Marine Cage Culture & The Environment

Photo courtesy of Brian O'Hanlon.

Twenty-First Century Science Informing a Sustainable Industry

NOAA Technical Memorandum NOS NCCOS 164

Marine Cage Culture and the Environment:
Twenty-first Century Science Informing a Sustainable Industry

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Executive Summary

Technological innovation has made it possible to grow marine finfish in the coastal and open ocean. Along with this opportunity comes environmental risk. As a federal agency charged with stewardship of the nation's marine resources, the National Oceanic and Atmospheric Administration (NOAA) requires tools to evaluate the benefits and risks that aquaculture poses in the marine environment, to implement policies and regulations which safeguard our marine and coastal ecosystems, and to inform production designs and operational procedures compatible with marine stewardship.

There is an opportunity to apply the best available science and globally proven best management practices to regulate and guide a sustainable United States (U.S.) marine finfish farming aquaculture industry. There are strong economic incentives to develop this industry, and doing so in an environmentally responsible way is possible if stakeholders, the public and regulatory agencies have a clear understanding of the relative risks to the environment and the feasible solutions to minimize, manage or eliminate those risks. This report spans many of the environmental challenges that marine finfish aquaculture faces. We believe that it will serve as a useful tool to those interested in and responsible for the industry and safeguarding the health, productivity and resilience of our marine ecosystems.

This report aims to provide a comprehensive review of some predominant environmental risks that marine fish cage culture aquaculture, as it is currently conducted, poses in the marine environment and designs and practices now in use to address these environmental risks in the U.S. and elsewhere. Today's finfish aquaculture industry has learned, adapted and improved to lessen or eliminate impacts to the marine habitats in which it operates. What progress has been made? What has been learned? How have practices changed and what are the results in terms of water quality, benthic, and other environmental effects? To answer these questions we conducted a critical review of the large body of scientific work published since 2000 on the environmental impacts of marine finfish aquaculture around the world. Our report includes results, findings and recommendations from over 420 papers, primarily from peer-reviewed professional journals. This report provides a broad overview of the twenty-first century marine finfish aquaculture industry, with a targeted focus on potential impacts to water quality, sediment chemistry, benthic communities, marine life and sensitive habitats. Other environmental issues including fish health, genetic issues, and feed formulation were beyond the scope of this report and are being addressed in other initiatives and reports. Also absent is detailed information about complex computer simulations that are used to model discharge, assimilation and accumulation of nutrient waste from farms. These tools are instrumental for siting and managing farms, and a comparative analysis of these models is underway by NOAA.

We anticipate this report will be useful to both industry and coastal and ocean managers. Farm owners and operators can learn about the current state of knowledge regarding environmental effects of cage culture and apply it to guide siting and other farm management practices. Coastal managers and community planners can use this information to make decisions about the environmentally responsible economic opportunities that aquaculture offers. Federal, state and local regulatory agencies can apply the analysis as they develop and implement permitting and monitoring processes for coastal marine finfish farming and the emerging U.S. offshore aquaculture industry. The scientific research community can use this report to guide future studies which will improve our knowledge of how fish cages function within the marine ecosystem, help improve farm efficiency and further decrease environmental effects. This report also provides a scientific basis for national and international outreach and education.

We hope this analysis will prove useful for integrating current scientific knowledge about the real, potential and perceived effects of marine finfish cage culture and support continued development of an industry which is both economically and environmentally sustainable. Below is a synopsis of observations and trends observed for various environmental effects discussed in this report.

Water Quality

The primary potential effects to water quality associated with marine cage culture include dissolved nitrogen and phophorus, turbidity, lipids and dissolved oxygen fluxes. Usually there are no measurable effects 30 meters beyond the cages when farms are sited in well-flushed waters. Nutrient spikes and declines in dissolved oxygen sometimes are seen following feeding events, but there are few reports of long-term risk to water quality from marine aquaculture. The trend of many studies over the last 20 years indicates that improvements in feed formulation and feeding efficiency are the major reasons for decreased nutrient loading and acceptable water quality in and near farms, and explains why significant enrichment to the water column at offshore farms is generally not detected. Impaired water quality may be observed around farms in nearshore or intertidal habitats where flushing is minimal and at farms using feeds that include unprocessed raw fish rather than formulated feeds. Protection of water quality will be best achieved by siting farms in well-flushed waters.

Benthic Effects

There is a great deal of scientific information about the biogeochemical processes in sediments near fish farms and how those processes may be driven under nutrient enrichment. Excess feed and fish waste are discharged from the farms and, if they accumulate, may alter the chemical processes of decomposition and nutrient assimilation. Well-managed farms may exhibit little perturbation and, where chemical changes are measured, impacts are typically confined to within 100 meters of the cages. Benthic chemical recovery is often rapid following harvest. In contrast, heavily impacted sites may have anaerobic conditions persisting in the sediment and extending hundreds of meters beyond the farm perimeter.

Organic matter can accumulate on the bottom and push the benthos to an anaerobic and ultimately azoic state. In heavily farmed or depositional areas, remediation of highly enriched sediments may take several years.

Impacts can be avoided by placing farms in deep, well flushed areas over erosional seafloor. This results in a net movement of organic matter away from the farm, dispersing nutrients over a broader area for decomposition and assimilation. While this approach protects the immediate farm perimeter, care must be taken to monitor areas downstream of the farms to detect far-field effects, especially in habitats sensitive to nutrient enrichment and sedimentation. The accumulation of some organic matter below farms is to be expected, especially toward the end of a grow-out period when farm biomass is at its peak. Visual observations of benthic conditions below farms are a valuable tool throughout a crop cycle for assessing whether operations are within the capacity of the ecosystem. Farms located in deep water with continuous or episodic benthic scouring of organic waste will be less likely to exhibit sediment degradation. As with water quality, benthic geochemical impacts are most pronounced at enclosed, nearshore or coastal farm sites with insufficient depth and flow to disperse organic wastes.

In some areas, nutrients from farm discharge may be absorbed as food for wild marine organisms. In other locations, deposition beneath cages will have minimal, ephemeral or acceptable effects. Still other farms may need fallowing periods ranging from a few months to one or two years to recover the benthos. Site specific characteristics such as hydrodynamics, trophic status of the water column benthic shear, sediment composition, water depth and nutrient loading will interact to determine which of these will be the scenario for any given farm site.

Effective sediment monitoring protocols should include key site-specific indicator parameters like sulfide, redox potential and total organic carbon to allow for early detection of impacts. Within an adaptive management framework, a good monitoring program can be used to adjust farm management to avert serious and persistent impacts to the benthos. Monitoring and research to quantify downstream, far-field and long-term effects of fish farms beyond the immediate cage perimeter will continue to be important. The use of stable isotopes as tracers of farm waste output at larger spatial and temporal scales is a promising tool to help in this area. Continued efforts comparing different monitoring technologies and protocols to provide reliable, accurate and cost effective methods of assessing enrichment and biogeochemical impacts will be beneficial to both the industry and regulatory entities. Image analysis and acoustic methods are being successfully tested in the field, thus offering cheap and quick alternatives to traditional geochemical analysis.

