Environmental Performance of Marine Net-Pen Aquaculture in the United States

Article *in* Fisheries · November 2014

DOI: 10.1080/03632415.2014.966818

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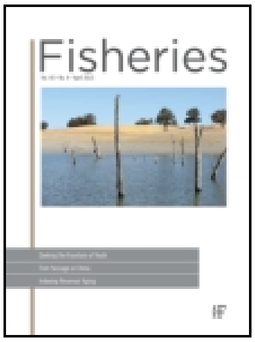

Fisheries

ISSN: 0363-2415 (Print) 1548-8446 (Online) Journal homepage: http://www.tandfonline.com/loi/ufsh20

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To cite this article: Michael B. Rust, Kevin H. Amos, April L. Bagwill, Walton W. Dickhoff, Lorenzo M. Juarez, Carol S. Price, James A. Morris Jr. & Michael C. Rubino (2014) Environmental Performance of Marine Net-Pen Aquaculture in the United States, Fisheries, 39:11, 508-524, DOI: 10.1080/03632415.2014.966818

To link to this article: http://dx.doi.org/10.1080/03632415.2014.966818

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ABSTRACT: *The United States has a small net-pen salmon industry dating back over 40 years and a nascent net-pen industry for other marine fish. The United States net-pen aquaculture sector has improved its resource efficiency in terms of the amount of fish meal and fish oil used in feeds and reduced its environmental impacts in terms of the mass loading and impact of nutrient discharge on the receiving ecosystem, the incidence and treatment of fish diseases, the use of antibiotics, and the number and impact of fish escapes, while increasing production. These changes can be attributed to a combination of advances in science and technology, rising cost of fish meal/oil, improved management, and informed regulatory practices. Net-pen aquaculture has become an efficient food production system. Existing laws and regulations in the United States effectively address most of the potential adverse environmental effects of net-pen aquaculture.*

Desempeño ambiental de la acuacultura marina con jaulas de red en los Estados Unidos de Norteamérica

RESUMEN: *Los Estados Unidos de Norteamérica (EE. UU.) poseen una pequeña industria de acuacultura de salmones mediante jaulas de red que data desde hace cuatro décadas y una incipiente industria de cultivo con jaulas de otras especies de peces marinos. El sector de la acuacultura con jaulas de red en los EE.UU. ha mejorado la eficiencia de sus recursos en términos de cantidad de carne y aceite de pescado utilizados para la engorda y en cuanto a la reducción de sus impactos negativos: el aumento de la producción versus la carga de masa y el impacto de la descarga de nutrientes en los ecosistemas receptores, la incidencia y tratamiento de enfermedades de peces, uso de antibióticos y el impacto del escape de peces. Estos cambios son atribuibles a la combinación de avances científicos y tecnológicos, el incremento en el costo de la carne y aceite de pescado, un mejor manejo y prácticas regulatorias informadas. La acuacultura con jaulas de red se ha convertido en un sistema eficiente de producción de alimentos. Las leyes y regulaciones existentes en los EE.UU. abordan de forma efectiva los efectos adversos potenciales de la acuacultura con jaulas de red.*

INTRODUCTION

Aquaculture is likely to supply most of the projected increased need for seafood over the next few decades (United Nations 2011; Food and Agriculture Organization of the United Nations [FAO] 2012; World Bank 2013). With available land and freshwater becoming scarce, marine aquaculture (finfish, shellfish, and seaweeds) will be an increasingly important contributor to the world's future food supply (World Bank 2013; Organization for Economic Co-operation and Development [OECD]/FAO 2014). Aquaculture is well established in many countries and continues to grow worldwide (FAO 2012). The United States is a global leader in aquaculture technologies and scientific advances (Natale et al. 2012) but has a relatively small aquaculture industry (National Oceanic and Atmospheric Administration [NOAA] 2012; World Bank 2013), providing less than 5% of the seafood consumed nationally (NOAA 2012). We estimate that the U.S. net-pen salmon industry (Atlantic Salmon *Salmo salar* and steelhead *Oncorhynchus mykiss*) produced about 12,000 tons (live weight) in Maine (US$78 million) and around 8,000 tons in Washington State ($52 million) in 2010. In the same year, the United States also imported over 280,000 tons of farmed salmon (NOAA 2012). We estimate that another

500–1,000 tons of various marine species were produced in net-pens from the remaining states (Figure 1).

The last 40+ years have seen significant advances in fish farming technology and management practices focused on decreasing the environmental footprint and increasing economic performance.

Marine finfish aquaculture in the United States represents an opportunity to provide healthy, domestic seafood (Merino et al. 2012), create jobs, contribute to coastal economies, and help reduce the trade deficit (National Research Council [NRC] 1978; Rubino 2008; Kite-Powell et al. 2013). The United States has one of the largest areas of exclusive economic zone that is environmentally and economically suitable for net-pen culture (Kapetsky et al. 2013). Given this potential, why is the marine finfish aquaculture industry not expanding? The reasons may lie, in part, with environmental concerns expressed about the salmon net-pen aquaculture industry (Naylor et al. 1998, 2000; Naylor and Burke 2005). Specific issues include impacts on water quality (Boyd et al. 2007), degradation of the seafloor under net-pens (Bridger and Costa-Pierce 2003; Beveridge 2004), the effect of fish escapes on the genetic diversity of wild populations (Waples et al. 2012), the sustainability of using fish meal and fish oil for feeds (Naylor et al. 1998, 2000; Adler et al. 2008), the use of antibiotics (Smith and Samuelsen 1996), and the potential transfer of diseases from farmed to wild populations (Johansen et al. 2011). These concerns have been widely publicized beyond the scientific community (Knapp et al. 2007; Baron 2010; Knapp 2012) and generate negative public perceptions that, in turn, reduce social acceptance for many types of aquaculture (Moffitt 2006; Amberg and Hall 2008; Mazur and Curtis 2008). Once established, negative public preconceptions may overshadow recognition of the progress made in the net-pen fish farming industry and other forms of aquaculture. A lack of social acceptance hinders efforts to simplify a complex and uncertain regulatory process (Gibbs 2009; Chu et al. 2010). In turn, regulatory and economic barriers to entry (e.g., onerous, lengthy, and uncertain permitting; high costs of coastal land, labor, and other inputs) reduce the ability of the United States to compete in the global farmed seafood market (Kite-Powell et al. 2013).

The last 40+ years have seen significant advances in fish farming technology and management practices focused on decreasing the environmental footprint and increasing economic performance (Kaiser and Stead 2002; Tveterås 2002; Asche 2008). Regulations have been developed to set performance standards in all jurisdictions of the United States where net-pen aquaculture occurs (see Box 1 and Table 1). Numerous organizations have developed purchasing policies, standards, and labeling programs that promote responsible aquaculture, creating financial incentives for producers to improve practices and become part of the responsible aquaculture movement (Boyd et al. 2007). How do these pressures translate to impacts of net-pen farming?

This article examines the current resource efficiency and environmental performance of U.S. marine net-pen finfish farming, considering the roles that administrative controls (regulation, economic, and management) and structural controls (science and technology) play in shaping a sustainable industry (Boyd et al. 2007; Belle and Nash 2008). We discuss issues related to feed, water quality and benthic effects, animal health, and potential genetic effects of fish escapes.

