RIGHT FROM THE START

OPEN-OCEAN AQUACULTURE IN THE UNITED STATES

March 2011

Ocean Conservancy
Start a Sea Change

President's Letter

In a world with a rapidly growing population and tragically overfished seas, we have come upon a crossroads. The ocean has reached a breaking point in productivity and in ecosystem health in the wake of our taking so many fish from the sea.

As a solution, some have proposed to greatly expand aquaculture—or "fish farming," as it is commonly known—to close the gap. Already, half of the world's seafood is farmed, and that amount is growing rapidly. In nations across the globe, however, the waning number of near-to-shore locations appropriate for fish farming has entrepreneurs looking out to the open ocean for new places to locate their operations. In fact, open-ocean fish farms are already in place in many countries, and in Hawaii.

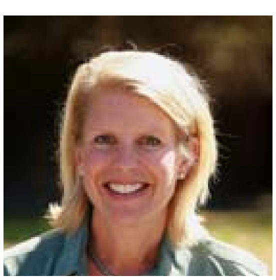
The United States industry is not yet so entrenched, but it is on the verge of rapid development. At present, however, we have no overarching policy to manage and guide the growth of the industry. The future of ocean fish farming has become the focus of considerable debate. Some entrepreneurs would like to see the industry develop as fast as possible. Others would prefer to see the industry go away entirely.

At Ocean Conservancy, we believe that open-ocean aquaculture may help meet our looming seafood challenges, but we know from experiences around the world that poorly planned, poorly operated aquaculture threatens marine life and wastes natural resources. Ocean Conservancy is not opposed to open-ocean aquaculture, but we believe the risks are too great, and the potential damage too long-lasting, to take chances. The growth of the industry, when it comes to our shores, must to be guided by a rigorous planning and regulatory framework that uses the best available science to protect public resources.

This report looks at the lessons learned from open-ocean aquaculture growth outside the United States. It details the risks and outlines policy recommendations we believe are necessary to ensure that when open-ocean aquaculture takes root in the US it does so with proper management oversight and environmental standards. Right now, the US has a critical window of opportunity to create an intelligent regulatory framework to guide the industry. We can establish a rigorous, precautionary framework that is both scientifically robust and responsive to new information.

Now is our chance to get open-ocean aquaculture right from the start.

Vikki Spruill
President and CEO
Ocean Conservancy



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Executive Summary

The concept of open-ocean aquaculture—fish farming miles from shore in the open ocean—has for decades captured imaginations across the world. Today, the traditional barriers to development of such an industry—the high capital requirements and technical challenges—have begun to change. The industry is making substantial headway across the globe. With further technological innovations, industry experts believe that several forms of open-ocean aquaculture could soon become feasible. When that moment comes, open-ocean aquaculture in the US could grow dramatically. But it will be accompanied by the potential for serious consequences for our wild fisheries, the livelihoods of traditional fishermen, and our coastal economies.

Some people are avidly interested in pursuing aquaculture as a solution to our growing population and appetite for seafood, while others are so concerned about the environmental impact that they oppose it altogether. The reality is that marine aquaculture may be a viable part of the solution to our ongoing hunger for seafood, but such a solution must not come at the expense of a healthy ocean.

A GLOBAL SHIFT

According to the United Nations Food and Agriculture Organization (FAO), the world consumed over 110 million tons of fish in 2006—with more than 50 million tons (some 40 percent) coming from fish farms, including fresh-water operations on land and ocean farming close to shore. The FAO estimates that 2010 will mark the first year in human history that fish farms will provide more seafood than all wild fisheries combined. Despite this expansion, the overall industry growth rate has slowed from a stunning twelve percent per year to about seven percent—not because demand has declined, but due mostly to a lack of suitable farming sites near to shore, where the majority of today's ocean farms are located. This has the industry looking farther out to sea. Advancing technologies and husbandry techniques are allowing farmers to grow fish and other seafood in environments that were inaccessible or unsuitable just 20 years ago. Fish farms situated miles out at sea are viewed as a new frontier.

Cautionary tales exist, however. Chile was, until recently, the world's largest producer of farmed salmon. Over the course of two decades, in the absence of strong environmental standards and national planning, the country massively expanded production of farmed Atlantic salmon. Then the outsized industry was ravaged by disease nurtured in pens densely packed with fish. Virtually overnight, production declined by half. Over 7,500 direct jobs were lost. The consequences for the marine environment have yet to be tallied.

AQUACULTURE AND THE UNITED STATES

Though aquaculture in the US is small compared to global operations, for four decades the US federal government has subsidized the development of aquaculture technologies. Starting with the passage of the 1966 National Sea Grant College Program Act, the government has consistently funded aquaculture research and full-time aquaculture staff through the 30 Sea Grant colleges across the US. In 1998, NOAA began the National Marine Aquaculture Initiative focused on fish and shellfish farming in the ocean. The Department of Commerce's stated goals include a quintupling of total US production to $5 billion per year by 2020. The Secretary of Commerce recently accepted a Fishery Management Plan developed by the Gulf of Mexico Fishery Management

Council that would expand open-ocean aquaculture in the Gulf under the auspices of the nation's primary fishery law, the Magnuson-Stevens Fishery Conservation and Management Act.

REGULATORY DISARRAY

At present, however, there is no comprehensive regulatory framework or consistent set of rigorous environmental standards to guide aquaculture development in the US. This regulatory environment satisfies no one: It is an enormous challenge for aquaculture entrepreneurs, and it provides little comfort to a public concerned about the health of marine ecosystems. The worst possible scenario is a continuation of the current approach, with inadequate environmental standards and piecemeal oversight.

At this moment, America has a window of opportunity that other nations missed. We can develop a proactive and considered approach to the industry *before* it begins to grow, drawing on the lessons and insights of aquaculture's expansion in other regions of the globe. If we get things right, we will establish a clear, scientifically robust national policy with environmental, socio-economic, and liability standards built in. The result would be a policy that supports viable businesses, while protecting the marine environment. If we fail however, there could be serious and long-lasting impacts for our fisheries, our ocean ecosystems, and our coastal communities.

RISKS

Like agriculture on land, the growth of a new aquaculture industry in the US will come with some degree of environmental impact. The question remains: How much? At present, much of the global aquaculture industry focuses on carnivorous and omnivorous fish in intensive operations (e.g., salmon). These fish are raised in a fashion analogous to livestock feedlots on land, a practice that has been widely criticized for its large environmental footprint: destroying habitat, endangering wild populations, and polluting watersheds. Compounding matters, fish farms in the ocean are intimately connected to surrounding environments in ways that their counterparts on land are not—water freely flows in and through the net pens that contain the fish.

In reviewing the experience of ocean fish farming internationally, the scientific literature identifies five types of environmental risk. Each must be addressed if there is to be environmentally responsible industry expansion in the US.

1. **Pollution:** Fish farms release fish waste, uneaten food, and chemical wastes directly into the ocean with meaningful consequences for the health of the

water column and the seafloor below. Like the poultry farms of Maryland's Eastern Shore, whose wastes flow into Chesapeake Bay, such "over-enrichment" of coastal ecosystems has generally emerged as a major environmental problem, occasionally resulting in algal blooms, habitat loss, and the serious depletion of dissolved oxygen. Aquaculture must proceed only in ways that do not contribute to the general problem of coastal eutrophication (over-enrichment).

2. **Escaped Fish:** Farmed fish invariably escape from aquaculture operations. In October 2009, 40,000 adult salmon escaped from Canada's largest farm. From 2004 to 2008, Norwegian authorities reported cod escapes from farms in excess of 800,000 fish. Annual escapes of farmed salmon in Norway ranged from 2 million fish to 10 million fish per year from 1995 to 2005. These are very large numbers. Without careful broodstock management, even the escape of native species can compromise the genetic fitness of wild fish through interbreeding.

   In Europe and the US, there are already legitimate concerns that escaped Atlantic salmon could contribute to the eventual extinction of wild salmon populations. If the fish that escape are exotic, or are genetically modified, the risks increase considerably, with the potential to permanently upset ecosystem balance as these newly introduced fish out-compete, displace, or prey on native species. Invasive species are listed second only to habitat destruction as a driver of extinction and are classified by the World Conservation Union as one of the four greatest threats to the world's ocean. The kinds of fish and the ways in which they are farmed must be carefully controlled to ensure ocean ecosystems are not harmed by fish escapes from ocean fish farms.

3. **Diseases, Parasites, and Chemicals:** Ocean fish farms can amplify and spread deadly diseases and parasites into natural environments. In turn, farm operators often apply drugs and chemicals to contain these threats, sometimes with subsequent harm to wild animals. White spot disease decimated the global shrimp farming industry in the 1990s. Today, infectious salmon anemia (ISA) is plaguing the salmon farming industry in Chile, leading to the intentional destruction of millions of farmed fish, with impacts confirmed on wild shrimp and likely on wild salmon. Several accounts have linked salmon farms to disease outbreaks in wild fish populations.

   In recent years, there has been a dramatic spread of parasitic sea lice from farms to wild salmon at a cost of nearly $5 billion annually. As for chemicals, fish farmers are known to regularly apply pesticides, antibiotics, fungicides, antifoulants, and other chemicals. These chemicals dissolve in the water and are carried outside the farms, sometimes with marked effects on surrounding ecosystems. Responsible aquaculture management must ensure that farms minimize the use of all drugs and chemicals, and that farms don't grow to a scale at which they become reliant on regular use of such substances as has happened in other parts of the world.

4. **Fish Meal and Fish Oil:** Finfish aquaculture as it is currently practiced still consumes more animal protein than it produces as harvestable product. Each year, about 25 million metric tons of fish are "reduced" into fish meal and fish oil—roughly 30 percent of all wild fishery landings. The lion's share goes to aquaculture, whose claim on global fish meal (68 percent) and fish oil (88 percent) is projected to grow further still. By some estimates, it requires 2-5 pounds of wild fish to produce a single pound of farmed salmon. Improvements are bringing this ratio closer to one-to-one, but the growth of the global industry is outpacing these improvements. The greatest concern is that a heavy reliance on wild fish for feed will result in reduced prey for whales, dolphins, sharks, marine birds, and other important parts of marine food webs. For aquaculture to be more sustainable, it must substantially reduce its reliance on wild-caught fish for food and ensure that any remaining use comes from healthy, well-managed fisheries that protect marine food webs.

5. **Predator Impacts:** Cages full of captive fish will naturally draw predatory fish, marine mammals, diving birds, and other wildlife, and this attraction can lead to harmful consequences. In 2007, the Canadian government reported over 110 sea lions drowned in salmon cages, including one event that claimed over 50 animals. In other instances, farmers may harass or kill predators in an effort to protect their stocks. Responsible aquaculture must employ non-lethal deterrents as a primary course of action and must not unreasonably disrupt wildlife or their use of important marine habitats.

POLICY RECOMMENDATIONS

Aquaculture has the potential to play a responsible role in meeting our burgeoning demand for seafood. However, it is imperative that the US establish policies to ensure that this nascent industry grows sensibly and safely. The US has the opportunity to be *the* leader of environmentally responsible open-ocean aquaculture. But to claim that mantle, it must craft a unified national vision that fosters “a race to the top,” rather than accept the current fragmented regulatory arena that may unintentionally create a “race to the bottom.”

Over the last decade, a number of high-level commissions and advisory bodies have made a range of recommendations concerning the principles and provisions of a coordinated, federal regulatory system for open-ocean aquaculture. In reviewing this body of work, a common set of guiding principles has emerged.

At its core, the policy solution is straightforward: the United States must establish a comprehensive framework for open-ocean aquaculture that is rooted in the precautionary approach. That framework must establish strong, legally-binding environmental standards for the development of the industry, while effectively protecting the broader public interest. Above all, the decisions we make must preserve wild fish stocks and protect ecosystems.

To help ensure the health of our ocean and a responsible future for the open-ocean aquaculture industry, Ocean Conservancy proposes four overarching principles of a national open-ocean aquaculture policy:

Principle 1 – A Comprehensive Structure
Open-ocean aquaculture should proceed only under a comprehensive national framework, including new federal legislation, to guide the industry’s development. This framework should integrate with relevant national and state laws and regional ocean planning and management efforts. NOAA should be the primary regulatory agency enforcing Congress’s vision—with the duty of ensuring environmental protection while deciding whether, where and under what conditions to permit aquaculture in federal waters.

Principle 2 – A Precautionary Approach
Precaution must be the core operating principle for this new use of US ocean waters. Given the inherent risks and uncertainties, and the natural tension between economic development and preservation of public trust resources, the national framework must ensure vibrant marine ecosystems are protected to the maximum extent possible. The governing structure should permit open-ocean aquaculture only when independent, peer-reviewed science provides reasonable assurances that it will avoid negative impacts, including cumulative effects, on marine ecosystems.

Principle 3 – Rigorous Environmental Standards
The national framework must establish rigorous environmental standards to guide federal rulemaking and industry performance. These standards must address fish escapes, disease, pollution, chemicals, impacts on wildlife and predators, and reliance on wild fish for aquaculture feed. Standards should be performance-based and should regulate facility siting, permitting, monitoring, and enforcement. For maximum effectiveness, the standards should provide incentives to facilities for performance beyond permit requirements and significantly penalize facilities that fall short.

Principle 4 – Protect the Commons
The marine environment is a public trust resource held by the government for the benefit of all its citizens. In every respect, the development of open-ocean aquaculture should be subject to a full, meaningful public process. Expansion of fish farming into this environment should not proceed unless public resources are adequately protected, the public is fairly compensated for the use of its resources, and facility owners are held liable for damages to the marine environment.

THE RIGHT START

It’s time for strong federal leadership on the future of open-ocean aquaculture in the United States. In a world in need of viable food sources, marine aquaculture may have a valuable role to play, but it must develop in the right way. The US must articulate a vision that protects the ocean, existing ocean users including recreational and wild fisheries, and the aquaculture industry itself from the threats of poorly regulated fish farms.

Now is the time: our one chance to get open-ocean aquaculture right from the start.

Introduction – The State of Open-Ocean Aquaculture

Ten thousand years ago, humanity began the transition from hunter-gatherers to an agrarian society. Our ancestors learned how to domesticate animals, plant crops, and tend soil. Over time, these practices reshaped entire ecosystems to meet society's needs: forests became farms, plains sprouted cities, and valleys were flooded to make lakes. Today, the human footprint stretches from pole to pole, claiming nearly 40% of the land's total primary productivity (Haberl *et al.,* 2007).

Until relatively recently, the ocean remained essentially untouched by humankind, but over the last two centuries, the development of industrial-scale fishing dramatically changed this calculus. Modern-day hunters have spread across the remaining two-thirds of the planet's surface. Today, essentially every major marine fishery is either fully fished or depleted (SAUP, 2009). And with wild fisheries fully exploited, the last 30 years have seen an unprecedented expansion of fish farming practices on land and in the ocean.

