact to wild population fitness, even a total loss of almaco jack had a negligible effect. Key differences in the simulated fitness risk associated with each program included, but are not limited to, broodstock source (domesticated or wild), encounter rate between wild fish and escapees, and the scale (size and longevity) of the operation.

**Key words**: Almaco jack, fitness, genetic risk, offshore aquaculture, sablefish

## Introduction

The rapid development of offshore marine finfish aquaculture worldwide has raised concerns due, in part, to the potential negative genetic and fitness impacts escaped farmed fish may have on natural populations (Hindar *et al*., 1991; Tufto, 2010; Waples *et al*., 2012). Fitness is measured in terms of an individual's relative reproductive success. The fitness of escapees in the wild is often inversely correlated with the level of domestication those fish experienced in culture (Baskett *et al*., 2012). Genetic and fitness-related impacts to the wild population then occur when escaped individuals from these cultured populations interbreed with wild conspecifics (Baskett *et al*., 2013). Changes in gene expression due to adaptation to the hatchery environment and fitness declines in a mixed population due to domestication can occur after only one or two generations (Araki *et al*., 2008; Christie *et al*., 2016).

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These impacts can threaten the adaptive potential of the wild population, which may make it less able to respond to and survive environmental changes (Tringali and Bert, 1998).

There is little scientific data, however, that reliably assigns the risk to fitness due to escapees, particularly for mariculture. Thus, existing regulatory standards addressing escapes are largely preventative, theoretical, or qualitative rather than quantitative. To address this knowledge gap, the NOAA Fisheries Office of Aquaculture (OAQ) developed a research initiative designed to explore the genetic interactions between wild and cultured fish. As part of this initiative, the OAQ solicited ICF International, Inc., (ICF) to develop the Offshore Mariculture Escapes Genetics Assessment (OMEGA) model. OMEGA is a Microsoft Excel-based program designed to simulate the risk posed to wild population fitness by escapes from marine aquaculture programs.

Simplified, risk to wild population fitness due to interbreeding with escapees is a function of the number of escapees relative to wild census size, the genetic difference between escapees and wild fish, and the fitness of escapees in the wild relative to wild fish. OMEGA is organized around three interacting components that incorporate these factors, including the aquaculture operation itself, wild population characteristics, and the potential for interaction between escapes and wild conspecifics. Under these components, OMEGA employs a modular format to describe assumptions used to model the potential interactions and impacts of escapees in the wild. There are nine modules requiring user input, ranging from basic settings and preferences for saving the workspace and running simulations to entering wild and cultured population data. Currently, there are 103 possible user-defined variables (Index of User Inputs available upon request), some of which are optional and a few that represent alternatives for which the user chooses one of two or more options.

Once the model has been parameterized with data describing the three interacting components, OMEGA employs a single trait phenotypic fitness model developed by Ford (2002) to simulate risk. This underlying model is a quantitative two population analysis of differential selection regimes and the effect of gene flow between the populations on the mean trait value. Initially, each of the two populations is exposed to a separate environment (hatchery or wild) and, therefore, selective regime (domestication or natural). The mean trait value of each population is equal to its environmental (and fitness) optimum, and any shift away from either environmental optimum trait value leads to a reduction in fitness (Lande, 2007; Tufto, 2010).

OMEGA is intended to provide insight into the variables affecting risk, help identify information gaps and research priorities, explore options for operational design or modification, and inform policy and management decisions (Volk *et al*., 2015). To illustrate OMEGA's application, we present results from evaluations of a theoretical sablefish (*Anoplopoma fimbria*) program and a real world pilot project for Almaco jack (*Seriola rivoliana*).

## Methods

Escape scenarios for both species varied from low to high base leak rates, cage failure probabilities, and catastrophic cage failure probabilities.

### Sablefish

Sablefish are a highly-prized groundfish found along the North Pacific Rim. The wild population includes a single stock along the west coast of the U.S. Fish live up to 80 years but old fish are rare. The female spawning biomass is 79 - 82 metric tons (mt), with maturity reached by six years. Models for population dynamics and harvest are well-established in this species.

Commercial culture of sablefish currently occurs in Washington State, USA, and British Columbia, Canada. The OMEGA scenarios were originally developed for model verification and explored a low versus a high incidence of escapes, with a high encounter rate between wild and farmed fish (Volk *et al*., 2015). A hypothetical sablefish hatchery program was sited in the U.S. Pacific Northwest and included using a domesticated broodstock to produce up to 10,000 mt of fish stocked among 50 offshore cage sites. Culture methods were recently developed, with fish reaching harvest size in one year.

OMEGA was run multiple times. For the low escapes scenario, the base leak rate and cage failure probability was set at a static 0.1%, regardless of fish size. The annual probability of a catastrophic event was set at 5% through the first 20 years of operation, decreasing to 1% by year 26 and thereafter, with a static assumed program loss of 20% per event across all years. For the high escapes scenario, the base leak rate, cage failure probability, and probability and magnitude of losses due to catastrophic events were increased. Base leak rate was dependent on fish size, with 3% of the smallest fish and 0.5% of the larger fish escaping. Cage failure probability was 0.5% for smaller fish and 1% for larger fish. Meanwhile, the probability of catastrophic events was set at 10%, with a 60% loss of fish per event, in year 1, which decreased to 5%, with a 40% loss, by year 16. Thereafter, probability was 5%, with a 20% program loss.