FEED AND FEEDING

The use of fish meal and fish oil in aquaculture feeds has been highlighted as a major sustainability issue and a limitation to the growth of carnivorous species aquaculture (Naylor et al. 1998, 2000; Kristoffersson and Anderson 2006). Yet raising fish, including carnivores, has efficiency advantages over terrestrial animals (see Box 2), and no animal has a nutritional requirement for fish meal or fish oil (NRC 1983, 1984, 2011). Further, formulated feeds with no fish meal or fish oil have been used experimentally to feed farmed Atlantic Salmon, resulting in growth and survival similar to those obtained with feeds containing fish meal and fish oil (Torstensen et al. 2008; Burr et al. 2012). The same is true of Rainbow Trout *Oncorhynchus mykiss* (K. J. Lee et al. 2002; Barrows et al. 2007; Gaylord et al. 2007), Red Sea Bream *Pagrus major* (Takagi et al. 2000), Grouper *Cromileptes altivelis* (Shapawi et al. 2007), White Sea Bass *Atractoscion nobilis* (Trushenski et al. 2013), Cobia *Rachycentron canadum* (Watson et al. 2012, 2013), and Pacific Whiteleg Shrimp *Litopenaeus vannamei* (Sookying 2010; Olmos et al. 2011). Modern fish feeds are formulated from a variety of ingredients in carefully determined proportions to provide a balanced mix of essential nutrients and energy at the lowest practical cost (Hardy and Barrows 2002; NRC 2011). Sources for these nutrients and energy are not limited to fish meal and fish oil, nor are there essential nutrients unique to fish meal or fish oil (Gatlin et al. 2007; Barrows et al. 2008; NRC 2011).

Traditionally, fish feeds have contained a high percentage of fish meal and fish oil because these ingredients provided a cost-effective means to satisfy the nutritional requirements of fish (Hardy and Barrows 2002). The balance of nutrients in fish meal and fish oil closely resembles and fulfills most nutritional requirements of fish with very few antinutritional factors (compounds that negatively impact the nutritional value of the feed). Alternative nutrient sources typically need to be treated, blended, and/or supplemented to adjust for missing nutrients, improve palatability, or remove antinutrients (Gatlin et al. 2007; Barrows et al. 2008). Partial or total replacement of fish meal and fish oil in fish feeds is fast becoming the norm, but the research to develop and the effort to apply these modifications adds cost to the feed and requires investment in research, processing, and infrastructure (Gatlin et al. 2007; Barrows et al. 2008; Naylor et al. 2009).

Over the past several decades, the supply of fish meal and oil coming from targeted fisheries has been more or less constant, whereas fed aquaculture has increased (See Box 3). The

BOX 1. Regulatory Requirements for U.S. Net-Pen Aquaculture

Multiple U.S. federal, state, and tribal government agencies regulate marine fish farms. Although aquaculture permitting processes can be complex and lengthy, federal and state local laws and regulations provide a comprehensive suite of requirements to address the environmental effects of fish farms outlined in this article. Table 1 lists the federal laws that apply to environmental sustainability of marine net-pen aquaculture in the United States and the agencies responsible for their implementation. State governments often impose requirements that are more stringent than these federal requirements.

For net-pen aquaculture, the key federal permits related to the issues discussed in this article are issued by the U.S. Army Corps of Engineers (USACE) to authorize the placement of structures in navigable waters and by the U.S. Environmental Protection Agency (USEPA) to authorize discharges into the environment. These permits are typically issued in coordination with state agencies; however, in the case of National Pollutant Discharge Elimination System (NPDES) permits, the USEPA vests the states with the authority to issue permits in state waters in accordance with the Clean Water Act. Before issuing permits, the USACE and USEPA are required to consult with the National Marine Fisheries Service (NMFS) and/or with the U.S. Fish and Wildlife Service on issues related to protection of habitat, endangered species, and marine mammals. Aquaculture operations must also comply with permitting, monitoring, and reporting requirements for aquatic animal health under regulations of the U.S. Department of Agriculture's APHIS. Regulations pertaining to chemical application require permits from the USEPA, whereas aquatic animal drugs and feed manufacture require approvals from the U.S. Food and Drug Administration (USFDA 2014). Fish feeds and ingredients are regulated for safety by the USFDA under the Federal Food, Drug, and Cosmetic Act and the Food Safety Modernization Act. The USFDA requires animal feed to be "pure and wholesome, to be produced under sanitary conditions, to contain no harmful substances, and to be truthfully labeled." Only approved ingredients can be used in animal feeds, and feed mills have to follow quality control plans. To be approved by the USFDA for use in animal feeds, ingredients must demonstrate utility and safety to both the target animal (fish) and to the humans consuming them. Harvest levels of fish species used in making fish meal and fish oil in the United States are determined by fishery management regulations under the provisions of the Magnuson-Stevens Fishery Conservation and Management Act and state laws. Fact sheets on all of these federal laws as they relate to aquaculture can be found at websites run by the Fish Culture Section of the American Fisheries Society (2013) and the National Association of State Aquaculture Coordinators (2013).

Currently, all commercial net-pen aquaculture production takes place in state waters. Commercial salmon net-pen farming is well established in Maine and Washington, which have correspondingly well-developed regulatory programs to authorize and oversee these operations. For example, Washington State laws and regulations specific to marine aquaculture give the Washington Department of Ecology and Washington Department of Fish and Wildlife regulatory authority over marine net-pens, disease, fish transfer, escapement, and best management practices (Lori LeVander, Washington Department of Ecology, personal communication). Hawaii has been authorizing and overseeing commercial-scale operations using submerged net-pens for more than 10 years. New Hampshire has done the same with smaller-scale research facilities, and a commercial facility recently started operations in New York. As interest in commercial production of finfish in marine waters expands, it is likely that additional states will become more actively engaged in the regulation of the net-pen aquaculture industry. In addition, NOAA is preparing regulations for a Fishery Management Plan for offshore aquaculture in the Gulf of Mexico, designed to allow NOAA to issue permits for finfish aquaculture of managed species in federal waters. Other regional fishery management councils may adopt similar plans, which would result in additional federal rules to regulate fish farming in additional regions.

BOX 2. Relative Efficiency of Aquatic and Terrestrial Animals

Farmed fish are more efficient protein and energy converters than terrestrial livestock (Bartley et al. 2007; Brooks 2007). This is because fish generally do not use energy to maintain body temperature and they do not need to support their own weight against gravity (R. R. Smith et al. 1978; Talbot 1993). Fish also invest less energy and body mass in a skeletal system compared to terrestrial animals (Moffitt 2006). Smil (2002) compared the protein efficiencies (the amount of protein in the product/protein fed × 100) of different farmed animals and found that carp had higher protein conversion efficiency (30%) than land animals (5% for beef, 13% for pork, and 25% for chicken). Salmon, trout, and other carnivorous fish have protein conversion rates that can range between 30% and 50%, depending on diet and other conditions (Refstie et al. 2004; Soto et al. 2007).