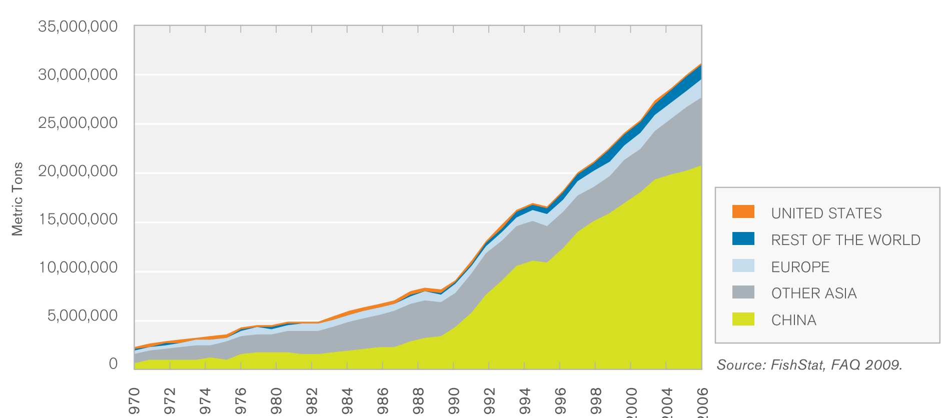
2010 will mark the first year in human history that fish farms will provide more seafood than all wild fisheries combined (FAO, 2008). With agricultural lands and fresh water in short supply, the importance of aquaculture will only grow. While aquaculture is most commonly practiced in freshwater ponds on land, it is increasingly common in the ocean as well, mostly near to shore.

Marine aquaculture is a relatively small but rapidly growing subset of the industry. The industry is expanding further offshore and delving into more exposed waters. New technologies and husbandry techniques are allowing farmers to grow fish and other seafood in exposed environments that were inaccessible or unsuitable just 20 years ago.

This spread of aquaculture into the coastal and offshore environment represents a fundamental transition in the human claim on the Earth's surface. According to a recent study, humans already have a "medium high" to "very high" impact on over 40% of the world's oceans, including the coastal areas accessible to aquaculture (Halpern *et al.,* 2008). Aquaculture will likely increase our impact on these ecosystems.

Proponents recommend aquaculture as a solution to our growing population and appetite for seafood, while others are so

GLOBAL AQUACULTURE PRODUCTION BY GEOGRAPHY



Source: FishStat, FAQ 2009.

concerned about the environmental impact that they oppose it altogether. In reality, marine aquaculture may be a viable part of the solution to our ongoing hunger for seafood, but it must not come at the expense of a healthy ocean.

In this country, the coming decades will see new opportunities for the growth of aquaculture with the potential to fundamentally alter how we manage our marine resources. Now is the appropriate time to think carefully and proactively about the future of our coasts and to set the conditions to make that vision a reality.

AQUACULTURE: BY THE NUMBERS

In 2006, the world consumed over 110 million tons of fish, of which more than 50 million tons originated on fish farms (FAO, 2008). Farmed fish thus made up about 15% of the total animal protein consumed by humans. In some parts of the world—particularly impoverished coastal communities—seafood comprises over half of the total supply of animal protein. Seafood is likewise a critical source of essential omega-3 fatty acids, increasingly recognized by aging populations as a healthy choice.

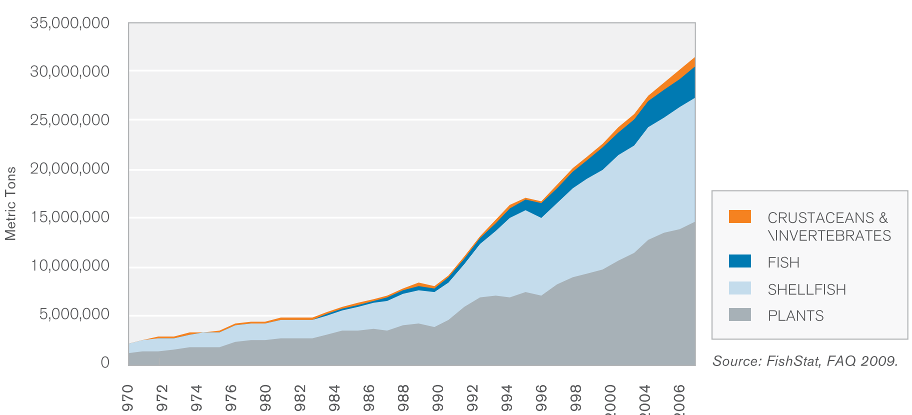
Demand is on the rise, and the world has effectively turned to aquaculture to meet it.

In practice for more than a thousand years, aquaculture, or “fish farming,” has become a substantial contributor to the global food supply. Today, Asia dominates, accounting for over 91% of global production in 2007. China alone represents nearly two-thirds (63%) of global production. Outside of Asia, the largest producers are Chile and Norway, which collectively represent just 2.5% of total production (FishStat, 2009).

Today, over 48% of global aquaculture occurs in the ocean, 45% in freshwater and 7% in estuaries. At present, marine aquaculture focuses heavily on plants and shellfish. Plants represent over 46% of aquaculture and shellfish another 41% (FishStat, 2009).

In the last 20 years, however, farming of marine finfish, like salmon and sea bass, has emerged as a lucrative sector. Marine finfish aquaculture generally involves raising fish in pens anchored to the seafloor and feeding the fish until they reach market size. Though small as a percentage of the global industry, marine finfish is the sector of choice for the developed world.

GLOBAL MARICULTURE PRODUCTION BY TYPE



Source: FishStat, FAQ 2009.

Global aquaculture production has grown rapidly for decades, making it one of the fastest growing segments of agriculture. The overall growth rate of aquaculture has slowed somewhat, dropping from a rate of 12% to a rate of 7%, in part due to the limited availability of suitable sites (FAO, 2008). Freshwater is scarcer in some regions, and suitable coastal locations are increasingly occupied. Consequently, many are looking farther out to sea for aquaculture’s future. As the United Nations Food and Agriculture Organization (FAO) summarizes, “… the need for suitable sites has resulted in cage aquaculture accessing and expanding into new untapped open-water culture areas … (Halwart *et al.,* 2007).”

THE OPEN-OCEAN AQUACULTURE INDUSTRY

While global aquaculture is based mainly on the cultivation of shellfish and plants raised near to shore, nearly all proposals for expansion into more exposed waters have been for finfish such as salmon, cod, and tuna. These high-value species offer the best chance to turn a profit in the open ocean, where start-up and operational costs are substantially higher. And these are the species in highest demand in the developed world.

The largest component of marine fish farming at present is salmon. The industry was pioneered in Norway in the 1970s and is today based mainly in Europe, Chile, and Canada. Salmon comprise about 60% of total farmed marine finfish. In 2007, global farmed salmon harvest neared 2 million tons of fish. For perspective, that is double the total wild salmon catch level.

Between 1986 and 2007 the salmon farming industry grew at an average rate of over 16% per year (FishStat, 2009). To provide a sense of the scale of the industry: in 2003 there were over 10,000 industrial marine cages in Chile, and that number has jumped substantially over the past six years (Rojas and Wadsworth, 2007). Only the onset of substantial disease and parasites in recent years has slowed the growth of the salmon industry in Chile.

There has been a simultaneous expansion, mostly in Asia, of other marine finfish species: Japanese amberjack, yellow croaker, sea bass, sea bream, cobia, and red drum (Tacon and Halwart, 2007). Japanese aquaculture, historically the epicenter of the marine finfish industry, has largely held constant since the 1980s. In contrast, China has seen considerable growth recently, eclipsing Japan in the late 1990s.

Today, China has the largest aquaculture industry in the world. It is still focused mostly on plant and shellfish production, but now includes over 40 species of marine finfish in both land-based and coastal aquaculture facilities. In 2003, over 1.5 million hectares (15,000 square kilometers) of Chinese waters were dedicated to aquaculture (Cao *et al.,* 2007). That is roughly equivalent to an area the size of Connecticut. It is estimated that the Chinese coastal aquaculture industry includes more than 1 million traditional marine fish cages, supplemented by over 3,000 modern industrial cages (Chen *et al.,* 2007). Most operations are located in shallow seas, mud flats, and protected bays (Cao *et al.,* 2007), but there are a few open-ocean facilities as well. In the 1990s, the Chinese offshore cage industry chiefly imported designs from Japan, Norway, Denmark, and the US. Today, there are a half-dozen Chinese companies and research institutions that manufacture their own cages (Chen *et al.,* 2007).

Outside of Asia, there is a significant sea bass and sea bream industry in the Mediterranean, which has grown to about 150,000 tons per year. The Europeans have also experimented with farmed cod, halibut, and other marine species.

Tuna "farming" is another notable industry, involving the capture of juvenile wild tuna, which are then fattened in cages before being shipped to market (Cardia and Lovatelli, 2007). More accurately called tuna "ranching," this industry is found primarily in the Mediterranean, Mexico, and Australia.

Elsewhere, the global marine finfish industry has pursued a slower path toward expansion primarily because of environmental concerns. Both Australia and New Zealand have limited industry growth due to "the strong emphasis on environmental management and reduction of environmental impacts" (Rimmer and Ponia, 2007).

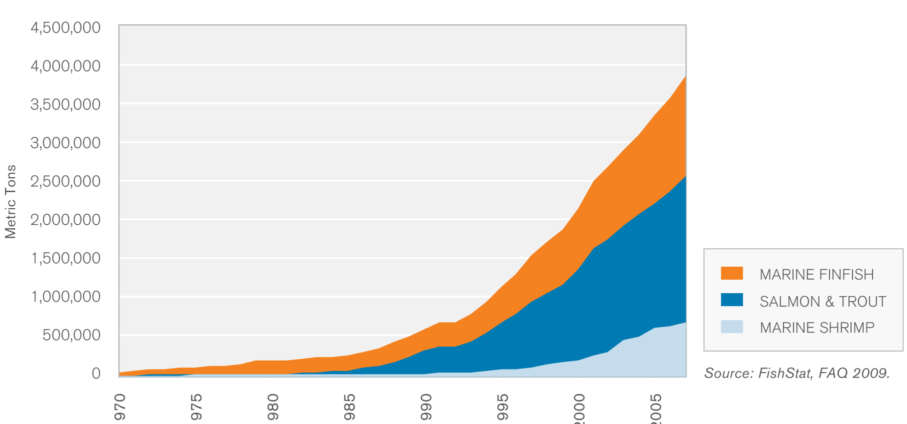
AQUACULTURE IN THE UNITED STATES

The United States is a relative newcomer to aquaculture. Yet, given global demand for seafood, the depleted state of our wild fisheries, and improving market economics, this industry could soon grow rapidly.

Today, the US aquaculture industry is centered on farming channel catfish in freshwater ponds in Mississippi and its surrounding states. In marine waters, 80% of US aquaculture production (by weight) is shellfish – specifically oyster, clam, and mussel farming. The remaining 20% comes from several salmon operations in Maine and Washington State as well as shrimp and other fish production (FishStat, 2009).

The US federal government has been an active supporter of aquaculture. Over the last 40 years, the government has subsidized the development of aquaculture technologies through a variety of agencies. With the passage of the 1966 National Sea Grant College Program Act, the government has consistently funded aquaculture research and full-time aquaculture staff through the 30 Sea Grant colleges across the US. In 1998, NOAA began the National

GLOBAL MARINE FISH AND SHRIMP PRODUCTION



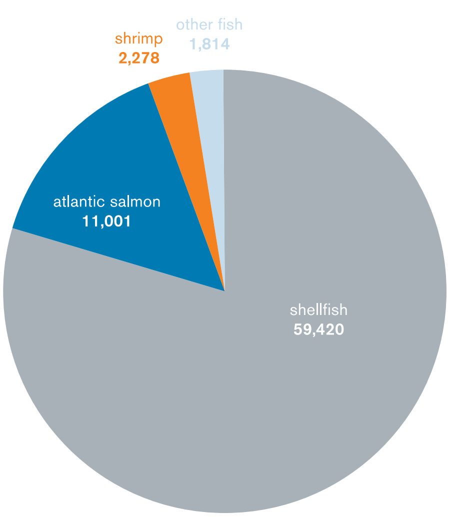
Source: FishStat, FAO 2009.

Marine Aquaculture Initiative, a competitive grant process that has awarded $15 million to date. NOAA's Saltonstall-Kennedy Grant Program supports industry development and technology research with matching funds. In 1994, Saltonstall-Kennedy money helped Ocean Spar Technologies develop the SeaStation, the first open-ocean fish cage. USDA's Agricultural Research Service also includes aquaculture in its five-year strategic funding plans; ARS received approximately $4 million for aquaculture grants in 2008.

In addition, the Atlantic Marine Aquaculture Center (AMAC) is located at the University of New Hampshire. Over the years the facility has raised summer flounder, cod, haddock, Atlantic halibut, and blue mussels. The AMAC receives direct appropriations through NOAA's budget, totaling over $18 million in the last 10 years.

Other proposals to create new open-ocean aquaculture operations include several in the Gulf of Mexico aiming to make use of the existing offshore oil platform infrastructure (Masser and Bridger, 2007), and Hubbs-SeaWorld Research Institute's current application to site a farm off of La Jolla.[1]

US MARICULTURE PRODUCTION IN 2007 (TONS)



THE FUTURE OF OPEN-OCEAN AQUACULTURE IN THE US

As technological breakthroughs and innovation continue to occur, most industry experts believe that open-ocean aquaculture will become economically feasible and therefore more attractive to US companies. When that occurs, open-ocean aquaculture could become a lucrative industry. To that end, the Department of Commerce's 1999 "Aquaculture Policy" promotes open-ocean aquaculture as a partial solution to the US's $9 billion seafood trade deficit (Bridger, 2004; Halvorson and Duff, 2008). The DOC's goals include quintupling total US aquaculture production to $5 billion per year by 2020. In the same vein, the Secretary of Commerce recently allowed to take effect a Gulf of Mexico Aquaculture Fishery Management Plan that would permit up to 65 million pounds of offshore fish production in the Gulf.[2] Independently, several entrepreneurs continue to push for permits for new ventures offshore.

REGULATORY DISARRAY

At present, however, there is no comprehensive regulatory framework or consistent set of rigorous environmental standards to guide aquaculture development in the US. This regulatory environment satisfies no one: it is an enormous challenge for aquaculture entrepreneurs, and it provides little comfort to a public concerned about the health of marine ecosystems. The worst possible scenario is a continuation of the current approach, with inadequate environmental standards and piecemeal oversight.

At this moment, America has a window of opportunity other nations missed. We can develop a proactive and considered approach to the industry *before* it begins to grow, drawing on the lessons and insights of aquaculture's expansion in other regions of the globe. If we get it right, we will establish a clear, scientifically robust national policy with environmental, socio-economic, and liability standards built in. The result would be a policy that supports responsible businesses, while protecting the marine environment. If we fail, however, there could be serious and long-lasting impacts for our fisheries, our ocean ecosystems, and our coastal communities.

1. In November 2009, Hubbs-SeaWorld opted to temporarily halt its application for permits to develop the first offshore fish farm in federal waters off San Diego, driven at least in part by the current regulatory confusion at the federal level.
2. Ocean Conservancy and other groups have challenged the government's authority to establish an aquaculture permitting system under existing law. This lawsuit was dismissed on August 12, 2010 on procedural grounds.