**Almaco jack**

Almaco jack (also known as kahala or kampachi in Hawaii) have a circumglobal distribution in tropical and temperate waters. Fish tend to school near reef slopes, offshore banks, and other objects, and they are often found in mixed schools with the greater amberjack (*S. dumerili*). The wild population in Hawaii is poorly characterized, and data used for populating OMEGA was supplemented with information from congenerics (e.g. greater amberjack size at maturity of 2.5 kg and fecundity at 130 thousand eggs per kg body weight).

In terms of U.S. commercial culture, Kampachi Farms has recently engaged in iterative open-ocean pilot projects directed at expanding offshore farming of almaco jack to a commercial scale near Kailua-Kona, HI, USA, and elsewhere. The OMEGA scenarios for Kampachi are based on well-developed operational plans. The project will use wild broodstock as required for permitting in Hawaii. Culture methods are established, and fish reach harvest size of 1.8 kg in one year. The F1 juveniles will be stocked in a tethered cage located approximately 11 km offshore of Kona, with production of about 14 mt per year for each of two years.

OMEGA was run multiple times. The assumed number of escapes was set at 50-100% per year. The natural spawning and total biomass was set equal to catches reported for all carangids in the Western Pacific Region reef fish trend report (2010). The encounter rate between wild and farmed almaco jack is likely to be low due to behavior characteristics (i.e. schooling near objects). Escapee survival and reproductive capabilities are known to be poor from previous pilot projects.

## Results

Over the default 100-year timespan of the simulations, the low escapes scenario for sablefish resulted in escapee percentage peaking at ≤ 5% of the total population and the spawning biomass soon after each escape event, with larger and/or successive events resulting in higher percentages, but gradually shrinking to < 1% of the population. High chronic escapes coupled with several acute escape events, in contrast, had a longer lasting impact on population make-up. The high escape scenario resulted in escapees comprising a significantly higher proportion of the population, averaging 5 -7%. Correspondingly, fitness in the wild was reduced (shifted toward the hatchery optimum; Fig. 1) more under the high escape scenario, whereas the low escape scenario remained near the wild optimum.

Whereas the high escapes scenario for sablefish resulted in a significant impact to wild population fitness, even a total loss of almaco jack had a

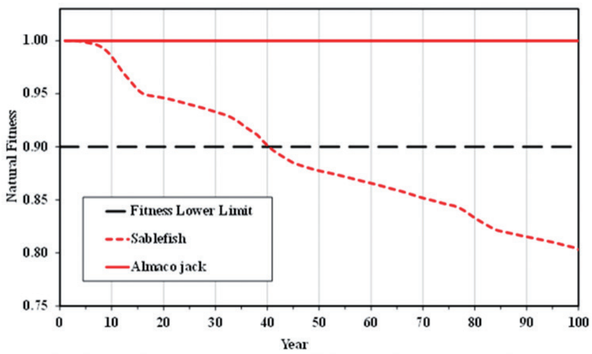


**Fig. 1.** Relative fitness effects for a sablefish (broken red line) and an almaco jack (solid red line) escape scenario, both with a high number and frequency of escapes. Almaco jack scenario results similar to no aquaculture. Dotted black line represents a hypothetical regulatory maximum 10% decrease in mixed population fitness.

negligible effect on the mean trait value (Fig. 1). The proportion of the wild almaco jack population and spawning biomass made up of escapees peaked at 0.45% and 0.87%, respectively, of the over 100-year span of the simulation. No significant decrease in fitness (< 0.02%) was predicted even when all 30,000 fish escaped and survived. Fitness impacts were realized, but still not significant, in attempts to force the model to show a fitness effect (i.e. to "break the model"), with a small estimated natural biomass, significantly more than two years of production, 100% annual escape and encounter rates, and 100% survival and spawning of escapees.

## Discussion

Results were in line with expectations according to Ford (2002), as well as results from related research (e.g. Baskett *et al*., 2013). Key differences in the simulated fitness risk associated with each program included, but were not limited to, broodstock source (domesticated or wild), encounter rate, and the scale (size and longevity) of the operation. The sablefish culture program was hypothetical and used originally to verify that the OMEGA was operating as expected. Were an offshore program to be developed for the species, results from these hypothetical scenarios could be used as a starting point in terms of designing a low risk program. Topics that may be important to consider when designing a program based in part on results from OMEGA include, but are not limited to, whether any scenarios are economically viable or ecologically sustainable and whether engineering or biological technology to minimize risk is available and economically feasible. In contrast, the almaco jack pilot program produced negligible effects. These results were included in an environment assessment submitted as part of the permitting process for the proposed pilot project for Kampachi Farms. It is recommended that reassessment of risk be performed, however, if Kampachi Farms wishes to modify protocols or scale production up to commercial levels.