Marine Life

The broader ecological role of aquaculture operations within the marine environment must be considered since fish farms in the open ocean must co-exist with a host of wild organisms including phytoplankton, benthic fauna, wild fish, marine mammals and corals. If farm nutrients accumulate and persist in the water column or sediment, marine organisms can be impacted. At appropriately-sited and well-managed farms, natural processes can be sufficient to assimilate nutrients. In nutrient limited marine environments these inputs may even fertilize marine food webs, boosting overall productivity.

At some farm sites, a phytoplankton response to nutrient loading was reported, but generally this is a low risk and causal linkages to algal blooms are not evident. Because a change in primary productivity linked to fish farm effluents would have to be detected against the background of natural variability, it is difficult to discern effects unless they are of great magnitude and duration. At larger scales, the occurrence of many anthropogenically derived nutrients in coastal marine waters, also make it difficult to attribute increased primary productivity directly to aquaculture. Hydrology of farms located near shore or in semi-enclosed water bodies which may be poor farm sites must be carefully examined to prevent eutrophication and increased primary productivity in coastal areas and habitats. A knowledge gap continues to be how dissolved nutrients are dispersed and assimilated over large marine areas, and how ecosystem productivity may be affected under increasing production from multiple farms.

Changes in the benthic community are evident when sediments become enriched with organic farm waste nutrients. At well flushed sites in deep water and with efficient feed management, ecological impacts tend to be minimal and confined to the area just beneath the cages. Under light organic enrichment an increase in benthic species abundance and biodiversity may be observed and can be a net benefit to the community. At moderately impacted farms, effects may extend to 100 meters beyond the farm edge. In enriched sediments, the benthic species composition and diversity shift toward tolerant generalists like capitellid polychaetes. The far-field effects of aquaculture to the ecological functionality of food webs and secondary production have not been studied, are difficult to ascertain and should be an area of future monitoring and research efforts.

The excess food and waste released from fish cages may be food for wild fish, especially benthic feeders. Cages may also provide shelter and foraging habitat for wild fish. These characteristics may be beneficial to the local and regional environment. Wild fish and other marine life often aggregate around fish cages and this may be considered a beneficial impact to marine life at some locations. As fish are attracted to farms, the potential for negative and positive interactions with human fishers may increase and farm management or regulatory steps should be considered to minimize conflicts. Likewise, marine fish and mammalian predators may also be attracted to farms. Little research has documented the extent to which marine predators target wild fish around farms, but this would be useful for understanding ecological interactions between farming and marine life.

At modern fish farms, impacts to predatory sharks and marine mammals are being minimized with improved net technologies and removal of dead fish from cages to prevent predation on cultured fish. Siting away from known aggregation sites and installing rigid predator exclusion nets are effective at preventing negative impacts to cultured fish, farm structures and marine predators. Acoustic deterrent devices are not consistently useful against sea lions and seals and may have deleterious impacts to non-target marine mammals. In the U.S., nonlethal interventions to prevent marine mammal predation are preferred. At marine fish farms, entanglement in the farm structures may pose a slight threat to sea turtles, dolphins, whales and seabirds. Keeping lines taut and the water free of debris are effective at minimizing or eliminating conflict with marine mammals and turtles.

The potential effect of marine cage culture to corals, seagrass and mangrove forests are of concern to resource managers and scientists. These ecosystems may be sensitive to nutrient enrichment and sedimentation, making them potentially vulnerable to farm effluent. If farms are located upstream of sensitive habitats, careful monitoring should be implemented for early detection of any perturbation.

Chemicals

The use of antibiotics, therapeutants and antifoulants at marine fish farms has declined greatly (up to 95%) in the last 20 years, resulting in decreased potential for secondary harmful effects of these chemicals on the marine environment. Vaccination, improvements in fish husbandry and best management practices are proven alternatives for achieving and maintaining fish health. Antifoulant chemicals are being replaced largely with onshore de-fouling or mechanical methods for controlling biofouling. Heavy metals from feed and antifoulants are known to accumulate beneath cages, but are often in low concentrations and sequestered in the sediment.

Management Tools

Beyond good site selection, fallowing and integrated multi-trophic aquaculture (IMTA) are two management tools that can be used to further reduce the potential environmental effects of marine fish farms. Fallowing is the practice of relocating or not re-stocking marine fish cages to allow the sediment below to undergo natural recovery, both geochemically and ecologically, from the impacts of nutrient loading. Under ideal conditions, farms should not require a fallowing period for the purpose of sediment recovery. Currently, this practice is widely and successfully implemented around the world as a method for preventing long-lasting damage to the benthic environment.

IMTA is the practice of culturing species from multiple trophic levels in systems that allow for the assimilation of fish waste particulates and dissolved nutrients into additional valuable crops, thereby reducing environmental discharge and expanding the economic base of a farming operation. The species most commonly selected for IMTA with marine fish are seaweeds, oysters and mussels, but lobsters, sea urchins, sea cucumbers and other invertebrates are also being used. Though largely experimental, the culture of additional marketable seafood products may provide dual benefits of economic profitability and reduction in nutrient enrichment.

The correlation of latitude, geographic area and trophic status of the receiving waters with the degree of biological and geochemical response to farm discharge is a critical area for further investigation. Comparative meta-analyses of environmental impacts are needed. The question of environmental impacts of any farm should be considered within a holistic context taking into account the array of oceanographic, hydrological and ecological characteristics of the site and the structural, technological and production aspects of the farm. One pattern that does emerge is that decreasing environmental risk from aquaculture appears to be driven by prudent siting of operations outside of shallow, enclosed, coastal and nearshore waters lacking dispersive current regimes, coupled with modern feed, aquatic health and farm management. This observation is important as it suggests that farming with minimal or acceptable environmental effects is possible in many ecosystems as long as proper safeguards are in place to minimize nutrient and chemical discharge and to manage its immediate and cumulative impacts. These safeguards may be in the form of regulatory oversight or industry-developed best management practices. Ideally, a combination of the two approaches would be most beneficial.

This report provides a broad perspective on a range of potential environmental impacts and their relative intensity, which should be coupled with detailed, site-specific information to make good management decisions about a proposed or operational farm site during its lifetime. As farming expands, cumulative impacts may become more apparent, and thus, robust monitoring protocols are necessary and should be proactively designed to discern both near and far-field environmental impacts.

INTRODUCTION

America's marine finfish aquaculture industry is poised to expand in the near future. Demand for seafood is on the rise and cannot be met by wild catch fisheries (Halwart et al. 2007). Domestic aquaculture production of seafood is certain to play an increasing role in fulfilling the need for reliable marine protein sources (National Oceanic and Atmospheric Administration 2007). The United States (U.S.) is committed to the growth of a modern ocean aquaculture industry that is both profitable and environmentally responsible (Gulf of Mexico Fishery Management Council 2009, National Oceanic and Atmospheric Administration 2011). To accomplish this, the most current knowledge will inform the public, support sustainable industrial practices, guide regulatory processes and strategically direct research. This technical memorandum comprises in depth summaries of the latest information and scientific research on the water quality and benthic effects of marine finfish cage culture on coastal and ocean environments. The report is a useful tool for a regulatory, industry, and research stakeholders making decisions about permitting, siting, and operating marine fish farms and to guide monitoring and further research.