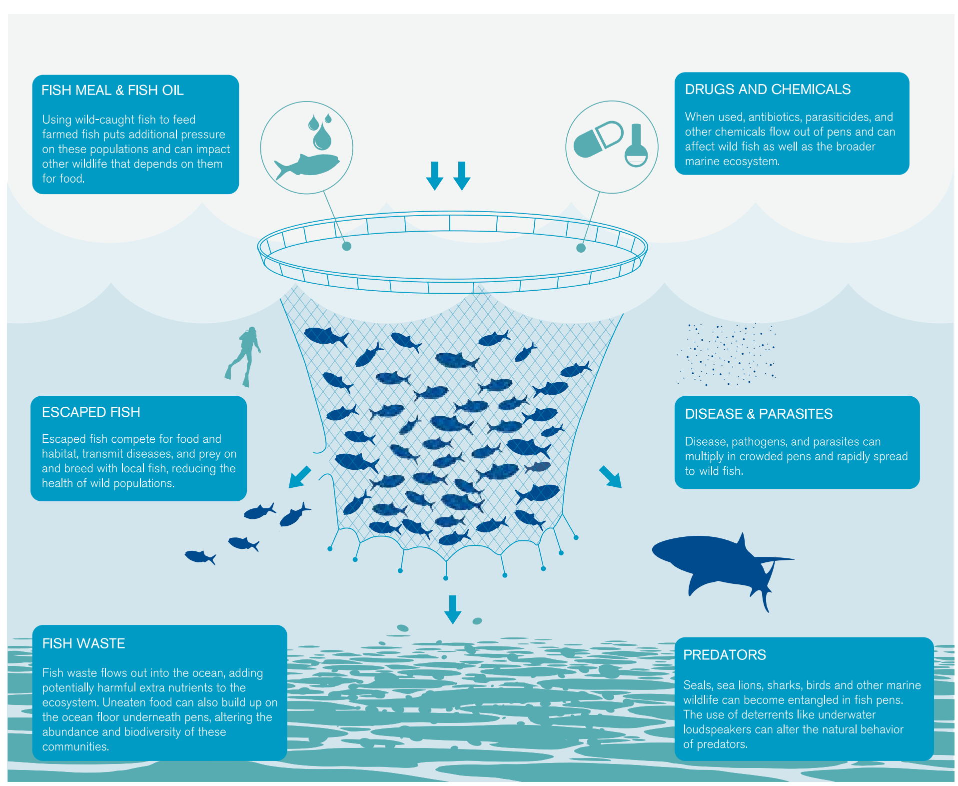
Open-Ocean Aquaculture and the Environment: A New Frontier

All food production systems have environmental effects. As such, aquaculture should be compared against other food production methods rather than examined in a vacuum (Diana, 2009). As a whole, aquaculture is a responsible sector. The large majority of the industry today is focused on seaweeds, shellfish, and herbivorous fish, which produce much-needed protein in many parts of the world. Because aquaculture typically raises cold-blooded animals in traditional pond systems on land, it can be a highly efficient food-production system with relatively little environmental harm.

However, a small but growing subset of the aquaculture industry focuses on carnivorous and omnivorous fish in intensive operations (e.g., salmon). This sector of the industry greatly resembles livestock feedlots on land, an industry that destroys habitat, endangers wild populations, and pollutes watersheds (Naylor *et al.,* 2000; Naylor *et al.,* 2005).

We don't yet know enough to characterize fully the effects of open-ocean aquaculture. While the industry appears to be evolving out of the mold of marine net-pen farming, it is too early to predict with certainty what the impacts will be, especially since most of the US and European experience with finfish production to date has come chiefly from the raising of salmon in nearshore waters. As the Marine Aquaculture Task

ENVIRONMENTAL IMPACTS OF OPEN-OCEAN AQUACULTURE



"the priority in aquaculture should be to anticipate any adverse environmental consequences and to tackle them [early], rather than struggle to recover after those consequences are already apparent."

–Dr. Andy Rosenberg, University of New Hampshire, 2008

Force summarized, "While the Task Force believes that the same kinds of risks—water pollution, escapes, disease, etc.—are inherent to all *in situ* finfish aquaculture, it is challenging to estimate the absolute and relative magnitude of these risks in a different environment in which we have little experience to date. The few demonstration projects conducted to date show negligible to modest impacts on the marine environment. However, these projects were conducted on small-scale operations, mostly at low densities of fish, so their application to large-scale and/or concentrated marine fish farming is limited. Additional research needs to be conducted on the effects, including cumulative and secondary impacts, of aquaculture on the marine environment (MATF, 2007)."

In comparing open-ocean aquaculture with other sectors of the aquaculture and agriculture industry, certain distinctive features are evident:

- Intensive open-ocean aquaculture occurs in a different habitat from traditional agricultural or aquacultural activities. Offshore operations will be intimately connected to their surrounding environments in ways that their livestock counterparts on land are not; currents flow through cages, farm wastes are dispersed, and escaped fish and diseases are directly released into the environment. The industry is attracted to the offshore environment because the waters are relatively clean and there are fewer conflicts at present with other resource users. However, it is precisely *because* of the relatively pristine nature of this ecosystem that it is important to safeguard its integrity from the outset.

- As an emergent industry, aquaculture is rapidly domesticating new species of fish. This domestication process is replete with environmental risks, including the introduction of non-indigenous species, translocation of diseases, and genetic effects on native populations through interbreeding. Farmed fish will inevitably escape when raised in the open-ocean environment. As a consequence, the selection of species to raise and the process by which they are raised have profound implications for the surrounding environment (Greenberg, 2010).

- Unlike terrestrial livestock farms, marine fish farms typically raise carnivorous species. On land, the farming of carnivores is virtually unheard of, with the exception of fur production abroad. It is resource intensive to provide protein-rich diets to such species. In fact, farming of carnivorous fish depends more on wild animals as feed (in the form of fish meal and fish oil) than any other industry or other sectors of the aquaculture industry, such as herbivorous catfish farming. As currently practiced, open-ocean aquaculture arguably does not contribute to global food supplies as it consumes more animal protein than it ultimately produces. Consumption of such species can have impacts on other wildlife, often in places far removed from farming operations themselves.

These features produce five main categories of environmental risk associated with marine aquaculture as outlined in the scientific literature:

1. **Pollution and Habitat Impacts:** Fish farms directly release waste into the ocean. These nutrients have implications for the health of the seafloor and the state of the water column.

2. **Escaping Fish and Ecosystem Impacts:** Farmed fish regularly escape from aquaculture operations. When the farmed animals are genetically different from wild fish, their presence can have serious and even permanent impacts on the surrounding ecosystem.

3. **Diseases, Parasites, and Chemical Use:** Farms can introduce or spread diseases and parasites. In turn, operators may apply drugs and various chemicals to try to contain the threat. Both the pathogens and the chemicals used to control them can harm wild animals.

4. **Fish Meal, Fish Oil, and Wild Fisheries:** The marine finfish industry is highly dependent on wild fisheries to provide feed ingredients to farmed animals in the form of fish meal and fish oil. By creating incentives for others to catch these wild fish, aquaculture may indirectly affect marine ecosystems thousands of miles away, including removing important food sources from predators such as marine mammals and seabirds.

5. **Predator Impacts:** Cages full of captive fish will naturally draw predatory fish, marine mammals, diving birds, and other wildlife and can lead to injury or death of these predators. In other instances, farmers may harass or harm the predators in an effort to protect their stocks.

POLLUTION AND HABITAT IMPACTS

Unlike agriculture, aquaculture operations release their wastes directly into the water. Waste products from fish farms include the bodily wastes of fish as well as uneaten food, chemical wastes, dead fish, and other marine trash. Upon release, these materials have different fates. Particulates or solid waste products typically settle onto the seafloor, while soluble wastes dissolve in the water column.

As a consequence, the most widely documented impact associated with marine net pens is the degradation of the seafloor beneath and around fish cages. When ambient currents are insufficient to disperse these pollutants, the accumulation of wastes can increase levels of organic carbon and sulfides in the sediment, altering the pattern of species diversity on the seafloor. At strongly impacted sites, species diversity in the benthos is often reduced to polychaetes (marine worms) and nematodes (Alston et al., 2005; Islam, 2005; Kalantzi and Karakassis, 2006; MBA, 2009). These diversity effects tend to be limited to the footprint of the net pen and the adjacent seafloor. When facilities are properly sited, the effects of pollution on the seafloor are generally minimal. Compared to other impacts, they are relatively easy to monitor, and reducing stocking densities or requiring fallow periods can effectively ameliorate the problem when it occurs.

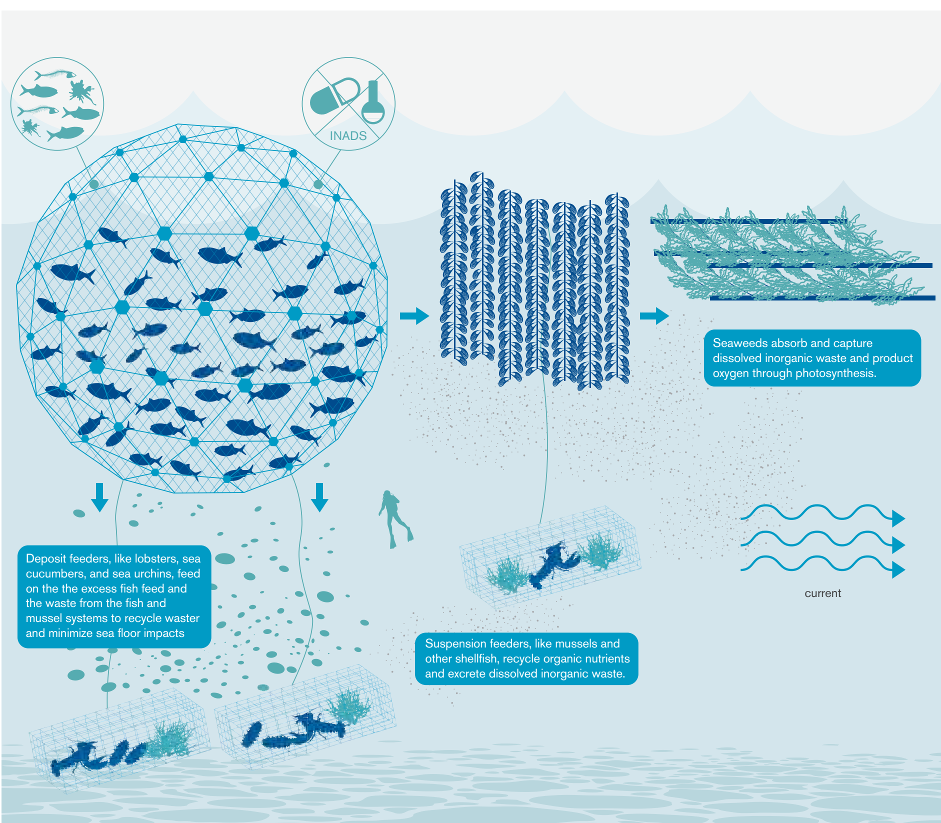
In terms of soluble wastes, aquaculture operations add nitrogen and phosphorus to the marine environment, which can contribute to nutrient enrichment. More than half of the total nitrogen and phosphorus fed to fish in commercial farms is not assimilated and flows freely beyond the farm site into the surrounding waters (Beveridge, 1996; Fernandes *et al.,* 2007). In the United States, coastal nutrient enrichment is already a serious issue. The over-enrichment of coastal ecosystems generally has emerged as “the most widespread and measurable effect of pollution on living marine resources and biodiversity in US coastal waters,” occasionally resulting in algal blooms, habitat loss, and the serious depletion of dissolved oxygen (Boesch *et al.,* 2001). Since colonization, the US has increased the annual flow of nitrogen into the Atlantic and Gulf of Mexico by a factor of between four and eight (Boesch et al. 2001). Input of additional nitrogen and phosphorous from aquaculture to these already stressed ecosystems should only be considered when mitigation measures can reduce or eliminate the harmful impacts from this type of nutrient loading.

In the US, salmon farms in Washington and Maine generally comply with state

regulations on pollutant monitoring and, on a regional basis, are only a small contributor to overall nutrient loading. However, this may change if the industry's expansion is not carefully managed. When poorly sited or too densely packed, aquaculture operations can have locally and regionally significant effects: the higher the intensity of production, the greater the risk of potential negative environmental impacts (Tacon and Forster, 2003). High-resolution models of waste transport from aquaculture pens indicate that dissolved nutrients do not disperse as rapidly and uniformly as was previously assumed. Relatively high concentrations of dissolved nutrients can thus persist at considerable distances from the farm site (Venayagamoorthy *et al.,* 2009).

In the most densely packed areas, such as the coastal waters of China, pollution has become a limiting factor for the growth of the aquaculture industry (Huiwen and Yinglan, 2007; Tacon and Halwart, 2007). In both 2007 and 2008, massive green algae blooms occurred in a coastal area of Qingdao. The 2008 bloom, which occurred prior to the Beijing Olympic sailing competition, was somewhere between 13,000 and 30,000 km^2 (roughly the size of Maryland), and consisted of 3 million tons of algae. Initial studies indicate that the movement of aquaculture from inland ponds to coastal farms played a significant role in the coastal eutrophication responsible for that algal bloom. The recurrence has "raised great concerns on the coastal environmental change" and the danger that decomposing algae could trigger a seasonal dead zone in the area not unlike the one found in the Gulf of Mexico (Sun *et al.,* 2008). While there are few studies published on the effects of aquaculture in regions like China, eutrophication associated with aquaculture appears to be an issue in several parts of that country, including Xiangshan Harbor and Dapeng'ao Bay (Cao et al., 2007; Huiwen and Yinglan, 2007).

INTEGRATED MULTI-TROPHIC AQUACULTURE



Direct effects of nutrient loading have also been detected near tuna farms and sea bream farms in the Mediterranean. With respect to sea bream, researchers found a high correlation between increased levels of toxicity in the benthic sediments (from elevated sulphides and ammonia resulting from aquaculture) and abnormal development of sea urchin larvae in the area (Marin *et al.,* 2007). A nearby tuna farm killed nearly 90% of coral colonies as a result of heavy phytoplankton and macroalgal blooms driven by nutrient loading (Kruzic and Pozar-Dumac, 2007). Vita and Marin (2007) identified a 220m radius transitional impact zone around tuna farms. While most of the affected area partially recovered during the farm's six-month fallow period, the region directly below the cages did not.

Pollution Experience at Open-Ocean Aquaculture Operations

One of the primary justifications for locating aquaculture further offshore is that there is a greater volume of water present to dilute the waste products (Bridger, 2004; ICES, 2002; Lee et al., 2006). It is thus thought that deeper waters and stronger currents help to wash away the environmental effects of aquaculture (Jin *et al.,* 2007). In addition to the greater depth, current, and volume of water, there are generally fewer fluctuations in water quality, temperature, low-dissolved-oxygen events, pH, and algal blooms—all positive factors for marine farming (Bridger, 2004). Pro-industry voices in China and elsewhere have used this as a general rationale for the development of offshore and deep-water cage culture technology (SOFIA, 2008).

In general, the deeper the water, the harder it is to measure any impacts on the seafloor (ICES, 2002; Kalantzi and Karakassis, 2006). However, the pollution still exists: without being treated, it has simply been watered down. The organic loading of seafloor communities has been extensively documented under nearshore aquaculture operations, but few studies have examined the effects of deeper, offshore operations. One of the few studies on the subject has found that "despite the open-water location and alongshore currents, the impacts of fish feed and waste on the benthic polychaete community were evident" (Lee *et al.,* 2006). This study of a moi farm located two kilometers offshore of Hawaii identified a change in the benthic community similar to what has been observed for other marine farms. The biodiversity of seafloor communities under the cages was "severely depressed" and one site was nearly devoid of life. Detritus from the farm built up under the cage, changing the nature of the biological community (Lee *et al.,* 2006). A follow-up study during a six-month fallowing period documented a partial recovery, but noted that "species diversity did not increase significantly during the fallow period, indicating that the affected communities had not been fully restored to pre-culture or distant reference conditions (Lin and Bailey-Brock, 2008)."

Similarly, a study of a Puerto Rican open-ocean submerged cage operation indicated substantial quantities of sediments and uneaten feed accumulating on the seafloor, on the order of 4% to 5% of total feed (Rapp *et al.,* 2007). The authors were surprised to find that the material was not more widely distributed in the deeper water. "Rather, the organic loading descends almost vertically, to make a footprint no bigger than the footprint under many near-shore cages … An impact study under a similar submerged SeaStation cage operating commercially in a similar open-ocean configuration (Lee *et al.,* 2006) found the bottom directly under the cage to be 'grossly affected' after 11 months. Another area 80 meters downstream was also found to be 'heavily impacted' after 23 months (Rapp *et al.,* 2007)."