U.S. consumers often prefer boneless meat and fish products. Because fish have relatively small skeletal systems, they have a higher percentage of edible portions than animals with larger skeletal systems. For example, as much as 68% of the weight of farmed salmon is edible compared to about 44% in cows, 52% in pigs, 46% in chicken, and 38% in sheep (Bjørkli 2002; Brooks 2007; Hall et al. 2011). Torrissen et al. (2011) suggested that Atlantic Salmon could be among the most efficient domesticated farm animals because 100 kg of dry feed yields 65 kg of boneless salmon fillets, compared to only 20 kg of edible product from poultry or 12 kg from pork.

Figure 1a. Submersible net-pen near Kona, Hawaii.

Figure 1b. Salmon farm in Washington State.

Figure 1c. Net-pens in Maine used for growing cod and salmon.

BOX 3. Fish Meal Supply and Demand

The world's annual supply of fish meal and fish oil has averaged 4 to 5 million metric tons of meal and around 1+ million metric tons of oil for the last 20 years (International Fish Meal and Fish Oil Organization 2013). Of these total quantities, currently, about 70% originates from "reduction" fisheries targeted at small, wild pelagic fish, such as sardine, anchovy, menhaden, and capelin. The remainder originates from processing wastes from both wild and farmed fish (Jackson 2012; FAO 2012; OECD/FAO 2014). Stocks historically used for reduction fisheries are more and more being used for human consumption, and processing wastes that were historically discarded are now being used for fish meal and oil production (Jackson 2012; World Bank 2013; OECD/FAO 2014).

Increased demand with fixed supply caused prices of fish meal (Figure 2) and fish oil to increase dramatically over the last decade (Adler et al. 2008; Jackson 2012; OECD/FAO 2014). This increasing cost differential relative to other protein and oil sources spurred development of replacements for fish meal and fish oil in aquaculture feeds (Gatlin et al. 2007; Tacon and Metian 2009; Tacon et al. 2011) and a greater recovery of fish trimmings from aquaculture and wild captured seafood (Shepard et al. 2005; Jackson 2012; OECD/FAO 2014). Prior to 2004, the price of fish meal was less than US$1,000/ton and was closely constrained by the prices of substitute proteins. After mid-2006, fish meal prices increased to $1,000–$1,500/ton, and by late 2009, they had further increased to $1,500–$1,800/ton. In 2012, for the first time, they peaked above $2,000/ton and were at $2,400/ton at the end of 2014. In comparison, during this same period, soybean meal, a leading substitute protein, increased from about $200 to a peak at $550/ton before settling down around $500/ton, widening the price gap between the two protein sources from less than $500/ton prior to 2004 to $1,000–$1,500/ton by 2009. Since 2002, the cost gap between soy protein and fish meal has increased almost fourfold. This provided the financial incentive to justify spending for the extra processing and supplementation needed to use increased amounts of alternative proteins and oils in fish feeds. Because feed accounts for more than 50% of the total operating costs in net-pen aquaculture and ingredients account for about 70% of the cost of making feed, there are strong economic incentives to use the most cost-effective mix of ingredients.

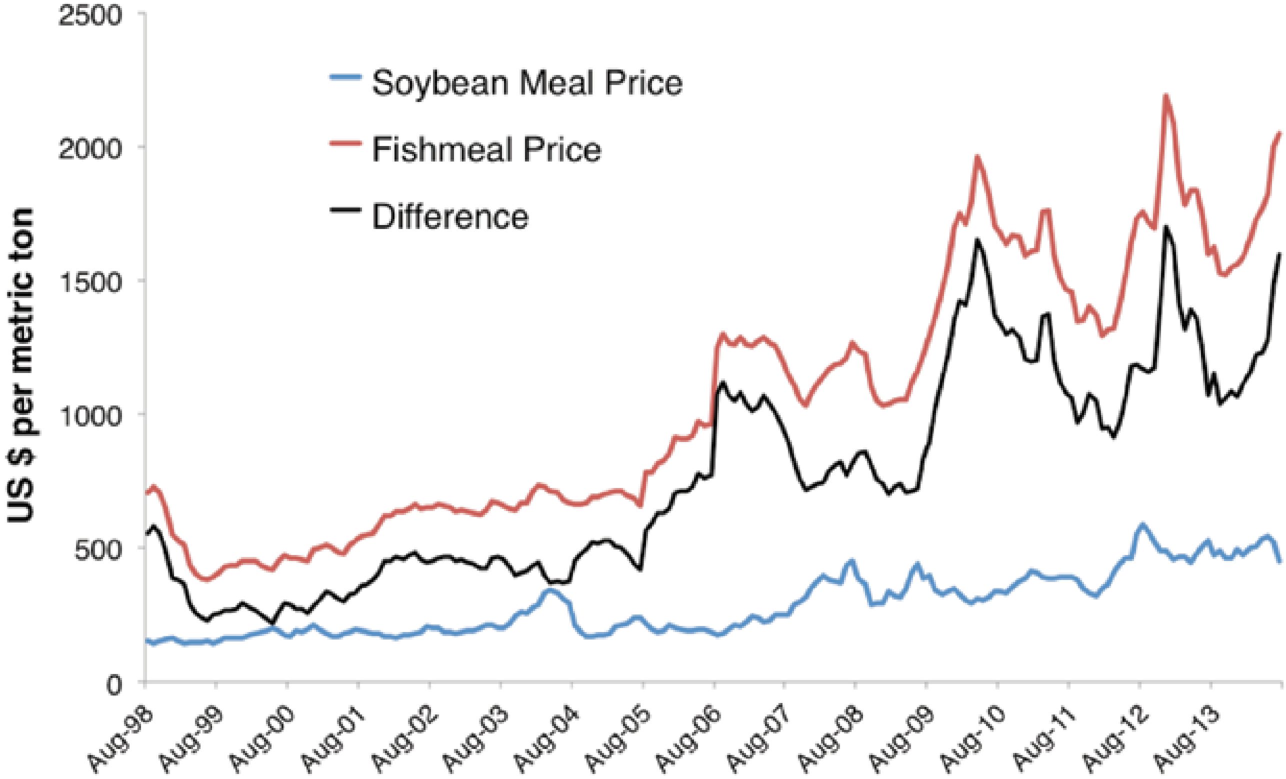

Figure 2. Cost in U.S. dollars per metric ton of 65% crude protein fish meal (Peru), 48% crude protein soybean meal (United States), and the difference between the two. Source: www.indexmundi.com (August 2014).

proportion of the world's supply of fish meal and fish oil going into aquaculture feeds increased by displacing use from terrestrial animal agriculture until it consumed an estimated 68% of world fish meal and 88% of world fish oil in 2005 (Tacon and Metian 2008, 2009; FAO 2011). However, by 2008, the amount of fish meal in aquaculture had fallen 13% from 2005 (FAO 2011; International Fish meal and Fish oil Organization 2013). Some stocks previously fished for producing fish meal and oil are increasingly being redirected toward human consumption (Jackson 2012; OECD/FAO 2014). Likewise, fish oil is increasingly being used as a human dietary supplement (Tacon and Metian 2009; FAO 2012; Jackson 2012). Tacon et al. (2011) and Jackson (2012) predicted that the percentage and the absolute amount of fish meal and fish oil consumed by aquaculture will continue to decrease as they become a smaller component of fish feeds, largely due to the development of lower cost alternative sources of protein (Gatlin et al. 2007; Barrows et al. 2008) and oil (Rust et al. 2011; Ruiz-Lopez et al. 2014). Similarly, Torrissen et al. (2011) reported that the Norwegian salmon farming industry has dramatically reduced the content of fish meal and fish oil in salmon feeds from >60% to <25% of the diet, largely by replacement with plant proteins and oils. Use of fish meal and fish oil in aquaculture has responded to the economic realities of the past few decades (see Box 3 and Figure 2), with increasing price differentials between fish meal/oil and other protein/oil sources leading to development of substitutes. Use of these substitutes is causing a decoupling of fed aquaculture and the harvest of stocks for fish meal and oil. Development of ingredient choice continues to be one of the most active areas of research in aquaculture nutrition.