Discharge from marine finfish farms and associated issues of siting such operations are among the most important environmental questions facing this industry. The National Oceanic and Atmospheric Administration (NOAA) has a variety of regulatory and marine management mandates that affect permitting of finfish farms in U.S. state and federal waters. For example, NOAA is required to consult with the U.S. Army Corps of Engineers (COE) on its permit applications to address the requirements of the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act, the Endangered Species Act and the Marine Mammal Protection Act. Siting and water quality models, water column and benthic monitoring data and best management practices are among the tools that NOAA and other agencies use in evaluating marine finfish farm permit applications and in monitoring operational farms.

The U.S. has everything required to develop a significant marine finfish aquaculture industry in coastal and open ocean waters including excellent locations, scientific expertise, state-of-the-art technology, innovative equipment and feed manufacturers and willing investors. Globally, aquaculture produces about half of the seafood people eat, but only 5% of U.S. seafood comes from domestic aquaculture. In the U.S., the aquaculture industry has not developed due to an uncertain permit processes at the state and federal levels, concerns about environmental effects and conflicting coastal uses. These factors contribute to trade imbalance, export of innovative technology and loss of potential jobs.

Over the last few decades, many reports, peer-reviewed journal articles, books and papers have been written about the environmental effects of marine finfish aquaculture. To keep our effort manageable, we narrowed our scope to focus on work published in English since 2000. Over 420 reports and papers, mostly from peer-reviewed professional journals, are cited in this report. Several key reports generated by government agencies, academic or research institutions, and private organizations are also cited. These are often good sources of summary information and data review, and provide relevant overviews of environmental issues. Only reports which included scientific citations were included. Not included in our analysis are newspaper or magazine articles or opinion pieces lacking scientific citations and review. Our sources include a vast body of work reflecting a global realization of the importance of understanding the interplay between this industry and the marine environment. While not an exhaustive compilation, this effort does provide a comprehensive look at the state of knowledge in the marine finfish aquaculture industry with regards to the environmental effects of cage culture. The collected literature originates from research conducted in countries around the world, covers a range of cultured fish species, includes many new and practical farm management approaches and addresses ecological processes at many scales.

This technical memorandum contains five main chapters each comprising several sections covering specific environmental effects. We have organized the research in the first three chapters by geographical location based upon the predominant climate regions of the world (Peel et al. 2007). Specifically, we have used the following latitudinal demarcations to arrange the works into tropical (from the equator to the Tropics of Cancer and Capricorn at 23.5° north and south), subtropical (from the Tropics of Cancer and Capricorn to 35°north and south and including the entire Mediterranean Sea) and temperate (poleward from 35° to 66.5 ° north and south). We do not include papers from aquaculture production in the polar region.

The U.S. has everything required to develop a significant marine finfish aquaculture industry in coastal and open ocean waters including excellent locations, scientific expertise, state-of-the-art technology, innovative equipment and feed manufacturers and willing investors.

Additionally, each section is organized in one of two ways. Shorter sections with less literature are organized by relative impact level. That is, studies that show no impacts are generally covered first, followed by a summary of work that did find impacts organized by climate zones. Lengthier chapter sections are arranged by climate zones first and then sorted geographically, usually from north to south and east to west. This organizational structure allows us to provide a geographical context for the research, and also tends to group often extensive content by species and to some degree culture techniques, as these are relatively similar within large areas. For example, most of the papers published in the northern Europe temperate zone address salmon culture in large off-shore net pen operations, while those in the subtropical Mediterranean report on sea bass and sea bream, often reared closer to shore. Though we did not conduct any quantitative analysis, this geographical organization also allows us to observe broad locational trends in terms of environmental impacts and factors affecting the level of those impacts. This grouping also makes it possible to consider and compare different management approaches implemented in aquaculture industries around the world. The reader should bear in mind that regional management approaches may influence how impacts are reported and interpreted. Within geographical area, work published from the same country is presented together, generally in chronological order. Finally, available summary reports or papers covering broadly applicable topics are included.

The **Water Quality** chapter includes sections on nitrogen, phosphorus, dissolved oxygen, turbidity and lipids. Next the **Benthic Effects** chapter focuses on abiotic impacts with sections addressing nitrogen phosphorus and carbon enrichment and sediment biogeochemical changes. A chapter on **Marine Life** reviews biodiversity effects on primary production, the benthic community, pelagic species and in sensitive habitats. The **Chemicals** chapter covers antibiotics, therapeutants, antifoulants and heavy metals. The final chapter, **Management Tools**, provides information about fallowing and integrated multi-trophic aquaculture.

This report was initiated by scientists at the NOAA Center for Coastal Fisheries and Habitat Research, National Centers for Coastal Ocean Science, National Ocean Service in 2011 in collaboration with the NOAA Fisheries Office of Aquaculture. The draft report was revised in 2012-2013 following review by NOAA scientists and other experts. Also, the draft paper served as a key reference paper for a NOAA sponsored workshop in March 2012. Participants at the workshop provided peer review which was additionally incorporated into the final report.

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Photo courtesy of Brian O'Hanlon.

WATER QUALITY

The environmental effects of marine finfish cage aquaculture to water quality are of primary concern to anyone interested in developing an ecologically responsible industry, and many review articles have addressed this topic (Wu 1995, Goldburg et al. 2001, Pearson and Black 2001, Hargrave 2003, Goldburg and Naylor 2005, Braaten 2007, Pittenger et al. 2007, Grigorakis and Rigos 2011). Regional efforts, many sponsored by governmental entities, are also underway to address questions about effects to water quality at varying spatial scales (Nash 2001, Wildish et al. 2004, Nash et al. 2005, Huntington et al. 2006, Costa-Pierce et al. 2007, Halwart et al. 2007, International Union for Conservation of Nature 2007, Olsen et al. 2008). This chapter summarizes results from research and monitoring projects at marine fish farms around the world investigating predominant water quality effects including dissolved nitrogen and phosphorus loading, dissolved oxygen depletion, turbidity and lipids.

While results and impacts vary among farm sites and species, there is agreement that the last twenty years has seen a significant improvement in the management of marine cage operations resulting in improved water quality. For example, in a recent review of more than 20 research papers, Holmer (2010) found none that detected significant enrichment to the water column at offshore farms. Improvements in feed formulation and feeding efficiency are repeatedly cited as major reasons for decreased nutrient loading and decreased impacts to water quality in and near farms. Siting farms in well-flushed, non-depositional waters with depth at least twice that of the net pen is recommended to ensure good water quality (Beveridge 2004, Belle and Nash 2008). Continued research to understand the complex array of forces driving nutrient dispersion in and around fish farms, including bathymetry, current flow, tidal fluctuation, and Earth's rotation (Karney and Venayagamoorthy *in press*), will provide additional tools to develop sustainable farming practices. Few comparative analyses have investigated the correlation between farm site (e.g., depth, latitude, current profile) and management characteristics (e.g., species cultured, volume of cages, biomass, feeding rate), and observed water quality impacts (Sarà 2007), so additional work in this area would provide useful guidance. The dispersal and assimilation of farm nutrients via the sea surface microlayer is another area warranting study. It is important to consider the trophic status and background nutrient flux of the receiving water, as well as other sources of nutrient loading, when assessing the relative contribution of marine fish farm discharge to the environment.