These studies show impacts from single farms, but it is difficult to estimate the effect of a more broadly established industry. In terms of water quality, site-level studies typically find very little change in nutrient concentrations around fish farms and even less variability in chlorophyll *a* or POC concentrations. Some data suggest that the nutrients generated by fish farming are being used by planktonic organisms and rapidly transferred up the food web: in other words, the nutrients cannot be measured in the water column because they have already affected the local ecology (Pitta *et al.,* 2005).

Not all forms of aquaculture contribute to eutrophication. Seaweed and shellfish farming can actually reduce coastal nutrient loads (Chopin, 2008; Neori, 2008). Farming seaweeds and shellfish in combination with finfish is already being used in some parts of the world to help reduce the environmental footprint of aquaculture. Production systems that use species at different trophic levels (known as Integrated Multi-Trophic Aquaculture, or IMTA) turn the waste products of one species into resources for another. Excess nutrients from fish farms actually increase the productivity of adjacent seaweed and shellfish operations (Chopin *et al.,* 2001; Troell *et al.,* 2009). IMTA has been practiced for centuries in Asian ponds, but is only now making its way into the marine environment. Its future in open-ocean aquaculture is promising, and pilot commercial operations are already underway in China, Canada, Japan, and elsewhere (Troell *et al.,* 2009). While many unknowns about the economic viability of offshore IMTA remain, there have been significant advances in the technological feasibility of production in recent years (Roesijadi *et al.,* 2008). As the industry develops, US policymakers should encourage the development of IMTA over monoculture systems and ensure that all operations are sited in suitable locations and at appropriate stocking densities and scale to avoid the negative effects of pollution.

Habitat Effects of Open-Ocean Aquaculture

Open-ocean aquaculture operations can have some positive effects. For one, they can serve as artificial habitat for other marine life. Like any artificial surface put into the sea, net pens become "fouled" by a range of algae and invertebrates. Net-pens provide a hard surface on which these species settle, and they provide shelter from predators for wild fish and other animals attracted to the structure. They also attract other species because of the excess food from the feeding operations. Rensel and Forster (2007) found that a typical net-pen in Puget Sound can be populated by over 100 species of seaweeds or invertebrates, which they argue "provide a locally important component of the food web, providing enrichment for a variety of marine food web life including marine bird species" and thus these authors consider this a 'beneficial" effect of fish farming. These pens also serve as artificial reefs, attracting ducks and other fish and creating a novel ecosystem. Whether fish farms actually boost local production or simply act as fish aggregating devices, however, remains an open question.

But there is also a considerable downside. Because they attract predatory fish, marine mammals, diving birds, and other wildlife, aquaculture operations can have difficulty keeping these animals out of the cages and have injured or killed them. The accidental entanglement and drowning of marine mammals is a serious and ongoing concern. In 2007, the Canadian government reported over 110 sea lions drowned in salmon cages, including one mass-drowning event of over 50 animals. That was up from 46 drowned sea lions in 2006 (CBC, 2007). Similarly, salmon farming in Chile has been connected to an increased mortality of sea lions from net entanglements and intentional shooting by fish farmers. The same phenomenon occurs with sharks and tuna ranching, harbor seals and salmon farms, bottlenose dolphins and sea bass farms, and diving ducks at mussel farms worldwide (Dionne et al., 2006; Rojas and Wadsworth, 2007; Sanchez-Jerez et al., 2008); it is likely to be common across all marine fish-farming operations. It is also possible that submerged net pens and their associated mooring lines could pose entanglement risks to whales (e.g., endangered northern right whales) and other cetaceans, whose migration routes or foraging behavior bring them in close proximity to fish farms (Upton *et al.,* 2007). Acoustic deterrents, such as "pingers," emit loud noises underwater to discourage marine mammals from approaching, but these deterrents can also have unintended consequences on wildlife, altering their natural behavior or causing other animals to avoid entirely areas that are otherwise suitable habitat (Morton and Symonds 2002).

Proper design and installation of the netting systems can help to address these problems. Some of the stronger submersible cage systems claim to be relatively impervious to predator attacks, but little is known about the potential interactions between fish farms and wildlife in open-ocean environments and enough evidence exists to make them an important concern. Mitigating the effects of a growing aquaculture industry on predators and wildlife will require additional research, regulations that are sensitive to the cumulative impact of these interactions on populations as a whole, and the ability to apply this information effectively within an adaptive management framework.

ESCAPING FISH AND ECOSYSTEM IMPACTS

One of the most severe potential impacts of aquaculture on the ocean environment is also one of the least intuitive: the escape of farmed fish. Escaping fish can be either native or exotic to the area where they are being raised. The escape of exotic or "non-indigenous" animals, in particular, has serious implications for ecosystems.

Unlike pollution, the ecological effects of new species can be profound and last forever: once established, exotic species permanently alter the shape and composition of a local ecosystem. They can outcompete, displace, or prey on native species. Consequently, in general, invasive species are second only to habitat destruction as a driver of extinction (Vitousek *et al.,* 1997) and are classified by the World Conservation Union as one of the four greatest threats to the world's oceans (IUCN, 2003). In marine waters, the introduction of invasive species from a variety of human activities has already resulted in "fundamental impacts on fisheries resources, industrial development and infrastructure, human welfare, and ecosystem resources and services" (Carlton, 2001).

Aquaculture has occasionally served as a method for exotic species introduction, particularly in the freshwater environment, causing concern over the ecological impacts that escaped species can have on wild species (Carlton, 2001; Naylor et al., 2005; Volpe et al., 2000). As a consequence, farming non-indigenous species should be a non-starter for US open-ocean aquaculture.

When the farmed species is native, the ecological risks may be less dramatic but are still potentially serious. If a farmed population genetically diverges from a wild population (e.g., through selective breeding programs), interbreeding can compromise the genetic fitness and integrity of the wild population. This is particularly true when the wild population is already at dangerously low abundance. To better assess and ameliorate these risks, it is important to take into account both the potential for fish to escape and the ensuing ecological effects.

The Potential for Escapes from Open-Ocean Aquaculture

It is difficult to quantify how many fish will escape from a given aquaculture operation, but empirical evidence demonstrates that, industry-wide, escapes are very difficult to prevent. While escape rates vary substantially by the system used, open net-pen systems appear to carry the greatest risk of escaped fish. Fish escape through large-scale catastrophic events (often weather-related) and through accidental, low-level leakage caused by human error (e.g., during transport or cage maintenance) (Thorstad *et al.,* 2008). For example, despite a relatively advanced industry with every motivation to prevent the economic loss associated with escaped fish, escapes of farmed salmon in Norway ranged from 2 million fish to 10 million fish per year from 1995 to 2005; commonly reported causes included damage to the cages from storms, collisions, ship propellers, and predators (Moe *et al.,* 2007).

Catastrophic damage to farms from storms is probably the most common cause of

> *"Probably the most important aspect of aquaculture as an influence on biodiversity is the negative impact of introducing new species or modified genotypes."*
>
> *–Dr. James Diana, University of Michigan, 2009*

major escapes. For example, in one incident in Chile, a winter storm led to the escape of a million salmon, leading the FAO to note that, "Such large-scale escapes of carnivorous salmonids can have a serious impact on indigenous fish populations due to increased predation, disease introduction and other habitat interactions (Rojas and Wadsworth, 2007)." However, escape events can also occur in less dramatic fashion, such as when predators or boats damage the nets or when moorings fail.

For example, in October 2009, 40,000 adult salmon escaped from Canada's largest farm due to holes in the net (Lazaruk, 2009). The previous month, nearly 60,000 fish escaped from a Scottish operation through a hole in the net (Ross, 2009). Sea lion damage to nets has also caused similar escapes in Chile (Rojas and Wadsworth, 2007).

Escapes occur in other farmed marine finfish species as well. In Europe, Atlantic cod farmers have been plagued by higher escape rates than the salmon industry (Uglem *et al.,* 2009). Norway reports industry-wide escape rates for cod of up to 6% each year between 2000 and 2005 (Moe *et al.,* 2007). From 2004 to 2008, Norwegian authorities reported cod escapes from farms in excess of 800,000 fish (Norwegian Ministry of Fisheries and Coastal Affairs, 2010). Contributing factors included wear on the net from cod biting the cages and increased predator attention. These escapes can sometimes go unnoticed if they occur in small numbers (Moe *et al.,* 2007).

Occasionally the effects of escapes are only evident by the large number of farmed fish being caught in the wild. Off the coast of Greece, landings of farmed sea bass and sea bream by fishermen pursuing wild fish have increased dramatically as the net-pen aquaculture industry for these two species has grown. Dimitrious et al (2007) documented an 80% increase in landings of small fish, consistent with fishermen's observations of a large increase in juvenile sea bass and sea bream attributed to accidental fish escapes.

Open-ocean aquaculture is likely to follow in the path of these nearshore net pens, with the compounding challenge that more exposed open-ocean environments produce currents, waves, and storms that are substantially stronger than those in sheltered bays. Early efforts with offshore net-pens found that random wave motion caused the failure of shackles and other critical components, and that storms often accounted for the failure of containment systems (Bridger, 2004). In the late 1990s, storms destroyed an experimental open-ocean aquaculture sea cage located adjacent to an energy platform in the Gulf of Mexico; the cage was never retrieved. In recent years, hurricanes have been severe enough to push entire oil rigs to shore in the Gulf. As a review of a Puerto Rican fish farm concluded, "Disastrous loss due to the passage of a hurricane is always a major risk in open-ocean aquaculture operations (Alston *et al.,* 2005)."

While offshore cage manufacturers have taken steps to substantially strengthen net-pen designs, in some cases turning to submersible cages, major escape events may still occur. While advances in technology have overcome some of the issues, significant engineering challenges remain (Bridger, 2004). The more day-to-day risks of fish slipping out through operator error or mechanical failure will persist as well. As a recent review of aquaculture summarized, "Escapement from aquaculture is almost inevitable in all but the most biosecure aquaculture systems … The best way to avoid the negative impacts of invasive species is to not culture species outside their native range (Diana, 2009)." Under these conditions, open-ocean aquaculture should be undertaken only with native species of a local genotype that have not been selectively bred to diverge genetically from wild stock.

The Ecological Risks of Native Fish Escapes

Even if fish are native to the region where they are being farmed, they can jeopardize the health of wild populations when poorly managed. Aquaculture follows in the footsteps of the terrestrial livestock industry, which slowly domesticated farmed animals through selective breeding designed to encourage the incidence of desirable characteristics (size, feed efficiency, disease resistance, etc.). Over time, these intensively-bred populations diverged genetically from their wild cousins; broiler chickens and Jersey cows are a far cry from their wild counterparts today.

Between intentional selection, founder effects, genetic drift, and inadvertent artificial selection as a result of the different rearing environment, farmed fish can show significant genetic changes by the fifth or sixth generation (Roberge *et al.,* 2007). This domestication process can "reduce the ability of fish to survive in the wild extremely quickly: even a few generations of domestication can have substantial negative effects on natural reproduction in the wild (Araki *et al.,* 2007)." When they escape, these fish not only compete for resources with wild fish, but they can significantly impact the wild gene pool through interbreeding (Castillo *et al.,* 2008; Thorstad *et al.,* 2008), resulting in reduced survival and performance of wild fish.

Because of the relatively large scale of global salmon farming and the highly vulnerable status of many wild salmon runs, studies have shown that wild salmon populations have been harmed by the growth of the salmon farming industry. A global analysis of empirical data suggests that salmon farming has reduced the survival of wild salmon and trout dramatically. The review found a significant decline in the survival of wild salmon populations exposed to salmon farms correlated with the increase in farmed salmon production. This decline corresponds to a reduction in the abundance of wild salmon populations of more than 50% per generation on average (Ford and Myers, 2008). In Europe and eastern North America, escaped Atlantic salmon could contribute to the eventual extinction of wild salmon populations (Ford and Myers, 2008; McGinnity et al., 2003).

While the trends are clear, the causes are complex and thought to include several factors, such as competition between escapees and wild fish, interbreeding, disease spread, and the artificial elevation of predator populations (Naylor *et al.,* 2005). In terms of genetic divergence, selective breeding in salmon currently focuses on making salmon bigger, fatter, pinker, more resistant to disease, and able to procreate earlier. As a result, farmed and wild salmon differ substantially in terms of growth rate, size, stress tolerance, risk-taking behavior, salinity adaptation, and other factors (Thorstad *et al.,* 2008).

Like broiler chickens, farmed salmon fare poorly in the wild. In addition, when farmed salmon mate with wild salmon, the hybrids also exhibit worse survival rates. Not surprisingly, when large numbers of farmed escapees attempt to spawn in a river, the number of wild salmon returning to the river the next year is reduced. Because repeated salmon escapes occur year upon year, a cumulative impact develops which has been characterized as an "extinction vortex" (McGinnity *et al.,* 2003).

These concerns arise for other species as well. For example, the cod farming industry is emerging in regions inhabited by local coastal cod. Escapes at cod farms are common, artificial selection is well underway, and many wild cod populations are at historically low abundances—all conditions that may make wild cod vulnerable to the same genetic

introgression and fitness depression seen in salmon (Meager et al., 2009; Skjaeraasen et al., 2009).

For less vulnerable populations, such as sea bass and sea bream in the Mediterranean, the effects are less evident. Genetic comparisons of farmed and wild populations of sea bream indicate that farmed populations are already highly divergent from wild populations and escapes are frequent, yet negative impacts on wild populations have not been as clearly documented as with other species (Alarcon *et al.,* 2004; Basaran *et al.,* 2007). For both cod and sea bass, the lower survival of farmed fish is thought to limit their ability to interbreed (e.g. Basaran *et al.,* 2007). However, there is still significant uncertainty with this conclusion, and the experience with farmed salmon provides a cautionary tale.

As a review led by Dr. Roz Naylor of Stanford University summarized, "The inadequacy of efforts to prevent or reduce impacts of farm salmon escapes is worrisome in the face of growing farm production of other marine finfish species. Escapes of all farm species raised in open net cages appear inevitable, and many new farm species share important characteristics with farm salmon. Wild populations of some of these fish are small in projected farming areas. Examples include Atlantic cod and Atlantic halibut for farming in the United States and Canada (Naylor *et al.,* 2005)." If the US is to prevent environmental damage related to fish escapes, explicit regulations for broodstock maintenance and fish escape standards are needed to account for both individual farm-level effects and the cumulative impact of low-level escapes occurring across a large number of farms. In the absence of these regulatory safeguards, allowing open-ocean aquaculture in federal waters risks creating an "extinction vortex" for already depleted species.

DISEASES, PARASITES, AND CHEMICAL USE

While the ecological effects of escaping fish can be reduced by properly selecting the species for cultivation and careful broodstock management, disease and parasite control have proven harder to manage.

Disease is a major concern for the aquaculture industry. Pandemics of white spot syndrome virus (WSSV) and Taura syndrome virus (TSV) decimated the global shrimp farming industry in the 1990s. Today, infectious salmon anemia (ISA) is plaguing the salmon farming industry. ISA emerged as a significant pathogen in Norway in the mid-1980s; it has since caused huge problems in Europe and North America, where its spread led to the intentional destruction of millions of farmed fish, with impacts confirmed on wild shrimp and likely on wild salmon (Bridger, 2004). In 2001, Maine ordered the destruction of almost a million farmed salmon in an effort to stem the further spread of the disease. Today, the Chilean industry is desperately trying to combat the disease. Chile predicts that 2010 will be the worst farming year since the virus first broke out there in 2007, with production down 50% from 2008 (Homan-Hamam, 2009).