NUTRIENT IMPACTS TO WATER QUALITY AND BENTHOS

Deleterious effects to water quality and the benthos around net-pen fish farms can occur when nutrient inputs exceed the physical, chemical, and biological capacity of the ecosystem to assimilate them (Pearson and Rosenberg 1978). Excess organic nutrients and suspended solids can lead to eutrophication and sedimentation in receiving waters (Boyd et al. 2007). Uneaten feed and fish wastes are the main sources of excess organic nutrients from net-pens. Because nutrients are discharged directly to the ocean, effluent treatment is not feasible. Instead, farms seek to manage nutrient waste with farm practices, efficient feeds and feeding (Figure 3), optimal pen configurations and farm orientation in order to optimize fish growth, waste distribution, and nutrient assimilation by the food web. Modeling interactions between farm production and environmental processes can guide decisions about sustainable farming (Aguilar-Manjarrez et al. 2010) and prevent exceeding the site's ecological carrying capacity.

Water Quality

Impacts to water quality at farm sites, including increased nitrogen, phosphorus, lipids, and turbidity, or oxygen depletion, have lessened significantly over the last 20 years (Soto and Norambuena 2004; McKinnon et al. 2008; Price and Morris 2013). These improvements are attributable to a combination of better understanding of siting requirements, improved feeding, better feed formulation, and better farm management practices. Good

Figure 3. Control room for a salmon farm in Washington State. Fish feeding, behavior, and health are monitored using underwater video and water quality data are collected and displayed on computer screens. Feeding is done based on a computer-controlled system, feedback from the video, and the operator's experience. Photo by Laura Hoberecht.

management practices include siting farms in well-flushed areas with adequate current (mean of >7 cm/s) and depth (Belle and Nash 2008). When net-pens are properly sited, water quality impacts are typically not detectable beyond 30 m from the pens (Mantzavrakos et al. 2005; Nash et al. 2005; Tlusty et al. 2005). Though a phytoplankton response to nutrient loading has been reported at some fish farms, this is generally considered low risk (Nordvarg and Hakanson 2002; Soto and Norambuena 2004; Apostolaki et al. 2007).

Causal linkages have not been established between fish farming and eutrophication (Pitta et al. 2005; Modica et al. 2006) or phytoplankton blooms (Silvert 2001; Anderson et al. 2008). In Maine and Washington, other factors besides nutrients, such as light availability and water temperature, often control natural variability in primary productivity. Naturally occurring nutrient fluxes from coastal ocean upwelling, or from land- and ocean-based sources, are often high relative to loads from aquaculture. Because nutrients may be flushed away from the immediate cage area and dispersed into the surrounding water body, it is difficult to assess whether far-field primary production is being affected over large areas and at longer timescales. The occurrence of many anthropogenically derived nutrients in coastal marine waters makes it difficult to attribute nutrification and phytoplankton response to any one source, including aquaculture.

Benthic Impacts

Benthic impacts result where organic nutrients in uneaten feed and fish waste accumulate on the seafloor (Pearson and Black 2001; Chamberlain and Stucchi 2007; Belle and Nash 2008) and do not decompose quickly enough by natural aerobic bacterial processes to keep up with the supply from the farm. In this case, sediments shift toward anaerobic conditions, and the benthic species diversity declines, with perturbation-tolerant generalists becoming dominant (Hargrave 2003; Holmer et al. 2005; Hargrave et al. 2008).

Benthic impacts from U.S. net-pens have reduced dramatically over the last few decades, due to improved siting and better management practices. Indicators to assess benthic condition include total organic carbon, redox potential, free sulfides, and abundance and diversity of marine organisms. Electrochemical and image analysis methods are also used (Schaaning and Hansen 2005; Wildish et al. 2003). These indicators inform site management decisions, such as when to fallow (leave a site empty of fish for a period of time) or to adjust feeding and harvest. Because feed typically accounts for more than half the operating costs, farmers have the financial incentive to use underwater cameras to monitor and regulate feeding to minimize wasted feed (Figure 3).

Accumulation of particulate waste is unlikely at farms over erosional seafloors (Kalantzi and Karakassis 2006). Under dispersive conditions, particulate wastes are spread away from the immediate farm footprint, aerobically decomposed, and assimilated by benthic organisms (Holmer et al. 2005; Phillips 2005; Giles 2008). Farm discharge can enhance productivity of macro-algae, invertebrates, and fish (Katz et al. 2002; Dempster et al. 2005; Rensel and Forster 2007). Conversely, depositional sites tend to accumulate organic waste. In this case, fallowing allows chemical and biological recovery of sediments (Wildish and Pohle 2005; Tucker and Hargreaves 2008; Borg and Massa 2011). Fallowing takes months to years for bottoms to return to pre-farm conditions depending on the site's flushing characteristics and level of accumulation (Brooks et al. 2003, 2004; Lin and Bailey-Brock 2008).

Modeling and Monitoring Water and Benthic Impacts

U.S. fish farms must monitor discharges to the benthos and water column to meet the standards of the Clean Water Act, which established the National Pollutant Discharge Elimination System (NPDES). In 2004, the U.S. Environmental Protection Agency (USEPA) developed a national effluent rule for net-pen aquaculture (USEPA 2004), establishing effluent limitations for aquaculture facilities into waters of the United States. Environmental impact models now allow regulators to assess the suitability of sites, understand the potential risks and benefits of proposed net-pen operations, and estimate the limits of acceptable farm biomass before they are permitted (Rensel et al. 2007; Black et al. 2008).

Monitoring data collected from U.S. marine fish farms (Alston et al. 2005; Lee et al. 2006; Langan 2007) and from other countries (Hargrave 2003; Wildish et al. 2004) often indicate few significant or persistent water quality or benthic issues (Price and Morris 2013). Such data help to validate and improve models to inform siting and management of current and future farms. In Maine and Washington, improved siting and pen configurations, better feeds, and improved feeding practices have decreased benthic deposition at salmon farms (Nash 2001; Langan 2007). Washington State regulations require no net increases in benthic nutrients (Lori LeVander, Washington Department of Ecology, personal communication). In Maine, the standard is "the habitat must be of sufficient quality to support all species of fish indigenous to the receiving waters and maintain the structure and function of the resident biological community" (Jon Lewis, Maine Department of Marine Resources, personal communication). Fish farms are required to have regular monitoring by independent third-party scientists with results reviewed by state agencies and made available to the public.