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Nitrogen

The trend of increasing nitrogen levels in coastal waters due to anthropogenic sources is a concern worldwide, especially because it may contribute to algal blooms and eutrophication (Cloern 2001, Galloway et al. 2004, Anderson et al. 2008, Holmer et al. 2008, Tett 2008). Marine cage aquaculture operations are a recognized source of nitrogenous discharge released in the form of uneaten food, feces and metabolic wastes including ammonia and urea (Cole 2002, Nash et al. 2005, Huntington et al. 2006, International Union for Conservation of Nature 2007, Pittenger et al. 2007).

Research and modeling have determined the amounts of nitrogen released from marine fish cages and the potential water quality and environmental effects of dissolved nitrogen (Hargrave 2003). Recently, Norði et al. (2011) calculated that about 63% of nitrogen fed at a rainbow trout *Oncorhynchus mykiss* farm in the Faroe Islands was lost as dissolved nitrogen. Olsen et al. (2008) constructed a mass balance estimate of nitrogen flow from a hypothetical Norwegian salmon farm producing 1000 metric tons of fish per year. Their estimated annual loading of 44 kg of nitrogen per metric ton was comparable to rates measured in Scottish farms. Islam (2005) provides a summary of nitrogen budgets in marine cage aquaculture. He reports that 68–86% of the nitrogen input as feed is eventually released to the environment, and notes that the percent of nitrogen lost varies due to the type of feed used, the feed conversion ratio of the cultured organism and feeding efficiency. Strain and Hargrave (2005) used mass balance to calculate that the total dissolved nitrogen released from farms in an inlet in southwestern New Brunswick was 33 kg of waste nitrogen per metric ton of fish produced. Total annual discharge depended upon production levels, but was determined to be a significant contributor to nutrient loading. A nitrogen budget for marine cage culture of mutton snapper *Lutjanus analis* and cobia *Rachycentron canadum* estimated that 79% of the nitrogen fed to the fish was released into the water (Alston et al. 2005). Wu (1995) and Pearson and Black (2001) cited nitrogen loss in European salmon *Salmo salar* farms between 52-95%, but noted an improvement due to advances in feeding efficiency. Nitrogen discharge to the water column continues to be cited as a major potential impact of marine cage culture (Cloern 2001, Hargrave 2003, Nash et al. 2005, Pittenger et al. 2007, Holmer et al. 2008, Olsen et al. 2008) and its potential to affect water quality have been studied around the world in various marine habitats.

In some cases, no nitrogen related effects to the water column are detected (Table 1).

Temperate

Tlusty et al. (2005) monitored water quality at Newfoundland salmon farms and found no increased nutrification of the water column despite collecting over 25,000 water samples and relatively low flushing rates of 5-20 days. Similar results are reported for salmon farms in Chile (Soto and Norambuena 2004), where no significant elevations in dissolved nitrogen were observed across nine farm and control sites. Likewise, Nordvarg and Johansson (2002) concluded that a fish farm in the Baltic's Åland archipelago had no measurable effect on dissolved nitrogen levels.

In some cases, elevated levels of dissolved nitrogen were detected, but no environmental effects were found. In Maine, Blue Hill Bay was assessed to determine the feasibility of adding more fish cages (Sowles 2005). While nitrogen levels in the bay were found to be elevated due to aquaculture, it was

IMPACT LEVEL	REFERENCE	LOCATION	SPECIES CULTURED
NONE DETECTED	Tlusty et al. 2005	Canada	Atlantic salmon
	Soto and Norambuena 2004	Chile	Atlantic salmon
	Nordvarg and Johansson 2002	Baltic Sea	Atlantic salmon
	Helsley 2007	Hawaii	Pacific threadfin
	Alston et al. 2005	Puerto Rico	Mutton snapper & Cobia
	Benetti et al. 2005	The Bahamas	Cobia
	Schembri et al. 2002	Malta	Bluefin tuna
MINIMAL	Norði et al. 2011	Faroe Islands	Atlantic salmon
	Rensel et al. 2007	Puget Sound	Atlantic salmon
	Sowles 2005	USA	Atlantic salmon
	Nash et al. 2005	Pacific Northwest	Atlantic salmon
	Matijevic 2009	Adriatic Sea	Sea bass & Sea Bream
	Neofitou and Klaoudatos 2008	Aegean Sea	Sea bass & Sea Bream
	Mantzavrakos et al. 2005	Aegean Sea	Sea bass & Sea Bream
	Pitta et al. 2005	Aegean Sea	Sea bass & Sea Bream
	Doglioli et al. 2004	Italy	Sea bass & Sea Bream
SIGNIFICANT	Aguado-Giminez et al. 2006	Mediterranean	Bluefin tuna
	Dalsgaard and Krause-Jensen 2006	Mediterranean	Sea bass & Sea Bream
	Hung et al. 2008	Taiwan	Unknown
	McKinnon et al. 2008	Australia	Barramundi
	Strain and Hargrave 2005	Canada	Atlantic salmon

Table 1. *Levels of dissolved nitrogen discharge reported and modeled at fish cage sites. At sites with minimal impact levels, the authors reported measurable increases in dissolved nitrogen, but these were statistically insignificant or were not thought to have significant environmental implications.*

concluded that the bay had the capacity to assimilate additional nitrogen loading from fish farming. Modeling to assess the feasibility of establishing cage farms in the Straits of Juan de Fuca predicted increased nitrogen in the farm plume, but did not predict enrichment or phytoplankton blooms (Rensel et al. 2007). Nash et al. (2005) concluded that extensive monitoring of net pens in Europe, Canada and the U.S. indicated only modest increases in dissolved nitrogen around fish cages, with farmers siting their operations in well flushed areas to avoid seasonal nutrient enrichment. Norði et al. (2011) measured dissolved ammonium levels up to 4.3 times higher at a trout farm in the Faroe Islands than at reference stations, but they remained within concentrations typical at efficiently flushed farm sites and no stimulation of primary production was evident.

Photo courtesy of Aaron Welch.

Sub-tropical

Off the Italian coast, Doglioli et al. (2004) modeled the regional dispersion patterns of nitrogen from an eight-cage (200 tons/year) sea bream and sea bass farm. They concluded that dissolved nitrogen concentration remained low due to flushing by strong currents. Predicted results agreed well with field sampling, validating their model. In an Adriatic sea bass *Sparus auratus* and sea bream *Dicentrarchus labrax* farm, Matijevic et al. (2009) reported slightly elevated dissolved nitrogen at farm versus reference sites, but only in surface waters. Schembri et al. (2002) found no consistent or significant changes to water quality, including dissolved nitrogen levels, at a tuna fattening operation in Malta. Neofitou and Klaoudatos (2008) measured elevated nitrogen at sea bass and sea bream cages in the Aegean Sea. Levels decreased quickly downstream of the cages (300 m), however, and never exceeded the permitted concentrations. Also in the Aegean Sea, Pitta et al. (2005) compared water column effects in farmed and reference sites and found significantly elevated nitrogen levels in bottom water (10 m) during September. However, they concluded that the levels of nitrogen were within the range of normal values reported in the Aegean and may have resulted from resuspension of benthic sediments below the thermocline. Surface and mid-water levels of nitrogen were not significantly different. In another study at northwestern Aegean sea bream and sea bass farms, increased nitrogen levels were found nearest cage sites, but dissipated within 30 m of the farm (Mantzavrakos et al. 2005).