> *"… sea-cage aquaculture is fundamentally different from terrestrial animal culture … sea cages protect farm fish from the usual pathogen-control mechanisms of nature … but not from the pathogens themselves. A sea cage thus becomes an unintended pathogen factory …"*
>
> *–Dr. Neil Frazer, University of Hawaii, 2009*

In terms of ecological risks, disease and its management pose three main dangers to marine ecosystems:

1. The unintentional introduction of new pathogens into the marine environment caused by the importation and transfer of fish between farming regions.

2. Elevated concentrations of diseases and parasites nurtured in densely packed and potentially stressed farm environments. Such amplification of wild pathogens can increase transmission rates back to wild populations, and farms can serve as a reservoir of disease.

3. Effects on surrounding animals and possibly human health from the chemicals fish farmers use to combat disease and parasites including: vaccines, antibiotics, and parasiticides.

The Introduction and Amplification of Diseases and Parasites

Just as aquaculture can introduce exotic species, it can also foster new species of diseases and parasites. Transportation of infected fish or eggs can release pathogens into waters where native fish lack appropriate defenses. Fortunately, there have been only a few cases of introduced diseases, and most of the commonly cited examples (e.g., monogean parasites in Norway or oyster drills in California) are decades old. While the introduction of exotic diseases is a very serious concern, the application of strict biosafety controls by importing nations and farms is helping to protect ecosystems.

But some exceptions reinforce the need for caution. Imported sardines used as feed on an Australian tuna farm were suspected of introducing a new viral infection that had major impacts on the indigenous Australian sardine population (Rojas and Wadsworth, 2007). Similarly, the emergence of ISA in Chile and the rapid global spread of WSSV and TSV may be connected to the international shipment of eggs and farmed products.

Amplification of existing diseases is a more easily demonstrated effect of aquaculture. Farms often have disease outbreaks, and net pens allow for the free movement of pathogens and parasites between farmed and wild fish. Moreover, aquaculture operations can create a reservoir for diseases and parasites, fundamentally altering the pattern of exposure for wild fish. "Even at low farm stocking densities, sea-cage culture holds fishes for months in the same location at high host densities; a situation that does not occur in nature for such long time periods. These conditions facilitate disease and parasite transmission within the farm (Costello, 2009)."

It is no surprise that several accounts have linked salmon farms to disease outbreaks in wild fish populations, including furunculosis, monogean parasites, infectious salmon anemia, and sea lice (MBA, 2009; Rojas and Wadsworth, 2007). The situation with salmon is not unique, as disease and parasite outbreaks have become common in other species of fish grown in net pens. For example, yellowtail farmed in the Mediterranean, Japan, and New Zealand have suffered substantial mortality from monogenean parasites (skin flukes) (Chambers and Ernst, 2005; Hutson et al., 2003). In European sea bass production, the pathogens *Vibrio anguillarum* (vibriosis) and *Photobacterium damselae* (pasteurellosis) impact production (Cardia and Lovatelli, 2007). In Asian cage culture, there has been an increase in the incidence of essentially all forms of disease in marine finfish. This has generated ongoing concerns that further intensification of marine cage farming will trigger major disease outbreaks (Da Silva and Phillips, 2007).

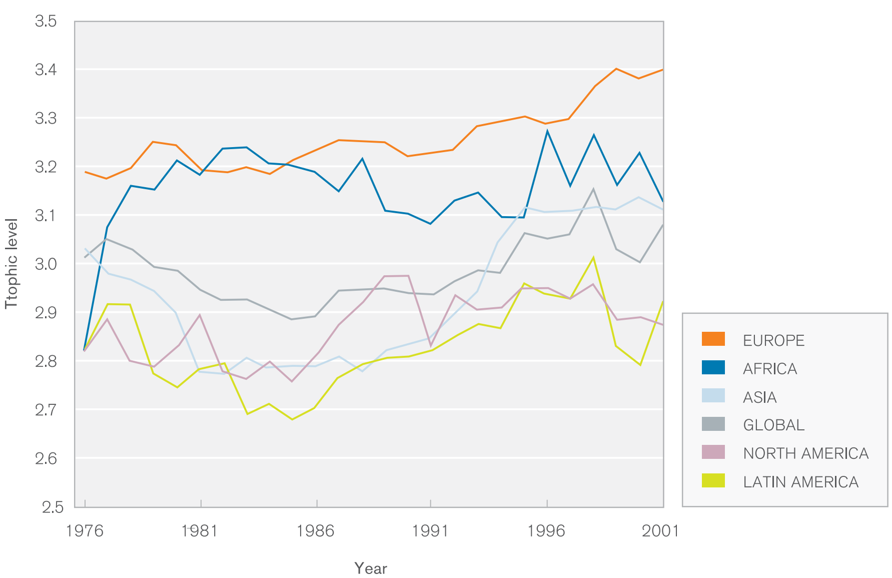
In recent years, the issue of disease and parasite amplification has received considerable attention due to the dramatic spread of parasitic sea lice from farms to wild salmon. Sea lice are copepods that feed on the skin of salmon and other fish. Infestations of sea lice reduce the fitness of salmon and can potentially be fatal. The outbreak of sea lice has had major economic implications for salmon farmers: sea lice costs the salmon farming industry nearly $5 billion annually in control efforts and reduced productivity (Krkosek *et al.,* 2009). The parasites are endemic in areas where salmon are farmed; however, prior to the development of the industry there were virtually no observations of sea lice outbreaks on wild fish. Today, sea lice are ubiquitous on farmed and wild adult salmon throughout the Northern Hemisphere. The evidence shows that salmon farms are the most significant source of outbreaks of sea lice on wild salmon in Europe and North America. Farms create a continuous source of sea lice, as do escaped farmed fish (Costello, 2009). As a result, sea lice may now be endangering wild salmon populations. While the order of magnitude of the impact of sea lice remains controversial, the direction is clear. Basic ecological principles dictate that "[p]opulation-level declines of wild fish in areas of sea-cage farming are unsurprising and extirpation is a real possibility (Frazer, 2008)." Given the information available today, adherence to the precautionary principle suggests that we should be very cautious about the disease and parasite transfer implications of aquaculture (Diana, 2009). While it is too early to know what specific diseases and parasites will be at play in open-ocean aquaculture, we do know that these general challenges will occur. Strong regulations and an adaptive approach can help minimize, but not fully eliminate, these concerns.

Chemical Use and Aquaculture

Like the terrestrial livestock industry, fish farmers routinely employ a variety of chemicals. These include antimicrobials, pesticides, antifoulants, and other chemicals (Major et al., 2009; Tacon and Forster, 2000), which are often released directly into the water.

The most toxic materials used in aquaculture may be pesticides, and they have become increasingly widespread in salmon farming due to the need to control sea lice. Applied either in feeds or in bath treatments, these chemicals have residues known to be harmful to other marine life; they have the most notable effect on the young life stages of shrimp, lobster, and other crustaceans (Abgrall *et al.,* 2000; Grant, 2002; Mayor *et al.,* 2009). As of 2000, there were 11 different chemical compounds used to treat sea lice worldwide (Roth, 2000).

FIGURE 1- AVERAGE TROPHIC LEVELS OF FISH TURNED INTO FISH MEAL AND FISH OIL BY REGION, FROM 1976-2001 (FROM ALDER ET AL.,2008).



For bacterial diseases, farmed fish can be given antibiotics as a component of their food, in baths, or in injections. When administered through feed, the majority of the drug is ultimately excreted unchanged through feces (Weston 1996). Antibiotic application can result in the development of antibiotic resistance in bacteria, which in turn has implications for human health. In many aquaculture systems, the use of antibiotics has been shown to result in bacterial resistance in nearby environments (Kerry *et al.,* 1996; Saptoka *et al.,* 2008). Le and Munekage (2004) found antibiotic residues in shrimp ponds and Samuelson et al. (1992) discovered residues in wild finfish near aquaculture facilities in Norway. Oxytetracycline-resistant bacteria are common near Chilean salmon farms (Miranda and Zemelman 2002). And bacteria found in the waters adjacent to Chinese marine finfish and shellfish farms are now multidrug-resistant, with defenses against both chloramphenicol and oxytetracycline (Dang *et al.,* 2009).

These results have triggered concern that farmed seafood could serve as a vehicle for resistance transmission to bacteria that are commensal or pathogenic to humans (Angulo and Griffin, 2000; Dang et al., 2009; Goldburg et al., 2001). Of particular concern is the effect of quinolones and other priority antibiotics on humans. The aquacultural use of quinolones remains totally unrestricted in countries like China and Chile. In Chile, aquaculture and other veterinary applications apply about 100 tons of quinolones each year, an amount that is ten times greater than the entire quantity used for human health in Chile (Cabello, 2006).

In the US, regulatory controls over the use of drugs and other chemicals in the marine environment are relatively strong. Few antibiotics are approved for US aquaculture operations, and none of the drugs approved in the US are "antibiotics of last resort in

"The accelerated growth of finfish aquaculture has resulted in a series of developments detrimental to the environment and human health. The latter is illustrated by the widespread and unrestricted use of prophylactic antibiotics in this industry …"

–Dr. Felipe Cabello, New York Medical College, 2006

humans", that is, antibiotics that are still effective when all others used to treat an illness in humans fail (NRC, 1999). Therefore, to the extent that drug-resistant bacteria emerge from US aquaculture operations, those bacteria would presumably not be resistant to these antibiotics of last resort. As a consequence, antibiotic use in the North American aquaculture industry compares favorably relative to the terrestrial livestock industry, where antibiotics are often applied for non-therapeutic purposes (Mellon *et al.,* 2001).

The use of "Investigational New Animal Drugs" or INADs bears close scrutiny, as it could result in widespread use of unproven drugs. Under the auspices of the FDA program, new drugs can be applied on an experimental basis even if they are not formally approved for use. For example, in a 2010 letter, the Pew Environmental Group asserts that 20 salmon farms in Maine used the parasiticide emamectin benzoate (Slice®) between 2006 and 2007.

With respect to all drugs, whether currently in use or under consideration, the US must avoid the trap that Chile, Norway, and other major net-pen farming regions have fallen into: heavy reliance on the application of chemicals to stave off outbreaks of chronic and increasingly drug-resistant pathogens.

FISH MEAL, FISH OIL, AND WILD FISHERIES

At the start of the "blue revolution," there was a tangible expectation that growth in aquaculture would help to reduce the pressures we place on wild fisheries (Tidwell and Allan, 2001; Ye and Beddington, 1996). Fish-farming was expected to fill our fish baskets, thereby making marginal wild fisheries obsolete. Echoes of this line of thinking continue to resonate, with some in the industry claiming that aquaculture production is more efficient than wild fisheries.[3]

Unfortunately, history shows that aquaculture does not reduce pressure on wild fisheries (Naylor *et al.,* 2000). The advent of salmon and shrimp farming has not decreased the landings of wild salmon, for instance, though it has reduced seafood prices and significantly impacted the livelihoods of the fishermen who catch those fish. To the extent aquaculture has had an effect on wild fisheries, it has increased demand for wild fish inputs used as feed in aquaculture.

Fish farming indirectly affects the marine environment by using wild marine life in feed for farm-raised fish. Fish meal, fish oil, crustacean meal, krill meal, and other marine-derived ingredients are commonly used feedstuffs in aquaculture. Commodities like fish meal and fish oil are produced by catching and processing wild pelagic fish such as sardines and anchovies, removing the water, and separating out the high-protein meals from the oils. While fish meal and fish oil are used in a variety of sectors, aquaculture is by far the largest user and may be driving the expansion of the fish meal and fish oil industry at the margins (Naylor *et al.,* 2009). The practice of turning wild fish into meal and oil is global, and it is enormous; between a quarter and a third of the world's fishery landings are converted into fish meal and fish oil each year. Today, most of that product is used to feed farmed fish.

Many reviewers have been critical of aquaculture's use of wild fish, for both ecological and ethical reasons (e.g. MBA, 2009; Naylor et al., 2000). As a practical matter, the removal of wild fish leaves fewer prey available for wild predators such as seabirds, marine mammals, and predatory fish. The removal may have top-down effects on ecosystems, potentially encouraging the growth of plankton and zooplankton (Dayton et al., 2002; Franklin, 2001). Ethically, some have objected to the fact that farming carnivores results in a net loss of protein in a world hungry for more food (Goldburg et al., 2001; Naylor et al., 1998). The open-ocean aquaculture industry will be subject to both criticisms: the farming of salmon and other marine finfish is helping to drive aquaculture's use of fish meal and fish oil, and it consumes several tons of wild fish as feed inputs for every ton of farmed product that reaches the market (Tacon and Metian, 2008).

The Ecological Effects of The Fish meal and Fish oil Industry

Each year, about 25 million metric tons of fish are "reduced" into fish meal and fish oil. This represents roughly 30% of wild

3. http://www.kona-blue.com/download/pr_ecologicalefficiencies.pdf

fishery landings, of which most are small-to medium-sized pelagic fish like anchoveta, sardines, and menhaden (Alder *et al.,* 2008). In addition, aquaculture consumes another 5 million tons of small or less popular fish fed directly to farmed animals (Tacon *et al.,* 2006). These so-called "trash fish" are species that, by virtue of their small size or low consumer preference, have little commercial value, but nonetheless are important components of marine food webs. Rather than being processed into fish meal and fish oil, a significant quantity of these fish are fed whole to aquaculture and livestock, mostly in Asia.

Typically, the fisheries targeted for fish meal and oil are fully exploited or over-exploited, and in a few cases are in decline (Watson *et al.,* 2006). As a result, there is very little room for this industry to expand.

Perhaps more importantly, scientists don't fully understand how the sheer magnitude of these removals is impacting the marine environment (Alder *et al.,* 2008). Although some have argued that the level of harvest in forage fisheries is sustainable, current fisheries science models do not generally incorporate the importance of small pelagic fish in the wider ecosystem in an adequate fashion (Tacon and Metian, 2008). Small pelagic fish are believed to play a crucial role in most ecosystems "because they are the group that transfers energy from the plankton to the larger fishes and marine mammals … Intense fishing pressure on small pelagics does result in, among other things, depleting the food base of seabirds and marine mammals (Alder *et al.,* 2008)." Removing these fish from the environment significantly reduces the amount of food available for other predators. A critical concern in the growth of US open-ocean aquaculture is that it will further contribute to this global problem.

Aquaculture's Contribution To The Fish meal and Fish Oil Industry

Traditionally, fish meal and fish oil were mainly used by poultry and livestock farmers. However, aquaculture's growth over the last two decades has largely displaced these buyers. In the last 10 years, aquaculture's share of global fish meal and fish oil consumption has more than doubled, to 68% and 88%, respectively, and is projected to grow even more (Alder *et al.,* 2008; Naylor *et al.,* 2009).

The increase has been driven in part by the high rate of growth of the marine finfish aquaculture sector. These types of farmed fish have generally had high concentrations of fish meal and fish oil in their diets (Naylor et al. 2009). In 2006, a typical salmon farm required nearly 5 tons of wild fish for every ton of farmed production. Similarly, a typical marine finfish farm required 2.2 tons of wild fish for each ton of farmed fish (Tacon and Metian, 2008). In contrast, aquaculture as a whole only required 0.6 tons of wild fish for each ton of production (Alder *et al.,* 2008). The development of a US open-ocean aquaculture industry can be expected to contribute to this trend. Currently, the list of candidate species for production is

"Fish meal is a limited resource, however, and most fish stocks are already overexploited. Because fish meal is composed of many captured species, overexploitation results in declining biodiversity."