OMEGA is still a work in progress, however, and requires further testing. The next steps toward finalizing the OMEGA model package for broader use include fostering external collaborations to develop model scenarios, evaluate model parameters, and validate the model with data from current and planned aquaculture operations worldwide; developing targeted scenarios, such as exploring the magnitude of risk associated with 1) using wild or selected broodstock; 2) widening the fitness gap between farmed and wild fish or keeping fish "wild-like;" focused research like induced sterility (e.g. triploidy; Hindar *et al*., 1991), and setting and enforcing spatiotemporal escape limits. Downstream steps include performing a sensitivity analysis of case studies, determining acceptable default parameters, and developing an economic analysis module. Work will also be directed at making OMEGA fully operational and friendly to a variety of user groups (e.g. managers, industry professionals, researchers), paving the way for the model to play a key role in genetic risk assessments for offshore culture in the U.S. and elsewhere.

Aquaculture must simultaneously support commercial interests; increase the availability of safe and nutritious fish, shellfish, and other products for consumers; and protect wild populations (IWG-A 2014). Toward that end, more specific questions that OMEGA may help user groups answer include how significant the impacts of escapes surviving to reproduce are and what the effects of our decisions about aquaculture operations, such a broodstock management (e.g. wild or selected), may be. More broadly, the intent is to use OMEGA to help define an acceptable risk to marine resources (e.g. 5% or 10% fitness decrease), as well as use it as a decision-making tool to assist in the assessment and management of marine aquaculture operations such that they may remain both commercially viable and environmentally responsible.

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OMEGA v1.0 and its user guide are freely available for download on the OAQ website at www.nmfs.noaa.

gov/aquaculture/science/omega_model_homepage.html.

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(1) Baskett M. L., Burgess S. C., and Waples R. S., 2013: Assessing strategies to minimize unintended fitness consequences of aquaculture on wild populations. *Evol. Appl.* **6**, 1090-1108.

Baskett *et al.* (2013) address various factors associated with the management of cultured populations and model their potential fitness impacts should farmed fish escape into the wild. Factors assessed include the origin and level of domestication in the cultured stock (i.e. degree of maladaptation), induced sterility in the cultured stock, and the magnitude and frequency of escapes (e.g. continuous low level leakage versus rare catastrophic events). Results indicate that, up to a point, the magnitude of the fitness impact rises as the maladaptation of escaped cultured fish increases; an extremely maladapted, non-local origin cultured population may actually have effects similar to a weakly diverged stock. Second, sterilization reduces unintended fitness consequences rapidly. Finally, it is more effective to reduce low-level leakage than guard against sporadic large-scale escape events.

(2) Ford M. J., 2002: Selection in captivity during supportive breeding may reduce fitness in the wild. *Conserv. Biol.* **16**, 815-825.

Escaped cultured fish may cause a potential loss of fitness in the wild, if breeding occurs between escapees and wild conspecifics. This drop in fitness is associated with a difference in the optimum trait values for hatchery and natural environments. The single-trait phenotypic fitness model in Ford (2002) describes how mean phenotype values of the mixed population (captive plus wild fish) may shift relative to the optimum values for each environment, based on the presence/absence and amount of gene flow (interbreeding) between the cultured escaped and wild fish. The overall fitness effect depends on the magnitude of the difference in optimum trait value, trait heritability, and selection pressure against domestication in the wild, as well as habitat capacity, magnitude and frequency of escape events, wild and captive population demographics, and the potential for interaction between wild fish and escapees. Ford (2202) was used most notably in Pacific Northwest salmonids, where the All-H Analyzer, or AHA, model helped the Hatchery Scientific Review Group explore the potential fitness consequences of supplementing wild populations and of cultured fish straying into wild populations.

(3) Hindar K., Ryman N., and Utter, F., 1991: Genetic effects of cultured fish on natural fish population. *Can. J. Fish. Aquat. Sci.* **48**, 945-957.

Hindar *et al.* (1991) represents one of the original manuscripts reviewing the genetic impact escaped farmed fish may have on wild populations and is one of the most often cited. The authors recommend several strategies for protecting the genetic integrity of wild populations, many of which remain the focus of aquaculture programs today. These strategies include improved containment technology and recovery, sterilization of the culture stock, and better breeding practices, coupled with monitoring the genetic contribution of escaped fish to the mixed population.

(4) Waples R. S., Hindar K., and Hard, J. J., 2012: Genetic risks associated with marine aquaculture. NOAA Technical Memorandum NMFS-NWFSC-119. US Department of Commerce NOAA NMFS, Washington, D.C.

Waples *et al.* (2012) is a comprehensive overview of the potential genetic impacts to wild populations associated with marine aquaculture. As such, the authors "provide managers with a better understanding of the genetic effects of marine aquaculture on natural populations," with the intent of informing policy and management decision-making. The document synthesizes relevant information and provides key references, identifies research priorities, provides a risk assessment framework, and gives recommendations for monitoring and evaluation toward sustainable marine aquaculture development in the US. Waples *et al.* (2012) focuses on commercial aquaculture of marine finfish but presents it in light of decades of research on salmon hatcheries and marine stock enhancement.