Tropical

A mutton snapper and cobia farm in Puerto Rico monitored water quality, and found no difference in dissolved nitrogen between farm and control samples (Alston et al. 2005). Likewise, no increase in dissolved nitrogen was measured at a submersible cage stocked with cobia in the Bahamas (Benetti et al. 2005) or Pacific threadfin *Polydactylus sexfilis* cages in Hawaii (Helsley 2007).

Some research indicates there can be environmental effects from increased dissolved nitrogen.

Sub-tropical

Aguado-Giminez et al. (2006) calculated the estimated dissolved nitrogen outputs of a bluefin tuna *Thunnus thynnus* fattening operation in the Mediterranean could be 2-5.6 times greater than a comparable sea bream farm, with the potential for significant environmental impacts during peak production periods. Dalsgaard and Krause-Jensen (2006) conducted bioassays using macroalgae and phytoplankton at four sea bream and sea bass farms in the Mediterranean. For both algae and plankton, growth was highest at cage sites and elevated within 150 m of the cages. Tissue nitrogen content of the algae was highest in samples growing closest to the cages, indicating a clear transfer of nitrogen from the farm to the algae.

Tropical

In Tapong Bay, Taiwan (Hung et al. 2008), removal of mariculture structures after decades of farming from the semi-enclosed lagoon resulted in a significant decrease in dissolved nitrogen in the water column contributing to an overall improvement in ecosystem quality. Monitoring at a barramundi *Lates calcarifer* farm in Queensland, Australia measured elevated dissolved nitrogen concentrations of 251 µg/L, exceeding the trigger value of 160 µg/L set in the Queensland Water Quality Guidelines (McKinnon et al. 2008). High nitrogen levels resulted during the wet season and nitrogen flux was locally mitigated by mangrove trees. By comparison, reference sites tended to have lower mean dissolved nitrogen levels with less variability.

Elevated dissolved nitrogen in the water column around fish farms is typically a localized effect...often with seasonal variation.

Nash et al. (2005) suggested that dissolved nutrient release may affect attached macroalgae, but that eutrophication due to aquaculture will be a distant, or far-field, rather than a local affect due to dispersal of dissolved nutrients by currents. Pittenger et al. (2007) reviewed research and monitoring at marine fish cage sites concluding that discharges from farms, including nitrogen, represent a significant influx of nutrients to the marine environment. They concluded that dilution is not a sufficient strategy to address the issue and recommend that proper siting, adherence to best management practices, improved feed formulation and integrated multi-trophic aquaculture (IMTA) — farming species from different trophic levels together to promote the uptake of waste nutrients — will be key to minimizing impacts to water quality.

Elevated dissolved nitrogen in the water column around fish farms is typically a localized effect (within a hundred meters), often with seasonal variation. Siting farm operations in deep waters with sufficient flushing rates will minimize water quality impacts. Advances in feed formulation and feeding practices have reduced nitrogen loading to the environment (Stickney 2002, Braaten 2007, Pittenger et al. 2007, Belle and Nash 2008, Olsen et al. 2008). Better understanding of temporal, species-specific differences in waste discharge due to variations in growth and metabolic rates will also provide a more accurate understanding of nitrogen effluent and how to manage environmental risk, especially when multiple species are cultured in close proximity (Piedecausa et al. 2010). Questions remain about the cumulative impacts of discharge from multiple, proximal farms, potentially leading to increased primary production and eutrophication at regional and far-field scales. Research focusing on such trophic implications is discussed in the **Marine Life** chapter of this report.

phosphorus
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Phosphorus

Although nitrogen is generally the limiting nutrient in many ocean waters, the trend of increasing phosphorus levels in coastal waters due to anthropogenic sources is also of concern because primary production in some marine systems such as tropical oceans is phosphorus limited (Cloern 2001, Nordvarg and Hakanson 2002). Increased phosphorus may contribute to algal blooms and eutrophication. Marine cage aquaculture operations are a recognized source of phosphorus released in uneaten food, feces, and metabolic wastes in the form of phosphate (Cole 2002, Nash et al. 2005, Huntington et al. 2006, International Union for Conservation of Nature 2007, Pittenger et al. 2007, Holmer et al. 2008, Tett 2008).

Earlier environmental impact summaries of marine cage culture included little about phosphorus. Wu (1995) reported that up to 82% of the phosphorus in fish feed was lost to the environment while Pearson and Black (2001) found that 34-41% of phosphorus in feed was released in dissolved form. More recently, Islam (2005) reviewed phosphorus budgets of marine cage aquaculture and reported an average of 71.4% of the phosphorus in feed being released to the environment, with the percentage varying with the species cultured, the type of feed used, the feed conversion ratio and feeding efficiency. Strain and Hargrave (2005) used mass balance calculations to estimate the total fish farm derived nutrient output of an inlet in southwestern New Brunswick. Total dissolved phosphorus released from farms was calculated at 4.9 kg of waste phosphorus per ton of fish produced. Total discharge depended upon production levels, but the researchers concluded it was a significant contributor to nutrient loading. The release of phosphorus into ocean waters and the potential for deleterious nutrification effects continues to be monitored, researched and modeled in marine ecosystems around the world. Similar to the case of nitrogen in the previous section, these efforts have reported a range of results (Table 2).

Some research has found negligible changes in phosphorus levels around marine fish farms.

Temperate

Two years of monitoring nutrients at salmon farms in Newfoundland found no changes in water quality (Tlusty et al. 2005) due to farm discharge. A simulation of the Strait of Juan de Fuca (Rensel et al. 2007) predicted no adverse effects to water quality due to fish farming, especially as sunlight is thought to be the limiting factor for primary production in that body of water. Dissolved phosphorus from salmon farms in the Pacific Northwest was not identified as a concern in Nash (2001), primarily because the system is nitrogen limited. Similarly, an ecological carrying capacity assessment including evaluation of the phosphorus profiles in Blue Hill, Maine concluded that the bay could assimilate nutrients from additional net pens (Sowles 2005). Soto and Norambuena (2004) evaluated 29 salmon farm sites in Chile and found no effect of farming on dissolved phosphorus concentrations compared to reference locations.

Subtropical

Schembri et al. (2002) reported that no consistent or significant changes to dissolved phosphorus levels were found at a tuna fattening operation in Malta. Likewise, sampling at Mediterranean fish farms (Pitta et al. 2005) found no increase in dissolved phosphorus compared to reference areas.