–Dr. James Diana, University of Michigan, 2009

almost exclusively composed of carnivores: cod and haddock in the Atlantic; sablefish, threadfin, and kahala in the Pacific; cobia, amberjack, red snapper, and red drum in the Gulf of Mexico (Masser and Bridger, 2007).

If aquaculture were to entirely cease purchasing fish meal and fish oil, most forage fisheries would find other buyers for their products (e.g., pig and poultry farmers). But the growing demand for fish meal and fish oil from aquaculture will stimulate higher prices; this, in turn, will create an economic incentive to further exploit economically marginal and/or poorly regulated fisheries (Naylor et al. 2009). Indeed, the FAO has documented that world prices of fish meal more than doubled between 2000 and 2008, while the price of fish oil quintupled (FAO, 2008). Given the continued expansion of aquaculture, prices are expected to continue to rise in the long run (Naylor et al., 2009; Tacon and Metian, 2008).

The FAO is concerned that "following the increase in the world price of fish meal, [processing] plants can afford prices much higher than US$100 per ton for the raw material, which would have been unthinkable for most plants not long ago. In the immediate future, this will lead to a more intensive fishery of stocks already exploited for fish meal, and the fishing of stocks not previously used as a source of fish meal. Where small pelagics and miscellaneous non-target species are the food of the poor, the pressure for increased fish meal production will create considerable controversy (SOFIA, 2008)."

A private study on the effects of rising fish meal prices concluded that:

> "Greater prices threaten to lead to the development of reduction fisheries where they currently do not exist. While the vast majority of current fish meal and fish oil production occurs in managed fisheries that are under regulatory control, there are many economically marginal fisheries spread across the globe that may be able to increase production of fish meal and fish oil at the edges. Anecdotally, over the past few years, 10 to 15 countries have become fish meal suppliers (e.g., Yemen, Morocco), arguably as a result of higher prices. These fisheries are presumably poorly regulated, and their development may pose challenges to local marine ecosystems. Similarly, the krill fishery in the Southern Ocean is the world's single largest 'under-utilized' fishery … If the prices of fish meal, fish oil, and related commodities rise enough there will be a point at which the fishing pressure on this stock increases (CEA, 2008)."

In terms of competition with the world's poor, there are legitimate concerns that humans are effectively "eating up the food chain" by converting large quantities of low-value fish into luxury consumer products like sashimi and lox. Three-quarters of the farmed finfish in developed countries are high-value carnivorous fish species; in contrast, less than 10% of the farmed finfish in developing countries are high-value (Tacon *et al.,* 2006). Increasingly, the fish meal industry is catching fish higher up the food web to convert into fish meal and fish oil; over the last two decades, the trophic level[4] of fish turned into fish meal and fish oil has increased significantly (Alder *et al.,* 2008). In contrast, the trophic level of global fisheries as a whole fell over this period, as we have continued to fish down higher-level carnivores.

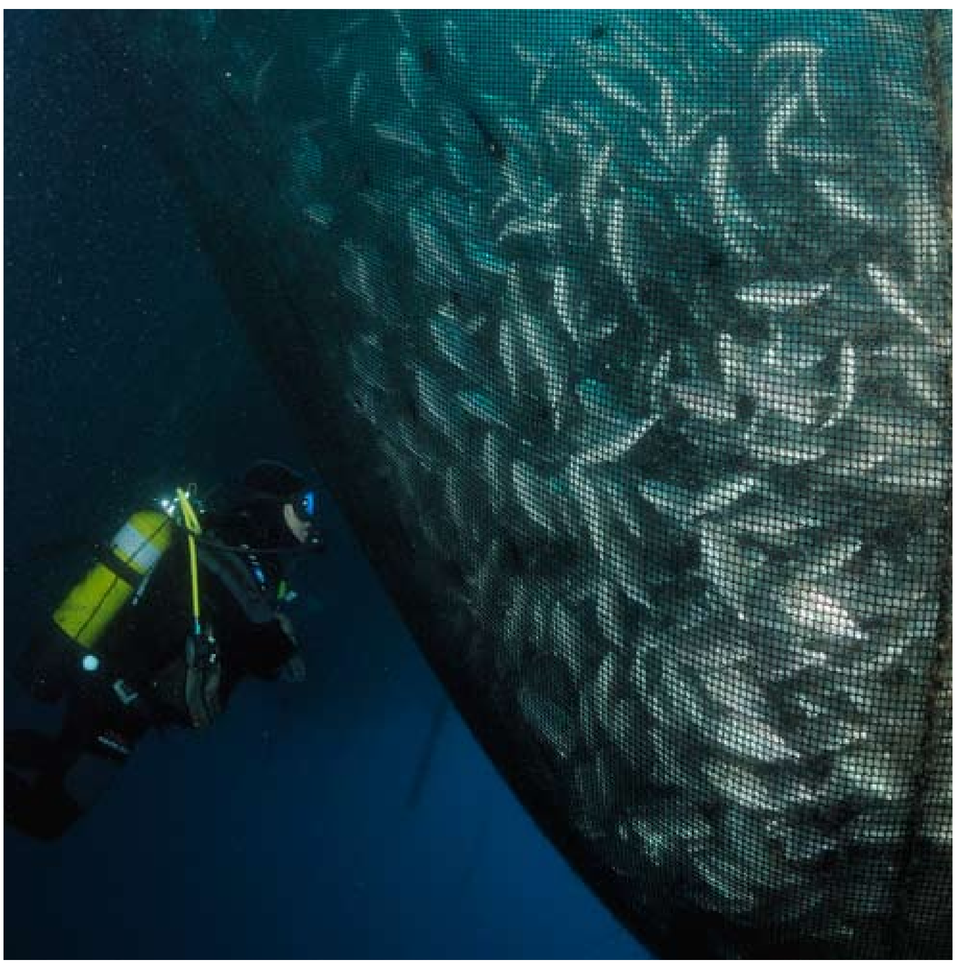
In addition to the problematic use of fish meal and fish oil in aquaculture, some sectors of the industry depend on wild fisheries to supply broodstock and juveniles. Two prime examples are the farmed eel industry's dependence on depleted populations of juvenile wild eels and the tuna ranching industry's practice of capturing and fattening young tuna in pens. The quotas governing the number of wild tuna that the aquaculture industry is permitted to catch "tend to be poorly regulated," such that tuna ranching is exacerbating the already high pressure on wild tuna fisheries (Rojas and Wadsworth, 2007).

One final dimension to the sustainability equation associated with fish meal and fish oil is the energy footprint of individual fish farms. According to one estimate, 90% of the life-cycle energy use of a salmon farm is associated with the production and application of feed. Of that, fish meal and fish oil have a particularly high impact (Tyedmers *et*

4. The trophic level of an organism is the position it occupies in the food chain. A food chain represents a succession of organisms that eat another organism and are, in turn, eaten themselves. The number of steps an organism is from the start of the chain is a measure of its trophic level. Source = Wikipedia.org

al., 2007). The open-ocean aquaculture industry's likely reliance on high concentrations of fish meal and fish oil—plus its greater dependence on energy usage for transportation and on stronger materials required in the offshore environment—will increase the environmental costs of an offshore facility relative to one located closer to shore.

The other important finding of life-cycle analysis has been its commentary on land-based aquaculture operations. Tank and recirculating aquaculture systems have often been identified as relatively sustainable alternatives to net-pen systems. Land-based facilities significantly reduce many of the proximate environmental risks associated with aquaculture, including escapes, disease, and eutrophication. However, life-cycle assessments have noted that the greater material and energy demands associated with these systems make them a much higher contributor to other impacts like global warming, non-renewable resource depletion, and acid rain (Ayer and Tyedmers, 2008). Ultimately it is difficult to weigh these different, legitimate environmental problems against each other. In any case, both open-ocean aquaculture and land-based aquaculture should proceed only if they can be done in an environmentally responsible fashion.



In the near term, open-ocean aquaculture is expected to remain dependent on wild fisheries for feed. Because there are many competing buyers for a limited supply of fish meal and fish oil, the ecological effects of this dependence are challenging to quantify. But it is likely that growth in the industry will keep the demand for fish meal and fish oil high, contributing to an increase in forage fishery landings in poorly managed fisheries.

If open-ocean aquaculture only pursues the cultivation of marine carnivores, it will have modest benefits for society. The industry will not contribute to global food supplies and it will not relieve pressure on wild fisheries (Liu and Sadovy, 2008). Instead, open-ocean aquaculture will convert large quantities of forage fish into smaller quantities of luxury seafood.

But the path for open-ocean aquaculture is not yet set in stone. The cultivation of marine plants, shellfish, herbivorous fish, or even carnivores raised on alternative diets rich in plant proteins and other feedstuffs could contribute greatly to global food supplies. The integration of these different species in multi-trophic farms has tremendous potential. Not only would it reduce the nutrient loading associated with open-ocean aquaculture operations, it would greatly enhance the industry's contribution to the global food supply.

Proactively charting a sustainable path for all of aquaculture from seed to product is thus the challenge before us.

Ensuring a Responsible Path Forward for Open-Ocean Aquaculture in the US

If a US open-ocean aquaculture industry is to be a responsible part of the nation's future seafood supply, it must fully recognize the challenges identified here, commit to resolving them, and embrace a science-based and adaptive approach to industry management that ensures oceans are protected from harm.

Over the last 20 years, the development of a US open-ocean aquaculture industry has been slowed by capital costs and operating economics that continue to disfavor industry growth relative to other forms of food production. Exploratory attempts to develop open-ocean aquaculture have also been limited by a fractured regulatory process that presents entrepreneurs with unclear permitting guidelines requiring numerous agency approvals.

But these barriers are beginning to crumble.

While the economics of open-ocean aquaculture remain challenging, technological innovations and greater experience in exposed environments are eroding many of the engineering obstacles. Particularly for high-value finfish (tuna, moi, pompano, cobia), entrepreneurs are beginning to see potentially viable opportunities to expand. As a result, there

has been greater incentive to work through the existing regulatory process. The current lack of overarching federal legislation in the US does not guarantee there will be no aquaculture in the US Exclusive Economic Zone (EEZ): it only guarantees that what development does occur will do so in the absence of strong regulatory oversight. Indeed, new open-ocean aquaculture initiatives continue to emerge.

- In the Gulf of Mexico, the federal government helped the regional fishery management council to develop an "Aquaculture Fishery Management Plan" (FMP) pursuant to the Magnuson-Stevens Fishery Conservation and Management Act (MSA). This plan will allow the production of up to 65 million pounds of farmed fish per year in the Gulf of Mexico. The Western Pacific Fishery Management Council is following the Gulf's lead and is revising its regulations to accommodate aquaculture. Legally, such an approach has been challenged under the premise that the MSA does not provide the authority to regulate aquaculture. Practically, the statute includes neither the key safeguards nor regulatory tools and approaches necessary to ensure that aquaculture is developed and managed in an ecologically sustainable manner.

- In California, Hubbs-SeaWorld Research Institute has announced plans to build the first fish farm in federal waters, located west of San Diego.[5] This facility, slated to occupy a space equivalent to 300 football fields, faces a complex regulatory approval process that includes a patchwork of permits from the Army Corps of Engineers, the Environmental Protection Agency, and other federal and state agencies. Because of the disjointed, overlapping, and confusing federal regulatory landscape, no single agency would take responsibility for the project.

- The state of Hawaii recently approved plans that could pave the way for additional development in offshore waters. Hawaii Ocean Technology has obtained permits to develop a substantial deep-water fish farm that would hover just below the ocean surface in nearly 3,000 feet of water. Unlike existing technology, the farm would not be attached to the bottom, but instead would use unproven technology to remain in place. Should it prove technologically feasible, this system would open the door for fish farms to move farther into the federal EEZ.

These cases illustrate that the lack of an overarching national framework is not preventing aquaculture development. Rather than continuing to lurch forward in a piecemeal fashion, we should establish a framework that establishes a precautionary approach from the start.

Unlike the expansion of agriculture on land, we have an opportunity today to create intelligent guidelines before an industry takes hold. It serves the interests of the environment, the public, and the industry to articulate that path now.

GUIDING PRINCIPLES FOR REGULATING OPEN-OCEAN AQUACULTURE

Over the last decade, a number of high-level commissions and advisory bodies have made a range of recommendations concerning the principles and provisions of a coordinated, federal regulatory regime for open-ocean aquaculture in the US.[6] Most notably, these include the US Commission on Ocean Policy (2004), the Pew Oceans Commission (2003), and the Marine Aquaculture Task Force (2007). In addition, the U.N. Food and Agriculture Organization, the National Research Council, the National Oceanic and Atmospheric Administration, the University of Delaware's Center for the Study of Marine Policy, and the Conservation Working Group of the Channel Islands National Marine Sanctuary Advisory Council have also contributed to defining the doctrines that should guide the development of the industry. The State of California also enacted the Sustainable Oceans Act (SB 201)[7] in 2006, currently the most comprehensive law in the US governing marine aquaculture.

This broad body of work contains a common set of guiding principles. The United States must establish a national framework for open-ocean aquaculture that is comprehensive, is rooted in the precautionary approach, sets strong environmental standards for the development of the industry, and effectively protects the broader public interest.

Within each of these four principles, a number of supporting provisions

5. In November 2009, Hubbs-SeaWorld opted to temporarily halt its application for federal permits, at least in part due to regulatory uncertainty at the federal level.

6. FAO Code of Conduct for Responsible Fisheries 1995; NOAA Code of Conduct for Responsible Aquaculture Development in the US Exclusive Economic Zone 2001; Pew Oceans Commission – Chapter 14 Guiding Sustainable Marine Aquaculture 2003; US Commission on Ocean Policy – Chapter 22 Setting a Course for Sustainable Marine Aquaculture 2004; Conservation Working Group of the Channel Islands National Marine Sanctuary Advisory Council – Open Ocean Aquaculture in the Santa Barbara Channel: An Emerging Challenge for the Channel Islands National Marine Sanctuary 2007; Marine Aquaculture Task Force – Sustainable Marine Aquaculture: Fulfilling the Promise; Managing the Risks 2007.

7. The California Sustainable Oceans Act, Chapter 36, Statutes of 2006. An act to amend Sections 15400, 5405, 15406, 15406.5, and 15409 of, and to add Sections 54.5 and 15008 to, the Fish and Game Code, and to amend Section 30411 of the Public Resources Code, relating to aquaculture.

emerge from the survey of the scientific literature contained in this study and the recommendations of these Commissions.

PRINCIPLE 1 – ESTABLISH A COMPREHENSIVE FRAMEWORK

Open-ocean aquaculture should not continue to develop in an *ad hoc* fashion. It should proceed only under the umbrella of a comprehensive national policy, including new federal legislation, to guide the industry's development. That legislation should be coordinated with other relevant national and state laws and be integrated into regional ocean planning and management efforts. The framework should:

1. Ensure NOAA has the authority to evaluate, plan, site, permit, and regulate aquaculture in federal waters. As the primary regulatory agency, NOAA must be empowered to require removal of fish stocks, closure of facilities, revocation of permits, imposition of penalties, and other appropriate remedial measures. NOAA should be required to take immediate action to avoid or eliminate damage—or the threat of damage—to the marine environment.

2. Create a comprehensive, ecologically-based research program to address the critical environmental issues summarized in this document, including preventing cumulative impacts from multiple fish farms.