FISH HEALTH AND DISEASE TRANSFER

Disease is a fact of life in all animal populations and production systems. Water moves freely between net-pens and the open marine environment, allowing the transmission of pathogens between wild and farmed fish (Kent 2000). Fisheries managers are concerned about the risk of pathogen amplification on farms followed by transmission of pathogens from farmed to wild fish, as well as the introduction of nonnative pathogens and parasites when live fish are moved from region to region. Culturists have incentive to work with resource managers and regulators to ensure that fish health is optimized on the farm and not negatively affecting wild populations. Robust health of farmed fish is economically advantageous to fish farmers, who depend on high survival rates and marketing healthy fish.

Experience and observation of disease outbreaks in farmed salmon (Hastein and Lindstad 1991; Jones and Beamish 2011) and hatcheries (Amos and Thomas 2002) provide information on disease risks to wild populations. Fish diseases occur naturally in the wild, but their effects often go unnoticed because moribund or dead animals quickly become prey for other aquatic animals. Clinical disease occurs only when sufficient numbers of pathogens encounter susceptible fish under environmental conditions that are conducive to disease (Rose et al. 1989). Observable disease events may occur in net-pens because (1) fish are reared at higher densities than those found in nature, increasing rate of contact between individual fish within the pen; (2) infected fish are not removed from the farm population as they would be in nature by predators; and (3) the farm population is easily observed. Therefore, pathogens that normally exist in low numbers and do not cause disease in the wild may result in disease and observable mortality in farmed fish (Raynard et al. 2007).

Managers of aquaculture facilities prevent and control disease events with biosecurity measures, effective vaccines, appropriate nutrition, genetically improved lines of organisms, appropriate rearing densities and other proven aquatic animal health measures, and therapeutants. In addition, regulatory bodies have implemented rules to prevent introduction of exotic pathogens into new regions/zones and transmission of endemic pathogens among animals within an area. Common health risks for and from farmed salmon include bacterial and viral diseases and parasites. Principles to prevent and treat these health risks developed by the farmed salmon industry are also applicable for other species and are specified by the World Organization for Animal Health (OIE 2013) and the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (APHIS 2008).

Bacterial and Viral Diseases

Although bacterial infections are common in farmed salmon and caused significant mortality in the early years of salmon farming, a number of measures, including vaccines, probiotics, limiting culture density, high-quality diets, and judicious use of antibiotics are effective at preventing and controlling bacterial diseases. Antibiotics are considered a method of last resort and are being replaced by other aforementioned management approaches (see Box 4 and Table 2).

The management of viruses is focused on monitoring for diseases and maintaining culture conditions that provide for healthy fish able to resist disease through good nutrition, genetics, and low stress husbandry approaches. When a reportable virus is discovered, farms are typically depopulated (see Box 5).

Parasites

Much of what we understand about risks associated with parasites on farmed fish comes from work done to control sea lice on salmonids, and this is still an active area of research (see Box 6). Controlling the level of parasites on farms significantly reduces the potential for transfer to wild salmon and trout (D. Jackson et al. 2002; Jones and Beamish 2011; Rogers et al. 2013) and the health of the cultured stock. Significant in-

BOX 4. Antibiotic Use in Salmon Net-Pens

In the Norwegian salmon farming industry, antibiotic use has decreased by approximately 95% in the past 20 years due to the introduction and use of efficacious vaccines (Midtlyng et al. 2011). During that same period, salmon production in Norway has increased from about 180,000 to 1,000,000 metric tons (FAO 2013). Similar numbers are available for British Columbia (Department of Fisheries and Oceans, Canada 2014). In the United States, three antibiotics are approved and labeled to treat specific diseases in specific aquatic species. The majority of these labels are for freshwater applications. Any use by species, conditions, or diseases other than those listed on the label must be done via extra-label use that requires a licensed veterinarian to approve (USFDA 2012). As in Norway, effective vaccines have significantly reduced the use of antibiotics in U.S. salmon farming. In Maine, no antibiotic use was reported in net-pen salmon farms starting from 2007 (Table 2). This trend has continued and no antibiotic use has been reported for salmon net-pens in Maine from 2007 to 2012 (the last year records are available; Jon Lewis, MDMR, Aquaculture Environmental Coordinator, personal communication). This contrasts with approximately 13,500 metric tons of antibiotics being used in 2010 for all animals used for human consumption in the United States (USFDA 2011).

BOX 5. Dealing with IHN and ISA Viral Diseases

Infectious hematopoietic necrosis (IHN) is an acute disease of salmon caused by the virus of the same name (World Organization for Animal Health 2012). It occurs naturally in the Pacific Northwest and causes varying degrees of mortality in wild salmon (Traxler et al. 1997). Atlantic Salmon are farmed in the Pacific Northwest, but they have little resistance to IHN and are particularly sensitive to this virus. This has resulted in significant outbreaks of IHN in marine salmon pens in British Columbia (Saksida 2006) and a recent event in Washington State (J. Kerwin, Washington Department of Fish and Wildlife, personal communication). However, there is no evidence that historic IHN outbreaks in farmed Atlantic Salmon have impacted wild Pacific salmon in the Pacific Northwest. Returning adult wild salmon populations did not appear to be affected in years in which significant IHN outbreaks occurred in farmed salmon in British Columbia (Pacific Salmon Commission 1993). Furthermore, in controlled water-borne transmission studies with IHN virus, researchers were unable to cause an infection in Chinook Salmon *O. tshawytscha* or Sockeye Salmon *O. nerka* but caused infection leading to a 10% mortality rate in Atlantic Salmon (Traxler et al. 1993). There is an IHN vaccine that has been used in the Pacific Northwest on Atlantic Salmon but with variable success.

Likewise, infectious salmon anemia (ISA) is a serious viral disease of farmed Atlantic Salmon. Although ISA has been observed in Atlantic Salmon farms in Europe, Chile, New Brunswick, and Maine (Gustafson et al. 2007), the OIE reports that there are no confirmed cases of this disease or causative virus in the Pacific Northwest in wild or farmed salmon (OIE 2013). Nevertheless, agencies and industry in the United States and Canada carry on an active surveillance program for the ISA virus. Attempts to induce ISA disease in Pacific salmon using water-borne laboratory challenges have been unsuccessful, suggesting that Pacific salmon are resistant to the ISA virus (Rolland and Winton 2003). Recent reports in British Columbia suggest that the ISA virus, but not the ISA disease, was found in wild Pacific salmon (Simon Fraser University 2011). However, the Canadian Food Inspection Agency has been unable to confirm these findings (Canadian Food Inspection Agency 2012). Because ISA is a very serious disease for Atlantic Salmon, increased surveillance and research is currently being undertaken by Canadian and U.S. agencies to determine whether ISA virus is truly present in the Pacific Northwest. To date, this surveillance in 2012 and 2013 in the Northwest has failed to demonstrate the presence of ISA disease or the ISA virus (J. Whaley, USDA/APHIS, personal communication; J. Constantine, Canadian Food Inspection Agency, personal communication).