Neofitou and Klaoudatos (2008) did find differences in dissolved phosphorus at fish farms in the Aegean Sea, but effects were reduced within 300 m of the cages and levels did not exceed those that could lead to eutrophication (0.01 mg/L). At Greek sea bream and sea bass farms, sampling stations closest to farms had increased dissolved phosphorus, but levels were decreased at 30 m from the cages (Mantzavrakos et al. 2005). Doglioli et al. (2004) modeled the

IMPACT LEVEL	REFERENCE	LOCATION	SPECIES CULTURED
NONE DETECTED	Tlusty et al. 2005	Canada	Atlantic salmon
	Soto and Norambuena 2004	Chile	Atlantic salmon
	Nash 2001	Pacific Northwest	Atlantic salmon
	Alston et al. 2005	Puerto Rico	Mutton snapper & Cobia
	Benetti et al. 2005	The Bahamas	Cobia
	Helsley 2007	Hawaii	Pacific threadfin
	Pitta et al. 2005	Aegean Sea	Sea bass & Sea Bream
	Schembri et al. 2002	Malta	Bluefin tuna
MINIMAL	Neofitou and Klaoudatos 2008	Aegean Sea	Sea bass & Sea Bream
	Matijevic 2009	Adriatic Sea	Sea bass & Sea Bream
	Mantzavrakos et al. 2005	Aegean Sea	Sea bass & Sea Bream
	Doglioli et al. 2004	Italy	Sea bass & Sea Bream
	Sowles 2005	USA	Atlantic salmon
	McKinnon et al. 2008	Australia	Barramundi
SIGNIFICANT	Strain and Hargrave 2005	Canada	Atlantic salmon
	Nordvarg and Johansson 2002	Baltic Sea	Atlantic salmon
	Piedecausa et al. 2010	Mediterranean	Bluefin tuna
	Aguado-Giminez et al. 2006	Mediterranean	Bluefin tuna
	Dalsgaard and Krause-Jensen 2006	Mediterranean	Sea bass & Sea Bream
	Hung et al. 2008	Taiwan	Unknown

Table 2. *Levels of dissolved phosphorus discharge reported and modeled at fish cage sites. At sites with minimal impact levels, the authors reported measurable increases in dissolved phosphorus, but these were statistically insignificant or were not thought to have significant environmental implications.*

dispersion of nutrients from aquaculture cages in the Italian Mediterranean predicting that prevailing currents provided flushing sufficient to avoid nutrient accumulation. Comparison with field data verified that phosphorus levels in the water due to fish farming remained very low. Sampling at sea bream and sea bass farms in the Adriatic found that dissolved phosphorus levels were only slightly elevated at farm versus reference stations, and only in the upper water column (Matijevic et al. 2009).

Tropical

Ocean fish farms in Hawaii (Helsley 2007), The Bahamas (Benetti et al. 2005) and Puerto Rico (Alston et al. 2005) reported no significant increases in dissolved phosphorus near cages. Monitoring at a barramundi farm in Queensland, Australia (McKinnon et al. 2008) found seasonally elevated dissolved phosphorus levels, but these did not exceed governmental water quality trigger value (20 µg/L).

In contrast, some studies document increased phosphorus levels due to marine fish farming.

Temperate

Nordvarg and Johansson (2002) measured phosphorus at farm sites in the Åland archipelago in the Baltic Sea. They found that farms in semi-enclosed bays had elevated levels as did some areas during high fish production, concluding that fish farming may have significant impacts on coastal areas. Complementing this work, Nordvarg and Hakanson (2002) developed a mass balance model for phosphorus for siting farms in this area and other phosphorus-limited coastal waters.

Subtropical

Dalsgaard and Krause-Jensen (2006) used macroalgal and phytoplankton assays to monitor nutrient release at fish farms in the Mediterranean. Growth was higher in samples taken closest to the fish cages, suggesting that nutrients are locally available for primary production. The phosphorus output from a tuna fattening operation was calculated to be about 3-5 times higher than from sea bream or sea bass farms because of differences in digestibility and feed formulation (Aguado-Gimenez et al. 2006). Model simulations comparing phosphorus outputs from sea bream, sea bass and Atlantic bluefin tuna (Piedecausa et al. 2010) indicated significant differences in nutrient waste production among species — with the tuna being the highest — which must be taken into account when managing the marine environment for multiple aquaculture facilities.

Tropical

The cessation of aquaculture activities in a semi-enclosed bay in Taiwan resulted in significantly decreased dissolved phosphorus levels, contributing to improved overall water quality (Hung et al. 2008).

In summary, increased dissolved phosphorus is generally not considered to be a primary concern for marine cage aquaculture (Nash et al. 2005, Costa-Pierce et al. 2007), mostly because primary production in most marine waters is nitrogen, not phosphorus, limited. With proper siting, effluents are flushed away from cage sites, diluted within a few hundred meters and dispersed for natural assimilation. Improvements in feeding efficiency and feed formulation will lessen the amounts of phosphorus released (Stickney 2002, Braaten 2007, Pittenger et al. 2007, Belle and Nash 2008). As with nitrogen, flushing of nutrients away from the immediate cage perimeter tends to minimize measurable impacts to local water quality, but there is need for monitoring and evaluation studies investigating possible cumulative impacts to downstream areas, especially in regions where multiple operational farms may be sited.

oxygen
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Dissolved Oxygen

Sufficient dissolved oxygen in the water column is essential to aquaculture operations and has been extensively studied and monitored in all types of culture operations. Oxygen concentrations in the water column near farm operations are lowered primarily through fish respiration, but also due to microbial metabolism. Wu (1995) reported only localized or insignificant affects to dissolved oxygen. Yet, concern remains that marine cage culture may significantly decrease dissolved oxygen concentrations capable of causing local short term impacts (International Union for Conservation of Nature 2007, Pittenger et al. 2007, Tett 2008).

Several recent studies reported no significant effects of marine cage culture on dissolved oxygen.

Temperate

In their assessment of Pacific Northwest salmon farms Brooks and Mahnken (2003) found little risk to the environment from dissolved oxygen depletion. In Scotland, modeling was used to predict the likely effects of fish farming to biological oxygen demand in 135 loch basins (Gillibrand et al. 2006) to assess the risk of oxygen depletion in these deep water environments. The results suggested that farming was unlikely to contribute significantly to hypoxic events in the majority of lochs.

Subtropical

In the Aegean Sea no effects were detected at tuna and sea bass farms (Basaran et al. 2007, Yabanli and Egemen 2009, Aksu et al. 2010).

Tropical

Vargas-Machuca et al. (2008) found no impacts to dissolved oxygen at snapper farms off Mexico's Pacific coast. Sampling at submerged cobia cages in Puerto Rico and The Bahamas found no significant effects on dissolved oxygen levels, with concentrations consistently above 5 mg/L (Alston et al. 2005, Benetti et al. 2010). Raw water quality monitoring data from the Kona Blue Water Farms Almaco jack *Seriola rivoliana* open ocean facility suggest no dissolved oxygen impacts from cage culture were detected (www.kona-blue.com/emonitoring.php), but no statistical tests were provided.

Some studies document decreased dissolved oxygen concentrations near fish farms.

Temperate

Hargrave's (2005) edited book focuses on environmental impacts of marine cage culture on the northeastern coast of North America and three of those papers addressing dissolved oxygen are discussed here. First, Page et al. (2005) provide a summary of monitoring efforts in New Brunswick. Decreases in oxygen are reported in and near salmon cages with the greatest declines occurring within fish cages, primarily due to lack of tidal flushing. Page et al. (2005) also present an oxygen depletion index, which models the potential for caged fish to deplete oxygen concentrations at multiple scales under varying flushing regimes. This is a tool that farmers and regulators can use to plan siting and fish stocking density. Next, Strain and Hargrave (2005) modeled nutrient fluxes and ecosystem processes around salmon farms in the Bay of Fundy. Their model estimated that fish farms could decrease oxygen concentration by up to 1.4 mg/L at individual farms, but concluded that ecosystem effects were likely minimal. Finally, Sowles (2005) investigated water quality parameters as part of an assessment of current and potential aquaculture impacts in Blue Hill Bay, Maine. Dissolved oxygen levels in the bay varied seasonally and geographically, but were found to be above the threshold value of 6 mg/L. Nash et al. (2005) found that long-term monitoring in the northeast Pacific showed maximum dissolved oxygen reductions of 2 mg/L under high density cage culture. Overall, however, dissolved oxygen reductions were generally less than 0.5 mg/L.