3. Require the development of regional programmatic environmental impact statements (PEIS) that explicitly address the potential local, regional, and cumulative impacts of an expanding industry before commercial permits are granted. These analyses should review existing scientific information, anticipate environmental impacts, and provide a regionally specific framework for managing marine aquaculture in an environmentally sustainable and spatially explicit manner. Each PEIS should evaluate whether appropriate areas in the relevant region exist for aquaculture development to ensure siting avoids adverse impacts on marine ecosystems and other ocean user groups.

4. Require that open-ocean aquaculture be integrated with future federal coastal and marine spatial planning efforts as the nation moves toward holistic ecosystem-based ocean management.

5. Provide states with the ability to determine if they wish to permit marine fish farming off their coasts without overriding their authority under the Coastal Zone Management Act.

6. Prohibit siting open-ocean aquaculture in or near specific sensitive marine habitats, including marine reserves and National Marine Sanctuaries, or on oil and gas platforms.

7. Create an inclusive, balanced, national advisory board to advise the Secretary of Commerce on all matters of open-ocean aquaculture, including emerging risks.

8. Nullify existing open-ocean aquaculture permits and permitting schemes such as the Gulf of Mexico Aquaculture Fishery Management Plan.

PRINCIPLE 2 – USE A PRECAUTIONARY APPROACH

A comprehensive national framework should ensure that, in the face of uncertainty, open-ocean aquaculture operations will proceed only when independent, peer-reviewed science provides reasonable assurances that it can be conducted in a manner that will prevent negative impacts on marine ecosystems. Given the range of uncertainties, the government's priority should be the protection of vibrant marine ecosystems. Irreversible environmental harm, including cumulative effects, to the marine environment from open-ocean aquaculture should be prohibited, and other environmental impacts should be minimized when they cannot be avoided. Specifically, the framework should:

1. Require that all decisions concerning aquaculture permits, siting, and industry expansion be based on the best scientific information available.

2. Ensure that the research program collects the information necessary to provide the foundation for commercial open-ocean aquaculture operations to be ecologically sustainable and compatible with healthy, functional ecosystems. The findings of the research program and the periodically updated PEIRs and other emerging information should be regularly incorporated into the permitting system.

3. Require NOAA to modify, suspend, or revoke permits for permit violations, emergencies, or the emergence of new information.

4. Require regular review of aquaculture permits to ensure ongoing environmental compliance.

5. Show a permitting preference for facilities that will use technologies that substantially exceed permit requirements, such as in-water, closed containment, and integrated multi-trophic aquaculture.

PRINCIPLE 3 –DEFINE AND ENFORCE RIGOROUS ENVIRONMENTAL STANDARDS

The national framework should establish rigorous environmental standards to regulate facility siting, permitting, monitoring, and enforcement. The standards should be performance-based, structured to reward facilities for performance beyond minimum requirements, and include significant penalties for facilities that fall short. The standards should address each of the specific environmental issues identified in this report as follows:

1. **Pollution and Habitat Effects**

   i. Effluent: The standards should set numerical effluent limits that prevent discharges to the maximum extent possible and prevent cumulative impacts.

   These limitations should meet water quality standards, and discharge permits should explicitly address cumulative and secondary impacts at the local and regional level. Integrated multi-trophic aquaculture (the farming of seaweeds, filter feeders, and finfish in close proximity) and in-water closed containment technologies should be given a preference over open net-pen, single species facilities.

   ii. Wildlife: Standards should require that permittees develop and implement a comprehensive predator management plan that employs non-lethal deterrents. As part of this plan, performance metrics, best-available technologies, and site selection should be used to avoid entanglement, disruption of migration, and predator attraction or repulsion so as not to disturb wildlife or affect their use of marine habitats. Underwater acoustic deterrent devices should not be permitted.

2. **Fish Escapes**

   i. Species Selection: Open-ocean aquaculture should be limited to native fish of local genotype. Species that are threatened, vulnerable, of special concern, or those with protected status under the Endangered Species Act should not be cultured.

   ii. Broodstock Management: Stocked fish should be limited to only two generations removed from the relevant wild stock. The use of genetically modified fish should be prohibited, as should ocean “ranching” operations.

   iii. Escape Prevention: All facilities and operations must be designed and operated to prevent the escape of farmed fish into the marine environment and to withstand severe weather conditions and marine accidents.

iv. **Reporting:** If escapes do occur, facility operators must document such escapes and the circumstances surrounding them, report them immediately to NOAA, and maintain publicly available records of such events. Proper marking of fish through physical or biophysical tags should be required.

3. **Disease Transfer and Chemical Use**

   i. **Disease Prevention:** Open-ocean aquaculture facilities should be designed, located, and operated to minimize the incubation and spread of disease and pathogens without relying on the use of chemicals. Individual permitting decisions must be informed by an analysis of reported industry-wide, on-farm disease and pathogen data as well as a scientific understanding of disease and pathogen distribution in the wild.

   ii. **Chemical Application:** Prophylactic use of antibiotics and other drugs should be prohibited. Biological options (e.g., cleaner fish and integrated pest management) should be prioritized over the application of chemicals. The application of any chemicals should be minimized and their use recorded, with that information made publically available. Only drugs and chemicals expressly approved by the Food and Drug Administration should be allowed in open-ocean aquaculture.

   iii. **Bio-security:** The transfer of fish and eggs between regions without proper bio-security safeguards should be prohibited.

4. **Use of Wild Fish for Feed**

   i. **Source of Wild Fish:** Fish meal, fish oil, and other marine derived ingredients used in open-ocean aquaculture should be sourced only from abundant stocks that are not subject to overfishing and are managed using effective ecosystem-based management measures.

   ii. **Inclusion Rates:** Facilitators should minimize the rate of inclusion of wild fish as ingredients in food for farmed fish and should use alternatives to wild fish (including seafood harvesting byproducts and non-marine foodstuffs) to the maximum extent possible.

PRINCIPLE 4 – PROTECT THE COMMONS

The marine environment is held by the government in public trust. The commercialization of that environment should not proceed unless public resources are adequately protected and the public is fairly compensated for the use of its resources. All aspects of the development of open-ocean aquaculture should be subject to a meaningful public process, regulators should require aquaculture operators to pay a fair return to the public for the use of federal ocean space and resources, and facility owners should be held liable to the public for damage to the marine environment.

Specifically, the national framework should include:

1. **A Balanced Public Process:** All aspects of the development and regulation of open-ocean aquaculture should be subject to a full, meaningful, balanced, and open public participation process. In particular, there should be a strong voice for fishing communities, whose livelihoods are most at stake from the expansion of this new industry. NOAA and other federal agencies should consult with the regional fishery management councils, interstate fishery commissions, and tribal fishery management organizations on all matters related to open-ocean aquaculture. No commercial aquaculture facility should be permitted without approval from the fishery management body with jurisdiction in the area in which the aquaculture facility would be located.

2. **Cost Recovery and Resource Rents:** Permit fees from open-ocean aquaculture operations should, at a minimum, be sufficient to pay for the costs of administering the permitting program and for monitoring and enforcing the terms of the permits. A reasonable portion of the resource rent generated from marine aquaculture projects should be used for the protection and restoration of marine and coastal habitats.

3. **Liability for Damages:** Operators of aquaculture facilities in federal waters should be held liable for environmental damages stemming from their operations. NOAA should be required to obtain financial guarantees from each permitee to safeguard against these damages and to ensure that all structures are removed and sites returned to their original condition upon termination of operations. A citizen suit provision should be included as an additional means to enforce violations should federal agencies fail to do so.

Conclusion

Now is the time for strong federal leadership on the future of open-ocean aquaculture in the United States. The world is changing rapidly, and it is impossible to precisely predict what new developments will emerge in open-ocean aquaculture. A national framework, including new federal legislation, is needed to prevent haphazard development lacking standardized protections. With bold action, we can ensure the protection of US federal waters while ensuring an environmentally and economically responsible industry.

The United States has a unique opportunity to craft a national vision that will foster “a race to the top,” precisely at a time when past missteps by other countries have created a “race to the bottom” that they have come to regret. This is nowhere more evident than in Chile, a country that until recently was the world’s largest producer of farmed salmon (Mardones *et al.,* 2009; Vike *et al.,* 2009). Without a sufficiently precautionary national plan, Chile massively expanded its production of farmed Atlantic salmon over the past two decades. Disease has begun to ravage the oversized industry; in the last two years there has been a 50% decline in salmon production and over 7,500 direct jobs have been lost, with untold consequences for the marine environment. This boom-and-bust cycle of development, where industry needs come before environmental protection, must be avoided at all costs if the United States is to move forward responsibly with open-ocean aquaculture.

Here in the United States, we must adopt a precautionary national framework, including new federal legislation, to ensure protection of the ocean, ocean users, and the industry. Marine aquaculture may have a responsible role to play in meeting our future seafood needs if it develops in the right way. But if it proceeds without appropriate safeguards, it may ultimately do more harm than good.

This is our chance to get it right from the start.

Citations

Abgrall P, Rangeley RW, Burridge LE, and Lawton P. 2000. Sublethal effects of azamethiphos on shelter use by juvenile lobsters (*Homarus americanus*). *Aquaculture* 181: 1-10.

Alarcon JA, Magoulas A, Georgakopoulos T, Zouros E, and Alvarez MC. 2004. Genetic comparison of wild and cultivated European populations of the gilthead sea bream (*Sparus aurata*). *Aquaculture* 230: 65-80.

Alder J, Campbell B, Karpouzi V, Kaschner K, and Pauly D. 2008. Forage fish: from ecosystems to markets. *Annual Reviews in Environment and Resources* 33: 153-166.

Alston DE, Cabarcas A, Capella J, Benetti D, Keene-Meltzoff S, Bonilla J, and Cortes R. 2005. Environmental and Social Impact of Sustainable Offshore Cage Culture Production in Puerto Rican Waters. Final Report, NOAA Federal Contract Number NA16RG1611.

Angulo F. and Griffin P. 2000. Changes in antimicrobial resistance in Salmonella enteric Serovar Typhimurium. *Emerging Infectious Diseases* 6(4): 436-437.

Anonymous. 2010. Strategy for an environmentally sustainable Norwegian aquaculture industry. Norwegian Ministry of Fisheries and Coastal Affairs. Online: http://www.fisheries.no/Key_statistics_fisheries_no/Strategy-for-an-Environmentally-Sustainable-Norwegian-Aquaculture-Industry/. Accessed April 1, 2010.

Araki H, Cooper B, and Blouin MS. 2007. Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science* 318(5847): 100-103.

Ayer NA and Tyedmers PH. 2008. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production* 17(3): 362-373.

Basaran F, Ozbilgin H., and Ozbilgin Y. 2007. Comparison of the swimming performance of farmed and wild gilthead sea bream (*Sparus aurata*). *Aquaculture Research* 38: 452-456.

Beveridge MC. 1996. *Cage Aquaculture* (2nd Edition). Edinburgh, Scotland: Fishing News Books.

Boesch DF, Burroughs RH, Baker JE, Mason RP, Rowe CL, and Siefert RL. 2001. *Marine Pollution in the United States.* Report to the Pew Oceans Commission, Arlington VA.

Bridger CJ, editor. 2004. Efforts to Develop a Responsible Offshore Aquaculture Industry in the Gulf of Mexico: A Compendium of Offshore Aquaculture Consortium Research. Mississippi-Alabama Sea Grant Consortium, Ocean Springs, MS.

Cabello FC. 2006. Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and the environment. *Environmental Microbiology* 8(7): 1137-1144.

Cao L, Wang W, Yang Y, Yang C, Yuan Z, Xiong S, and Diana J. 2007. Environmental impact of aquaculture and countermeasures to aquaculture pollution in China. *Environmental Science and Pollution Research* 14(7): 452-462.

Cardia F and Lovatelli A. 2007. A review of cage aquaculture: Mediterranean Sea. In, Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 156–187. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Carlton J. 2001. Introduced Species in US Coastal Waters. Arlington, VA, Pew Oceans Commission.

Castillo AGF, Ayllon F, Moran P, Izquierdo JI, Martinez JL, Beall E, and Garcia-Vazquez E. 2008.

Interspecific hybridization and introgression are associated with stock transfers in salmonids. *Aquaculture* 278: 31-36.

(CBC) Canadian Broadcast Corporation. 2007. Dozens of sea lions drown at B.C. fish farm. *CBC News* April 20, 2007.

(CEA) California Environmental Associates. 2008. Fish meal and Fish Oil Market Analysis: June-September 2008. Commissioned by Environmental Defense Fund with the support of the David and Lucile Packard Foundation. San Francisco, CA.

Chambers CB and Ernst I. 2005 Dispersal of the skin fluke *Benedenia seriolae* (Monogenea: Capsalidae) by tidal currents and implications sea-cage farming of *Seriola* spp. *Aquaculture* 150: 60-69.

Chen J, Guang C, Xu H, Chen Z, Xu P, Yan X, Wang Y and Liu J. 2007. A review of cage and pen aquaculture: China. *In,* Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 50–68. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Chopin T, Buschmann AH, Halling C, Troell M, Kautsky N, Neori A, Kraemer GP, Zertuche-Gonzalez JA, Yarish C, and Neefus C. 2001. Integrating seaweeds into marine aquaculture systems: a key toward sustainability. Journal of Phycology 37: 975-986.

Chopin T. 2008. Let's not make IMTA an afterthought in open ocean development. Fish Farmer March/April 2008: 40-41.

Cicin-Sain, B., S.M. Bunsick, M.R. DeVoe, T. Eichenberg, J. Ewart, H. Halvorson, R.W. Knecht, and R. Rheault. 2001. Development of a policy framework for offshore marine aquaculture in the 3-200 mile US ocean zone. Technical Report. Center for the Study of Marine Policy, University of Delaware. 166 pp.

Costello MJ. 2009. How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proceedings of the Royal Society: B* 276: 3385-3394.

(CRS) Congressional Research Service. Upton HF and Buck EH. 2008. Open Ocean Aquaculture. CRS Report for Congress. June 12, 2008.

Dang H, Zhao J, Song L, Chen M, and Chang Y. 2009. Molecular characterizations of chloramphenical- and oxytetracycline-resistant bacteria and resistance genes in aquaculture waters of China. *Marine Pollution Bulletin* 58: 987-994.

Dayton P, Thrush S, and Coleman FC. 2002. *Ecological Effects of Fishing in Marine Ecosystems of the United States.* Arlington, VA, Pew Oceans Commission.

De Silva SS and Phillips MJ. 2007. A review of cage aquaculture: Asia (excluding China). *In,* Halwart M, Soto D, and Arthur RJ (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 18–48. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Diana JS. 2009. Aquaculture production and biodiversity conservation. *BioScience* 59(1): 27-38.

Dionne M, Lauzon-Guay JS, Hamilton DJ, and Barbeau MA. 2006. Protective socking material for cultivated mussels: a potential non-disruptive deterrent to reduce losses to diving ducks. *Aquaculture International* 14: 595-613.

(FAO) United Nations Food and Agriculture Organization. 2008. Opportunities for addressing the challenges in meeting the rising global demand for food fish from aquaculture. Committee on Fisheries, Sub-Committee on Aquaculture; Fourth Session, Puerto Varas, Chile; October 6-10, 2008.

(FAO) United Nations Food and Agriculture Organization. 2008. *The State of the World Fisheries and Aquaculture.* Rome; 192 pp.

FAO. 2009. Aquaculture Production Database (Quantities and Values): 1950-2007 (Release date: March 2009). FAO Fisheries and Aquaculture Department, Fishery Information, Data and Statistics Unit. FishStat Plus version 2.32. Universal software for fishery statistics time series. Rome (www.fao.org/fishery/statistics/software/fishstat/en).