Management of viral diseases is focused on monitoring for the diseases and maintaining culture conditions that provide for healthy fish through good nutrition and low stress husbandry changes. When viral diseases are discovered, farms are depopulated. In the future, we may see vaccines for viral diseases, but so far they remain experimental.

tegrated lice management programs that have been instituted in Norway (Ministry of Fisheries and Coastal Affairs 2009) and Ireland include treatment of lice on farmed fish with approved therapeutants, fallowing of farm sites, and zonal single year-class management strategies. Cleaner wrasses and other species have been used commercially with success to reduce the lice load on salmon in pens and are an important part of integrated pest control programs there (Torrissen et al. 2013).

BOX 6. Sea Lice Impact Is Still an Active Area of Scientific Research

Sea lice have varying effects on wild and farmed fish depending on geographic location, ocean salinity, temperature, and infected fish populations in the vicinity (Jackson et al. 2012). Extensive studies conducted in Europe (Torrissen et al. 2013) showed that lice transmission initiates from wild to farmed fish and then can be transmitted back to wild fish (Raynard et al. 2007). Detrimental effects have been described for both wild and farmed hosts. The impact of sea lice from farmed salmon on wild fish has been reported to be substantial in some cases (e.g., wild Sea Trout in Ireland; Tully and Whelan 1993). Conversely, a 10-year study by D. Jackson et al. (2013) a decade later indicated that overall survival of out-migrating juvenile Atlantic Salmon in Ireland was only slightly impacted by sea lice, accounting for about 1% mortality compared to approximately 94% mortality for all other causes (5% survival to spawn). This study suggests that lice from salmon farms have a relatively small impact on wild Atlantic Salmon.

Observations by some researchers suggest that sea lice originating at salmon farms in British Columbia have caused infections and significant mortality in wild juvenile Pacific salmon (Krkosek et al. 2005; Morton and Routledge 2005). These authors postulated that marine salmon farms were responsible for depressions in wild Pacific salmon populations, including a low return of adult Pink Salmon *Oncorhynchus gorbuscha* to the Broughton Archipelago. In contrast, other research (Beamish et al. 2006; Jones et al. 2006; Jones and Beamish 2011) indicates that sea lice populations fluctuate due to climatic and water conditions and that wild Three-Spine Sticklebacks *Gasterosteus aculeatus* and wild salmon act as natural carriers and reservoirs of infection for other wild fish. After reviewing 20 years of data on sea lice in farmed Atlantic Salmon in British Columbia and its relationship with wild Pink Salmon survival (Pink Salmon are potentially the most impacted because of their relative small size upon entry to sea water as compared to other salmon species), Marty et al. (2010) concluded that wild salmon productivity was not associated with farmed fish production or prevalence of sea lice.

Researchers have investigated the use of vaccines and genetic resistance of hosts to combat lice. Although both approaches show promise in the laboratory, to date they have provided limited commercial success.

Similar approaches are used to manage sea lice on salmon farms in Maine and British Columbia, Canada (Rogers et al. 2013). In 2002, Maine salmon farmers and state resource agencies implemented an integrated pest management plan that includes monitoring, coordinated stocking of defined bay management areas, and a 3-year production cycle to include 8–12 months of fallowing between salmon harvest and restocking (Maine Department of Marine Resources [MDMR] 2007). A permit from the MDMR is required to stock a bay management area during the first year of the production cycle after fallow periods are met. The MDMR also monitors the movements and prevalence of sea lice on wild salmon smolts (MDMR 2007). Conversely, in Washington, significant sea lice infestation of farmed salmon has never been an issue because net-pens are located in areas where the salinity is too low for lice proliferation (Nash et al. 2005); therefore, treatment has not been necessary.

These approaches appear to have reduced the shedding and potential impacts of sea lice from salmon farms (D. Jackson et al. 2002; Torrissen et al. 2013). Common elements of successful lice control programs that are in use and are successful both in Europe and North America include treatment of severe infestations with appropriate and approved therapeutants (such as hydrogen peroxide and emamectin benzoate), rearing a single year-class of fish at a marine pen site or zone, fallowing sites between production cycles to minimize cross-infection between groups, and general management practices that ensure the health of aquatic animals (Torrissen et al. 2013). It is important that research continues to optimize and improve lice control on farmed salmon.

Prevention of Fish Disease Transfer

Most states have comprehensive aquatic animal health regulations that are prescriptive in preventing the introduction of diseased animals into the state and methods for managing disease events should they occur. In Maine, for example, laboratory fish health certification and a transfer permit from the MDMR are required prior to any movement of fish. Similar requirements are in place in other states. In addition, the federal agencies that have a role to play in fish health (U.S. Department of Agriculture [USDA], NOAA, and U.S. Fish and Wildlife Service) have developed a National Aquatic Animal Health Plan (APHIS 2008). Evidence from salmon farming indicates that operations that follow structured disease prevention programs and best management practices do not amplify pathogens sufficiently to cause disease in wild populations (D. Jackson et al. 2002). Effective programs include (1) routine health exams by aquatic animal health specialists; (2) health inspections prior to movement of fish between regions or health management zones; (3) accurate record keeping by the farmer to include mortalities, growth, and feed conversion; (4) implementation of a biosecurity plan for each farm site; and (5) use of preventive medicine such as vaccines and probiotics. Such programs are already in place for U.S. salmon farms.

Another concern is that escaped farmed fish could be vectors of disease transmission to wild stocks or produce other

Figure 4. Fingerling Yellowtail ready to stock.

demographic impacts, such as competition with or predation on wild stocks. Should escapees carry a disease agent, the risk of them being the source of an outbreak in wild fish is low because (1) native pathogens are already a part of the environment where wild fish are routinely exposed and have developed some natural immunity; (2) escapees are unlikely to generate an infectious dose (or infective pressure) sufficient to result in disease in a healthy, wild population; (3) the mere presence of a pathogen alone will not cause disease without environmental factors that play a large role in triggering disease events (McVicar 1997; Moffitt et al. 1998; Amos, Appeby et al. 2001); and (4) most escaped farmed fish have low fitness for the wild and quickly become easy victims of predators such as marine mammals, other fish, and birds (Amos, Thomas, and Stewart 2001). Nevertheless, escapes should be minimized, and cultured stock health should be maximized for both ecological and economic reasons.

Table 1. Main issues associated with marine net-pen aquaculture addressed by federal laws and the agencies responsible for their implementation.