Dissolved oxygen at a rainbow trout farm in the Faroe Islands decreased 11- 26% from July to September compared to a reference station, although generally the water was supersaturated (Norði et al. 2011). The decreased oxygen levels were due to fish respiration and current velocity was sufficient to avoid severe oxygen depletion.

Subtropical

A study in Turkey's Güllük Bay (Demirak et al. 2006), monitored dissolved oxygen at seven sea bass cages and three control sites. Dissolved oxygen at the cage sites was significantly lower than control sites, but remained above the 4 mg/L criteria.

Tropical

Monitoring in Queensland, Australia also found decreased dissolved oxygen at barramundi cage sites often tied to seasonal tidal fluctuation, but the extent and severity were similar to unfarmed sites (McKinnon et al. 2008).

In conclusion, a meta-analysis of 30 peer-reviewed articles (Sarà 2007) found that dissolved oxygen was generally not affected by aquaculture operations. In general, low dissolved oxygen is not a serious problem in offshore fish farms (Braaten 2007) and changes in dissolved oxygen due to open ocean cage culture are not detected or are negligible. Seasonal, tidal and diurnal fluxes often cause more changes in dissolved oxygen than do fish farms. Thus, proper siting of farms in areas with sufficient flushing rates is recommended. Oxygen bubblers (Srithongouthai et al. 2006, Endo et al. 2008), mechanical aeration (Goldburg and Triplett 1997) and lowering sea cages below the ocean surface (Dempster et al. 2009) are management tools that can be implemented on farms to minimize or eliminate dissolved oxygen depletion.

Turbidity

Particulates or dust from feed and fish waste are two primary sources of turbidity associated with cage culture (Pergent et al. 1999, Ruiz et al. 2001, Hargrave 2003, International Union for Conservation of Nature 2007). Scraping of biofouling may also result in temporary decrease in water clarity (Hargrave 2003, Alston et al. 2005). In general, high flushing rates will minimize increases in turbidity at cage sites. However, when flushing rates are low due to tidal or seasonal shifts in water currents (Tanaka and Kodama 2007, McKinnon

Photo courtesy of NOAA.

et al. 2008) or due to siting in areas with decreased flow, feed and waste suspended in the water column may increase turbidity. Increased turbidity may result in lower light penetration affecting phytoplankton production (Harrison et al. 2005) and may affect photosynthesis of benthic aquatic vegetation like seagrasses (Cole 2002).

Prolonged changes in turbidity associated with freshwater aquaculture facilities have been documented (Sarà 2007), but less data is available for marine cage culture. Because of high flushing rates in open ocean conditions, turbidity is likely to be more of a concern at nearshore sites than open ocean sites. This is especially true in coastal waters in the vicinity of critical habitats such as corals and seagrass beds which could be light limited.

Temperate

A recent study conducted in Maine (Sowles 2005) found that light penetration levels (an indicator of turbidity) at both cage and control sites met water quality targets. Conversely, Harrison et al. (2005) report that in southwestern New Brunswick, Canada, Secchi depth readings at cages were significantly lower than at control sites.

Subtropical

Secchi readings at three control sites in Turkey were higher than at sea bass and sea bream sites (Aksu and Kocatas 2007), but this brief report did not include statistical values.

Tropical

Similarly, data figures of turbidity monitoring reported from the Kona Blue Water Farms open ocean facility in Hawaii suggest that no impacts from cage culture were detected even at high production levels (www.kona-blue.com/emonitoring.php), but no statistical tests were conducted. At the Snapperfarm site, turbidity values at the cobia cage were normal for ocean waters around Puerto Rico and did not differ from the control site (Alston et al. 2005). An environmental assessment of a barramundi farm in Queensland, Australia (McKinnon et al. 2008) reported turbidity differences between cage and control sites, but these were transient and the authors attributed them to seasonal and tidal differences in flushing rather than aquaculture operations. Generally, turbidity impacts at marine cage sites are not included among high priority concerns in the reviewed literature. Proper siting to ensure flushing and improvements in feed composition and feeding efficiency are generally the two management guidelines recommended to minimize aquaculture effects on turbidity. Using fish feed with low fines (i.e., feed dust particulates) and automated feeders that do not overly erode feeds will also help to minimize turbidity effects.

Lipids

Lipids are an essential component of fish feeds and are a primary source of organic waste discharged from fish farms (Hargrave 2003, Nash et al. 2005, Huntington et al. 2006, Trushenski et al. 2006, Pittenger et al. 2007, Rust et al. 2010). Fish feeds vary significantly in composition, with lipids comprising 4–40% (Tucker and Hargreaves 2008) of commercial diets. As the industry has expanded, so has the amount of fish oil released in feed products (Pittenger et al. 2007). Advances in feed formulation has resulted in some vegetable oil replacement of fish oil in feed (Nash et al. 2005, Rust et al. 2010).

Little research or monitoring data is available directly addressing lipid levels in the water in or near marine cages. Cole (2002) reported that in New Zealand lipids are often seen floating at the surface after feeding. Klaoudatos et al. (2000) reported that the mean lipid output from a 200 ton cage fish farm in Greece was 0.357 kg/day. This is the only report discovered which includes a value for lipid release at cage sites. A study (Bodennec et al. 2002) found that three ichthyotoxic unialgal species grown in media supplemented with fish feed showed altered lipid composition which could increase their toxicity. Overall, lipid output as a surface or water column pollutant has received little attention and does not appear to be a significant environmental concern.

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Photo courtesy of NOAA.

BENTHIC EFFECTS

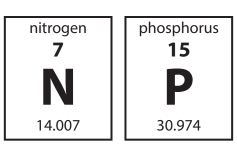
This chapter examines the most significant particulate nutrients and organic matter released from marine cage operations — nitrogen, phosphorus and carbon — and the resulting sedimentation, interstitial oxygen depletion and chemical alterations of impacted sediments. Fish food and feces are flushed from marine cages and descend through the water column. With proper siting and good water circulation, accumulation of waste from cage operations may be minimal. However, if the solid wastes are not flushed from the site, they may accumulate at rates beyond the assimilative capacity of the sediments below and around farms. In enriched sediments, the increased respiration from microbial decomposition leads to decreased oxygen in the sediments as well as changes in sediment chemistry.

Earlier reviews identify these sediment impacts as leading concerns (Wu 1995, Goldburg and Triplett 1997, Pearson and Black 2001). More recent assessments of potential impacts of marine aquaculture also identify benthic organic enrichment and sediment chemistry change as primary environmental impacts of marine cage aquaculture in the U.S. (Goldburg et al. 2001, Nash 2001, Stickney 2002, Nash et al. 2005, Phillips 2005, Pittenger et al. 2007, Johnson et al. 2008), Canada (Hargrave 2003, Wildish et al. 2004, Johannessen et al. 2007), Europe (Black et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Braaten 2007, Devlin et al. 2007, The Mediterranean Science Commission 2007, Tett 2008), the Mediterranean (International Union for Conservation of Nature 2007), New Zealand (Cole 2002), South America (Buschmann et al. 2009) and globally (Beveridge 2004, Halwart et al. 2007, Holmer et al. 2008a, Tucker and Hargreaves 2008, Holmer 2010). In this chapter, the effects of marine cage culture to benthic biogeochemistry are summarized. The biotic implications of organic enrichment are addressed in the following chapter, **Marine Life**.