Ford JS and Myers RA. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. *PLoS Biology* 6(2): e33.

Fernandes M, Angove M, Sedawie T, and Cheshire A. 2007. Dissolved nutrient release from solid wastes of southern blue fun tuna (*Thannus maccoyii, Castelnau*) aquaculture. *Aquaculture Research* 38:388-397.

Franklin H. 2001. The most important fish in the sea. *Discover* 22(9): 44-50.

Frazer LN. 2009. Sea-cage aquaculture, sea lice, and declines of wild fish. *Conservation Biology* 23(3): 599-607.

Gibbs MT. 2009. Implementation barriers to establishing a sustainable coastal aquaculture sector. *Marine Pollution* 33: 83-89.

Goldburg RJ, Elliott M, and Naylor R. 2001. *Marine Aquaculture in the United States.* Arlington, VA, Pew Oceans Commission.

Grant A. 2002. Medicines for sea lice. *Pest Management Science* 58: 521-527.

Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, Gingrich S, Lucht W, and Fischer-Kowalski M. 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences* 104: 12942-12947.

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, and Watson R. 2008. A global map of human impact on marine ecosystems. *Science* 319: 948-952.

Halvorson HO and Duff J. 2008. Offshore aquaculture legislation designed to balance production and protection. *Marine Pollution Bulletin* 56: 1673-1675.

Halwart M, Soto D, and Arthur JR (eds.). 2007. Cage aquaculture – Regional reviews and global overview. *FAO Fisheries Technical Paper.* No. 498. Rome, FAO. 241 pp.

Homad-Haman G. 2009. Chilean salmon industry expects worst production ever in 2010. *MercoPress* October 27, 2009.

Huiwen C and Yinglan S. 2007. Management of marine cage aquaculture: Environmental carrying capacity method based on dry feed conversion rate. *Environmental Science and Pollution Research* 14(7): 463-469.

Hutson KS, Whittington ID, Gillanders BM, Rowntree JE, Ernst I, Chambers CB, and Johnston 2. 2003. Potential for parasite interactions between wild and farmed kingfish, discrimination of farmed and wild fish and assessment of migratory behavior. Final Report to FRDC (Project No. 2003/20). The University of Adelaide, Adelaide. 83 pp.

(ICES) International Council for the Exploration of the Seas. 2002. Report of the Working Group on Environmental Interactions of Aquaculture. ICES Headquarters, 8-12 April 2002. 105 pp.

Islam S. 2005. Nitrogen and phosphorus budget in coastal and marine aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. *Marine Pollution Bulletin* 50: 48-61.

IUCN. 2003. Recommendations: Vth IUCN World Parks Congress, Durban, South Africa. IUCN, Gland, Switzerland.

Jin D, Kite-Powell HL, and Hoagland P. 2007. Anticipating the growth of an ocean aquaculture industry. *Aquaculture Economics & Management* 11(3): 225-242.

Kalantzi I and Karakassis I. 2006. Benthic impacts of fish farming: Meta-analysis of community and geochemical data. *Marine Pollution Bulletin* 52: 484-493.

Kerry J, Coyne R, Gilroy D, Hiney M, and Smith P. 1996. Spatial distribution of oxytetracycline and elevated frequencies of oxytetracycline resistance in sediments beneath a marine salmon farm following oxytetracycline therapy. *Aquaculture* 145:31-39.

Krkosek M, Ford JS, Morton A, Lele S, Myers RA, and Lewis MA. 2007. Declining wild salmon populations in relation to parasites from salmon farm. *Science* 318:1772-1775.

Krkosek M, Morton A, Volpe JP, and Lewis MA. 2009. Sea lice and salmon population dynamics: effects of exposure time for migratory fish. *Proceedings of the Royal Society B: Biological Sciences* 276: 2819-2828.

Kruzic P and Pozar-Domac A. 2007. Impact of tuna farming on the banks of the coral *Cladocora caespitosa* in the Adriatic Sea. *Coral Reefs* 26:665.

Lazaruk S. 2009. Thousands of salmon escape from B.C.'s largest farm. *Ottawa Citizen* October 28, 2009.

Le TX and Munekage Y. 2004. Residues of selected antibiotics in water and mud from shrimp ponds in mangrove areas in Viet Nam. *Marine Pollution Bulletin* 49(11-12): 922-929.

Lee HW, Bailey-Brock JH, and McGuff MM. 2006. Temporal changes in the polychaete infaunal community surrounding a Hawaiian aquaculture operation. *Marine Ecology Progress Series* 307: 175-185.

Lin DT and Bailey-Brock JH. 2008. Partial recovery of infaunal communities during a fallow period at an open-ocean aquaculture. *Marine Ecology Progress Series* 371: 65-72.

Liu M and Mitcheson YS. 2008. Profile of a fishery collapse: why aquaculture failed to save the large yellow croaker. *Fish and Fisheries* 9: 219-242.

Mardones FO, Perez AM, and Carpenter TE. 2009. Epidemiologic investigation of the re-emergence of infectious salmon anemia virus in Chile. *Diseases of Aquatic Organisms,* 84:105-114.

Marin A, Montoya S, Vita R, Marin-Guirao L, Lloret J, and Aguado F. 2007. Utility of sea urchin embryo-larval bioassays for assessing the environmental impact of marine fishcage farming. *Aquaculture* 271:286-297.

(MATF) Marine Aquaculture Task Force. 2007. *Sustainable Marine Aquaculture: Fulfilling the Promise;*

Managing the Risks. Report of the Marine Aquaculture Task Force. January, 2007. 142 pp.

Masser MP and Bridger CJ. 2007. A review of cage aquaculture: North America. *In,* Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 102–125. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Major DJ, Solan M, McMillan H, Killham K, and Paton GH. 2009. Effects of copper and the sea lice treatment Slice on nutrient release from marine sediments. *Marine Pollution Bulletin* 58: 552-558.

(MBA) Monterey Bay Aquarium. 2009. *Turning the Tide: the State of Seafood.* Monterey, CA. 80 pp.

McGinnity P, Prodohl P, Ferguson A, Hynes R, Maoileidigh NO, Baker N, Cotter D, O'Hea B, Cooke D, Rogan G, Taggart J, and Cross T. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon *Salmo salar* as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society, London B* 270(1532): 2443-2450.

Meager JJ, Skjaeraasen JE, Ferno A, Karlsen O, Lokkeborg S, Michalsen K, and Utskot SO. 2009. Vertical dynamics and reproductive behavior of farmed and wild Atlantic cod *Gadus morhua. Marine Ecology Progress Series* 389: 233-243.

Mellon M, Benbrook C, and Benbrook KL. 2001. *Hogging it: Estimates of Antimicrobial Abuse in Livestock.* Cambridge, MA, Union of Concerned Scientists.

Miranda C and Zemelman R. 2001. Antimicrobial resistant bacteria in fish from the Conception Bay, Chile. *Marine Pollution Bulletin* 42(11): 1096-1102.

Moe H, Dempster T, Sunde LM, Winther U, and Fredheim A. 2007. Technological solutions and operational measures to prevent escapes of Atlantic cod (*Gadus morhua*) from sea cages. *Aquaculture Research* 38: 91-99.

Morton A and Symonds H. 2002. Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada. *ICES Journal of Marine Science* 59: 71-80.

Naylor RL, Goldburg RJ, Primaver JH, Kautsky N, Beveridge MC, Clay J, Foke C, Lubchenco J, Mooney H, and Troell M. 2000. Effect of aquaculture on world fish supplies. *Nature* 403: 1017-1024.

Naylor RL, Hindar K, Fleming IA, Goldburg RJ, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, and Mangel M. 2005. Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. *BioScience* 55(5): 427-437.

Naylor RL, Hardy RW, Bureau DP, Chiu A, Elliott M, Farrell AP, Forster I, Gatlin DM, Goldburg RJ, Hua K, and Nichols PD. 2009. Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences* 106(36): 15103-15110.

Neori A. 2008. Essential role of seaweed cultivation in integrated multi-trophic aquaculture farms for global expansion of aquaculture: an analysis. *Journal of Applied Phycology* 20: 567-570.

(NRC) US National Research Council. 1999. *The Use of Drugs in Food Animals: Benefits and Risks.* National Academies Press. Washington, D.C., US.

Olin PG. 2006. Regional review on aquaculture development. 7. North America – 2005. FAO Fisheries Circular No. 1017/7. Rome, FAO. 2006. 25 pp.

Pew Oceans Commission. 2003. *America's Living Oceans: Charting a Course for Sea Change. A Report to the Nation.* Arlington, Virginia. 79 pp.

Pitta P, Apostolaki ET, Giannoulaki M, and Karakassis I. 2005. Mesoscale changes in the water column in response to fish farming zones in three coastal areas in the Eastern Mediterranean Sea. *Estuarine, Coastal and Shelf Science* 65: 501-512.

Rapp P, Ramirez WR, Rivera JA, Carlo M, and Luciano R. 2007. Measurement of organic loading under an open-ocean aquaculture cage, using sediment traps on the bottom. *Journal of Applied Ichthyology* 23: 661-667.

Rensel JE and Forster JRM. 2007. *Beneficial Environmental Effects of Marine Finfish Aquaculture, Final Report.* Prepared for NOAA National Marine Fisheries Service National Sea Grant College Program. NOAA Award # NA04OAR4170130. 62 pp.

Rimmer MA and Ponia B. 2007. A review of cage aquaculture: Oceania. *In,* Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 208-231. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Roberge C, Einum S, Guderley H, and Bernatchez L. 2006. Rapid parallel evolutionary changes of gene transcription profiles in farmed salmon. *Molecular Ecology* 15: 9-20.

Roesijadi G, Copping AE, Huesemann MH, Forster J, Benemann JR. 2008. *Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products.* IR Number: PNWD-3931. 115 pp.

Rojas A and Wadsworth S. 2007. A review of cage aquaculture: Latin America and the Caribbean. *In,* Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 70–100. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Rosenberg AA. 2008. The price of lice. *Nature* 451: 23-24.

Ross J. 2009. The great escape: 60,000 salmon on loose. *The Scotsman* October 27, 2009.

Roth M. 2000. The availability and use of chemotherapeutic sea lice control products. *Contributions to Zoology* 69: 109-118.

Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J, Valle C, Dempster T, Tuya F, and Juanes F. 2008. Interactions between bluefish *Pomatomus saltatrix* (L.) and coastal sea-cage farms in the Mediterranean Sea. *Aquaculture* 282: 61-67.

Sapkota A, Sapkota AR, Kucharski M, Burke J, McKenzie S, Walker P, and Lawrence R. 2008. Aquaculture practices and potential human health risks: current knowledge and future priorities. *Environment International,* 34:1215-1226.

Simms N. 2009. The Ecological Efficiencies of Farmed Fish. Kona Blue Water Farms, LLC position paper. http://kona-blue.com/download/pr_ecologicalefficiencies.pdf <accessed December 15, 2009>

Skjaeraasen JE, Mayer I, Meager JJ, Rudolfsen G, Karlsen O, Haugland T, and Kleven O. 2009. Sperm characteristics and competitive ability in farmed and wild cod. *Marine Ecology Progress Series* 375: 219-228.

Sun S, Wang F, Li C, Zhou M, Ding L, Pang S, Duan D, Wang G, Yin B, Yu R, Jiang P, Liu Z, Fei X, and Zhou M. 2008. Emerging challenges: Massive green algae blooms in the Yellow Sea. *Nature Proceedings* September 7, 2008.

Tacon AGJ and Forster IP. 2000. Global trends and challenges to aquaculture and aquafeed development in the new millennium. *International Aquafeed: Directory and Buyers' Guide 2001.* T. RIA. Uxbridge, UK: 4-25.

Tacon AGJ and Forster IP. 2003. Aquafeeds and the environment: policy implications. *Aquaculture* 226: 181-189.

Tacon AGJ and Halwart M. 2007. Cage aquaculture: a global overview. *In,* Halwart M, Soto D, and Arthur JR (eds). *Cage aquaculture – Regional reviews and global overview,* pp. 1–16. FAO Fisheries Technical Paper. No. 498. Rome, FAO. 241 pp.

Tacon AGJ, Hasan MF, and Subasinghe RP. 2006. Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. *FAO Fisheries Circular* No. 1018. Rome, FAO. 96 pp.

Tacon AGJ and Metian M. 2008 Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* 185: 146-158.

Tidwell JH and Allan GL. 2001. Fish as food: aquaculture's contribution: ecological and economic impacts and contributions of fish farming and capture fisheries. *EMBO Reports* 2(11): 958-963.

Thorstad EB, Fleming IA, McGinnity P, Soto D, Wennevik V, and Whoriskey F. 2008. Incidence and impacts of escaped Atlantic salmon *Salmo salar* in nature. *Report from the Technical Working Group on Escapes of the Salmon Aquaculture Dialogue.* January, 2008. 113 pp.

Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, and Fang JG. 2009. Ecological engineering in aquaculture – Potential for integrated multi-tropic aquaculture (IMTA) in marine offshore systems. Aquaculture 297: 1-9.

Tyedmers P, Pelletier N, and Ayer N. 2007. Biophysical sustainablility approaches to marine aquaculture development policy in the United States. *A Report to the Marine Aquaculture Task Force.* February 2007. Woods Hole Oceanographic Institution, Woods Hole, MA. 48 pp.

Upton HF, Buck EH, and Borgatti R. 2007. *Open Ocean Aquaculture: CRS Report for Congress.* Congressional Research Service, Order Code RL32694.

Uglem I, Bjørn PA, Dale T, Kerwath S, Økland F, Nilsen R, Aas K, Fleming I, and McKinley RS. 2009. Movements and spatiotemporal distribution of escaped farmed and local wild Atlantic cod (*Gadus morhua* L.). *Aquaculture Research* 39(2): 158-170.

U.S. Commission on Ocean Policy. 2004. Setting a Course for Sustainable Marine Aquaculture. In, *An Ocean Blueprint for the 21st Century.* Final Report. Washington, D.C.

Venayagamoorthy SK, Fringer OB, Koseff JR, Chiu A, and Naylor R. 2009. Numerical modeling of aquaculture dissolved waste transport in a coastal embayment, Environmental Fluid Mech., submitted.

Vike S, Nylund S, and Nylund A. 2009. ISA virus in Chile: evidence of vertical transmission. *Archives of Virology,* 154:1-8.

Vita R and Marin A. 2007. Environmental impact of capture-based bluefin tuna aquaculture on benthic communities in the western Mediterranean. *Aquaculture Research* 38:331-339.

Vitousek P, Mooney H, Lubchenco J, and Milillo JM. 1997. Human domination of Earth's ecosystems. *Science* 277: 494-499.

Volpe JP, Taylor EB, Rimmer DW, and Glickman BW. 2000. Evidence of Natural Reproduction of

Aquaculture-Escaped Atlantic Salmon in a Coastal British Columbia River. *Conservation Biology* 14: 899-903.

Watson R, Alder J, and Pauly D. 2006. Fisheries for forage fish, 1950 to the present. p. 1-20. *In,* Alder J and Pauly D (eds.). On the multiple uses forage fish: from ecosystems to markets. Fisheries Centre Research Reports 14(3). Fisheries Centre, University of British Columbia.

Weston DP. 1996. Environmental Considerations in the Use of Antibacterial Drugs in Aquaculture. *Aquaculture and Water Resource Management.* Eds: Baird DJ, Beveridge MCM, Kelly LA and Muir JF. pp 140-165. Blackwell Science.

Ye Y and JR Beddington. 1996. Bioeconomic interactions between the capture fishery and aquaculture. *Marine Resource Economics,* 11: 105-123.

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