Issues	Laws	Regulatory agencies
Fisheries management, protection of habitat, marine mammals, and endangered species	Magnuson-Stevens Fishery Conservation Management Act Marine Mammal Protection Act Endangered Species Act National Environmental Policy Act Coastal Zone Management Act National Marine Sanctuaries Act	NOAA (NMFS) NOAA (NMFS) NOAA (NMFS), FWS USEPA, NOAA (NMFS), USACE NOAA (National Ocean Service) NOAA (National Ocean Service)
Nutrient discharge	Clean Water Act, NPDES discharge permits Safe Drinking Water Act Marine Protection, Research, and Sanctuaries Act	USEPA, USACE USEPA USEPA, NOAA (NMFS), USACE
Siting, hazards to navigation, permitting and construction of structures, transporting product	Rivers and Harbors Act Lacey Act 14 U.S.C. 83 (marking structures in navigable waters) Outer Continental Shelf Lands Act	USACE FWS U.S. Coast Guard Bureau of Safety and Environmental Enforcement and Bureau of Ocean Energy Management
Seafood safety, feed ingredients, animal health, use of veterinary drugs	Federal Insecticide, Fungicide, and Rodenticide Act Federal Food, Drug, and Cosmetic Act Food Safety Modernization Act Hazard Analysis and Critical Control Points Program Surveillance and Monitoring Program	USEPA USFDA USFDA USFDA USFDA
Health management, best management practices	Animal Health Protection Act Virus Serum Toxin Act 9 CFR 101-124 (regulations on the spread of disease)	USDA (APHIS) USDA (APHIS) USDA (APHIS)
Escapes, broodstock management, monitoring and reporting	Magnuson-Stevens Fishery Conservation and Management Act State and local regulations with requirements for reporting and response	NOAA (NMFS) State and local agencies

Table 2. Annual use of therapeutants by Maine marine fish farms from 2001 to 2008. The use of trade names does not imply endorsement (reproduced from Maine Department of Marine Resources 2009).

Compound	2001	2002	2003	2004	2005	2006	2007	2008
Antibiotics								
Romet 30	None	None	None	None	None	None	None	None
Terramycin (kg)	349	6.7	1,229	316	313	None	None	None
Aquaflor (g)	None	None	None	None	None	0.13	None	None
Parasiticides								
Cypermethrin (L)	778	None	None	None	None	None	None	None
Slice (kg)	0.59	1.12	0.66	1.72	0.80	1.01	1.44	0.75

BOX 7. Understanding Genetic Risks and Benefits—Make Them Different or Keep Them the Same?

Understanding genetic risks from escaped fish to wild populations comes primarily from studies of farmed and wild populations of Atlantic Salmon (McGinnity et al. 1997, 2003; Hindar et al. 2006) and studies of hatchery released and wild populations of Pacific salmon (Ford 2002; Araki et al. 2008). Genetic and fitness risks from interbreeding of farmed and wild fish include loss of genetic diversity within and among populations and loss of fitness (Ford 2002; Naylor et al. 2005; Waples et al. 2012). Loss of diversity within a population or among populations may occur when cultured animals with low genetic diversity escape and interbreed at very high levels with locally adapted wild populations, making the next generation of the wild population more homogenous. Loss of fitness can occur when cultured fish genetically suited to survival in captivity interbreed with wild populations and the resulting offspring have reduced ability to survive and reproduce in the wild (Fleming et al. 2000; McGinnity et al. 2009; Araki et al. 2008).

Genetic selection in aquaculture is usually viewed in terms of increased profitability through gains in traits of commercial importance, such as growth rate, disease resistance, feed conversion, or product quality. However, genetic selection can also have implications on resource efficiency and environmental sustainability. Selected organisms may use less feed, produce less waste, pose less of a disease risk, and/or be more efficient at converting animal feed into human food than wild counterparts. Specific selection objectives in aquaculture that relate to environmental sustainability include better feed utilization to reduce waste and improved ability to utilize plant products to reduce dependency on fishmeal.

Managing for risks associated with loss of diversity and the benefits of selected breeding may involve trade-offs. For example, choosing unselected local wild broodstock, thereby keeping the genetic makeup of the cultured animals as similar as possible to that of the wild population, may minimize the impacts of escapes once they interbreed. However, this negates the ecological advantages of selective breeding for traits with commercial and environmental benefits (Gjoen and Bentsen 1997; Gjedrem et al. 2012). One approach could be to use highly domesticated animals with reduced survival and reproductive success in the wild. These fish may have low or no direct genetic impact on wild populations (Baskett et al. 2013) because such animals are less likely to breed and pass on genes to their wild counterparts and, therefore, less likely to influence the long-term genetic makeup of wild populations. Offspring from those that do breed successfully are also less likely to survive and so on as natural selection impacts future generations of wild fish. The loss of fitness in cultured animals for life in the wild generally increases with increasing number of captive-bred generations (Araki et al. 2008; Christie et al. 2011). Although domesticated organisms often have reduced reproductive success in the wild, when highly domesticated animals do breed successfully in the wild, the genetic impact on the natural populations could be greater than if undomesticated (wild-type) organisms were involved (Figure 4).

This dichotomy results in two opposite strategies to manage genetic risks: (1) strong domestication or make-them-different and (2) minimal or no domestication or keep-them-similar. Both strategies may have environmental merit depending on the specific situations and considerations.

GENETICS AND ESCAPES

Managing risks associated with escapes requires clear delineation of the risks, followed by measures to reduce escapes and their effects (Table 3) A variety of approaches based on analysis of risks and critical control points exist for reducing the number of escapes and their potential harm to wild stocks, including advances in infrastructure, veterinary science, and breeding (Naylor et al. 2005; Jensen et al. 2010; Laikre et al. 2010).

Fish may escape from net-pens in large numbers during singular events like severe storms, in small losses through damaged nets (Morris et al. 2008; Jensen et al. 2010), or during harvest operations (Dempster et al. 2002). Although catastrophic losses may be easily identified, more attention is needed to identify and prevent chronic, low-level escapes. Efforts to reduce escapes in salmon farming in Washington State and British Columbia, Canada, have been successful, as shown in Table 4. In the 10-year period from 1987 to 1996, the average annual escape rate was 3.7% of annual harvest, whereas more recently (2000–2009) escape rate averaged 0.3%. Similar trends are evident in Maine (unpublished) and in Chile (Sepulveda et al. 2013). Farm operators in the United States are required to develop best management practices for the prevention of escapes, have recovery plans if escapes should occur, mark all farmed salmon, and report any escapes.

Even with this improving trend, prevention of all escapes is unlikely; therefore, understanding the biological significance of escapes and dealing with the risks posed by escapes is necessary. The primary concern of escaped fish is the potential for them to interbreed with wild conspecifics and reduce the long-term fitness of the wild population (see Box 7).

Risks are typically species, site, and operation specific. The magnitude and type of genetic risk associated with the escape of farmed fish on wild counterparts is a function of (1) the number and survival of escapes relative to the population of wild conspecifics, (2) the difference in genetic makeup between the escaped farmed and wild fish, (3) the reproductive fitness of the escaped fish (Ford 2004; Waples et al. 2012), and (4) the opportunity for reproduction with wild fish. As domestication advances, survival and reproductive success in the wild decreases (items 1, 3, and 4) tending to reduce the risk, while genetic difference increases (item 2), which tends to increase the risk.

The approach used to deal with the trade-offs between selectively breeding cultured animals to be genetically different (make-them-different strategy) or maintaining wild broodstock (keep-them-similar strategy) may depend on the specific situation (Lorenzen et al. 2012). Comparison of alternate genetic strategies reveals varied degrees of consequences depending on the relative timing of natural selection, density dependence, and time of escape during the life cycle of the fish (Baskett and Waples 2013). For example, the make-them-different strategy can be a viable alternative to the keep-them-similar strategy, reducing risk if natural selection is significant between when escapes occur and reproduction happens. In addition, if selection in the captive environment is minimal, then demographic (e.g., competition and natural selection) effects outweigh fitness effects; if selection is significant, then fitness effects dominate (Baskett and Waples 2013).

Mitigation strategies to minimize the risk of genetic impacts include improved containment through better management and design of net-pen systems and antipredator nets; shore-based rearing for part of the grow-out period; improved fish handling practices during stocking, rearing, and harvesting; and use of sterile fish to eliminate reproduction (see Box 8). Maintaining large and healthy wild stocks, or choosing species for culture that have large, healthy populations, also decreases risk by decreasing the ratio of escapes to wild fish (Figure 4).

The trade-offs in genetic management and operational parameters of aquaculture can be complex, and one approach does not fit all species and locations. Models have been developed and are being refined to understand and manage risks to promote good management under a range of conditions (Tufto 2010; Baskett et al. 2013; NOAA 2014). Much of what we know about the underlying conservation genetics and mitigation strategies comes from modeling work done to understand and create genetic management plans for hatcheries producing fish for restocking programs (Ford 2002); that information is applicable to the management of escapes from commercial aquaculture operations (Hindar et al. 2006; Besnier et al. 2011). For example, salmon hatchery program managers can use models to simulate how changes in hatchery practices impact the genetics of enhanced populations (Paquet et al. 2011). Quantitative models provide insight for commercial operators and public hatchery managers to focus attention on risk reduction, for scientists to focus research efforts, and for resource managers to focus on monitoring and regulation.

CONCLUSIONS

Advances in technology and regulation over the last few decades now allow net-pen marine fish farms to produce significant amounts of seafood sustainably. Fish are very efficient converters of feed into human food, but as with other animal farming, care must be exercised to avoid harming the environment. In the United States, the Salmon farming industry and the government agencies that regulate aquaculture have had decades to develop the science, technology, management options, and regulations to successfully address key environmental concerns.

Table 3. General approaches for mitigating risks from aquaculture escapes.

Indentifying risks	Escape prevention	Reducing escape effects
Potential magnitude and route of escape (leakage, catastrophe, harvest, etc.)	Engineering, design, materials, anchoring	Siting, colonization potential
Life stage of escape (gametes, larval, juvenile, adult)	Management practices, monitoring, net repair, net replacement	Biological (sterilization, complete domestication, out-of-cycle reproduction)
Genetic effects (loss of diversity and fitness, domestication, drift)	Siting	Recapture plans and technologies Sterilization
Ecological effects (competition for space, food, predation, disease)		Domestication
Escape dispersal, geography		Genetic guidelines developed and followed
Site-specific risks		Maintain large and resilient natural populations Marking for recapture

BOX 8. Making Farmed Fish Sterile?

Research to produce sterile farmed fish may eliminate the direct genetic risks and reduce some of the demographic effects of escapes. Sterilization of cultured fish is more compelling as a risk reduction strategy and more effective when significant genetic differences exist between farmed and wild populations and escapees are still reproductively fit. Sterilization of fish may also benefit industry by allowing companies who invest in selective breeding some control over the use of proprietary high-performance domesticated lines. Sterilization of fish by inducing triploidy has been effective, with some triploids exhibiting survival and growth similar to diploids (Taylor et al. 2011). Research has also explored repressible sterile fish (fish that require dietary additives for maturation), which would be unable to reproduce if they escaped (Thresher et al. 2009). Even though these approaches are promising, much work remains to develop a cost-effective method of reliably producing sterile fish.

Progress over the last four decades has been significant. Research has produced feeds that contain reduced amounts of fish meal and fish oil, opening the door for carnivorous fish farming systems to become net producers of fish oil and fish meal. Vaccines, improved nutrition, and better health management have greatly reduced the need for antibiotics and the risks associated with diseases. Proper siting and feeding has greatly reduced negative impacts of nutrients on ecosystems. Escapement has been reduced by improved net-pen engineering and management, and our understanding of the genetic consequences of escaped fish has advanced to the point where models can be used to identify and manage the risks.

Table 4. Escaped farmed salmon in Washington State (WA), United States, and British Columbia (BC), Canada. BC salmon production levels in tons were used to estimate percentage of escapes for each year.

Year	WA Escapes[1]	BC Escapes[2]	BC Production (mt)[3]	Percentage BC Escapes[4]
1987	NA	54,998	1,936	11.36
1988	NA	2,000	6,553	0.12
1989	NA	390,165	11,883	13.13
1990	NA	165,000	13,512	4.88
1991	NA	236,150	24,362	3.88
1992	NA	69,178	19,814	1.40
1993	NA	21,113	25,555	0.33
1994	NA	65,109	23,657	1.10
1995	NA	57,883	27,275	0.85
1996	107,000	13,137	27,756	0.19
1997	369,000	46,428	36,465	0.51
1998	22,639	82,875	42,200	0.79
1999	115,000	35,954	49,700	0.29
2000	0	68,247	49,000	0.56
2001	0	55,414	68,000	0.33
2002	0	20,455	84,200	0.10
2003	0	40	65,411	0.00
2004	0	43,985	55,646	0.32
2005	24,552	64	63,370	0.00
2006	0	19,085	70,181	0.11
2007	0	19,246	70,998	0.11
2008	0	111,826	73,265	0.61
2009	0	72,745	68,662	0.42
2010	0	No data	70,831	NA
2011	0	12	74,880	0.00
2012	0	2,754	NA	NA

[1] Data for Atlantic Salmon escapes (number of fish) from Washington Department of Ecology. Reports of escapes of 1,000 or more fish began in 1996.

[2] Data for Chinook, Coho, and Atlantic Salmon and steelhead (number of fish) for 1987–2009 from British Columbia Ministry of Agriculture and Lands (www.al.gov.bc.ca/fisheries/cabinet/Escape_Stats.PDF). Data for 2011 and 2012 for Atlantic Salmon from the Department of Fisheries and Oceans Canada (www.pac.dfo-mpo.gc.ca/aquaculture/reporting-rapports/escape-evasion-eng.htm).

[3] Data for Chinook, Coho, and Atlantic Salmon and steelhead in metric tons from the Department of Fisheries and Oceans Canada (www.dfo-mpo.gc.ca/stats/aqua/aqua-prod-eng.htm).

[4] Calculated from number of fish estimated from production assuming harvest size of 4 kg.

Marine fish farms are required to comply with regulations similar to those of other food-producing and marine industries. Existing U.S. regulations address the environmental effects of net-pen aquaculture effectively. Technological progress, better monitoring, and adaptive oversight of the U.S. net-pen aquaculture industry have resulted in sustainable, affordable, and domestically produced seafood.

ACKNOWLEDGMENTS

The authors thank Dave Alves, Jess Beck, Susan Bunsick, Alan Everson, Brian Fredieu, John Hargreaves, Dennis Hedgecock, Laura Hoberecht, Nicole Kirchhoff, Lori LeVander, Jon Lewis, Patti Marraro, Jack Rensel, Jill Rolland, Paul Sandifer, Jeff Schaeffer, Jesse Trushenski, Diane Windham, and anonymous reviewers for valuable review and contributions.

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