Nutrient Enrichment

Excess feed and feces are the predominant sources of nutrient outflow from marine farms (Beveridge 2004, Belle and Nash 2008, Holmer et al. 2008b). Biological debris from on-site biofouling removal may also contribute to nutrient loading but this input tends to be episodic and relatively small compared to the loading from feed and feces. The total nutrient loading at a farm site depends upon a variety of factors including the size of fish being fed, the number of cages in operation, stocking density, the type of feed being used and farm management measures implemented to maximize feeding efficiency (Holmer et al. 2005). As fish mature to harvest size, more feed is required. Larger farms with more cages will discharge higher net nutrient loads. Water bodies with multiple farms may be additively affected.

Modern extruded fish feeds result in less waste than compacted pelleted feeds, and both are more efficient than using raw and unprocessed fish as feed (Rust et al. 2010). Farms which carefully monitor each feeding, either directly or with cameras, can also decrease the nutrient loading into the surrounding marine environment. Siting plays an essential role in determining the amount of nutrient accumulation in the sediments below cages. Farms located in areas with good flushing and net erosive flow conditions (versus net depositional conditions) will show fewer or no benthic effects near the farm site. In such sites, far-field or regional accumulation of nutrients is possible, especially if many farms are present.



Nitrogen and Phosphorus

Eutrophication in coastal waters may be driven by nutrient enrichment directly to the water column and by nutrients sequestered in and then resuspended from the sediments. Reviews of research on the release and accumulation of nitrogen and phosphorus from fish farms in sediments report that, when averaged globally, 20– 463 kg of nitrogen and 5–80 kg of phosphorus are released per metric ton of fish produced (Wu 1995, Islam 2005, Pittenger et al. 2007). This wide range of loading estimates reflects the variety of species cultured, feed sources and farm practices. These reviews indicate that as much as 95% of the nitrogen and phosphorus input originally as food can be released into the environment. About half of that may be in the form of solids waste which ultimately can end up in onsite or nearby sediments. Today, nitrogen and phosphorus release and accumulation are monitored routinely at farm sites around the world and research is underway to refine estimates of loading and the potential environmental impacts. Here we review recent studies which report the measured discharge of these nutrients from fish farms in North and South America, Europe, the Mediterranean and Asia.

TEMPERATE REGIONS

North America

Research has been conducted at Canadian fish farms to understand nitrogen and phosphorus accumulation in sediments below and near salmon farms. As in the U.S., it is generally thought that improved management practices have resulted in decreased nutrient loading. A fish growth model and mass balance calculations were used to estimate the nitrogen flux from salmon farms in New Brunswick at the level of individual farms and at larger scales including multiple farms (Strain and Hargrave 2005). They estimate that 9 kg of nitrogen and 2.3 kg of phosphorus per ton of fish production accumulate in the sediment over a three year grow out cycle, with the highest levels occurring in the first and third years. These values are believed to be widely applicable to salmon farms in other parts of Canada and are in close agreement with similar estimates from a comparable study in Scotland. The authors also wished to assess the wider area impacts of nutrient discharge since, even in net depositional areas, most of the waste may be transported away from farms. They calculated the total amount of discharge from fish farms within each of four hydrologically separate Coastal Management Regions. Nitrogen and phosphorus discharge estimates varied greatly between the regions because of differences in approved production limits for each region. Yearly waste also varied as fish grew from smolts to harvest size. Predicted inlet-scale changes in nutrient loading which take into account inlet volume and turnover time were also presented. Nitrogen flux attributable to salmon

Photo courtesy of NOAA.

farms in farmed bays was calculated to be between 1.7-330% higher than natural processes, with variability within and between the Management Regions. This study reflects that aquaculture may contribute significantly to alterations in nutrient loading and cycling, especially in heavily farmed areas. Because large impacts close to farms may be smaller when averaged over larger geographical regions, the authors highlight the importance of considering multiple scales when assessing potential environmental impacts of nutrient enrichment since site-specific factors such as water depth and flushing rates may significantly influence the magnitude of near-field versus far-field effects (Hargrave 2003, Wildish et al. 2004).

In the past, benthic enrichment beneath marine fish cages in the U.S. was a concern at early sites in Washington and Maine. However, relocation of farm sites and industry improvements have resulted in less enrichment mostly confined to the areas just below the cages (Goldburg and Triplett 1997, Nash 2001, Stickney 2002, Nash et al. 2005, Phillips 2005). Modern diets have improved feed retention, and best management practices have contributed to reducing unconsumed waste feed at U.S. salmon farms to less than 5%, thus decreasing nutrient accumulation beneath cages. An assessment of nitrogen inputs to Blue Hill Bay, Maine estimated that marine aquaculture discharged 42-49 metric tons of nitrogen to the system annually (Sowles 2005). This represented less than 10% of the nitrogen loading to the bay and an ecological carrying capacity assessment indicated the area could support additional net pens. A field and modeling study of hydrographic conditions in the Strait of Juan de Fuca suggest that marine cage culture would result in minimal benthic accumulation of nutrients because flushing rates are high enough to disperse farm wastes (Rensel et al. 2007).

South America

Significant nitrogen and phosphorus accumulation was found in 29 fish farms in Chile (Soto and Norambuena 2004). Phosphorus levels were nearly six times higher at farms (115 mmol/kg) than at control sites (21 mmol/kg). Average nitrogen levels (124 mmol/kg) in farm sediments was about 4 times that at control sites (32 mmol/kg), but high variability among farm sites suggested that other geographical sources of nitrogen were also a factor. Buschmann et al. (2009) later used a mass balance approach to estimate that 15% of nitrogen and 65% of phosphorus feed inputs to Chilean salmon farms settles in the sediments below cages.

Northern Europe

Early feeding practices at many European fish farms have been replaced with more efficient feeds and feed management, resulting in greatly decreased nutrient enrichment to benthic sediments (Huntington et al. 2006). Summary tables compiled by Huntington et al. (2006) show salmonid and sea bass farms release between 31-62% of nitrogen and 11-34% of phosphorus in feed as soluble waste, and that an estimated 22 g of nitrogen and 9.5 g of phosphorus as particulate waste are produced per 1000 g fish harvested. Olsen et al. (2008) estimate that 38.2% of the nitrogen and 30.7% of the phosphorus in feed are assimilated by cultured fish, with the remainder being lost as waste to the environment. They also modeled nutrient discharge from a hypothetical fish cage producing 1000 metric tons of salmon, calculating benthic loading of 14 tons of particulate nitrogen and 5.2 tons of particulate phosphorus. Braaten (2007) reported that 19% of nitrogen and 50% of phosphorus in salmon feed are ultimately deposited in the sediment below cages. Sediment and sediment trap sampling over two years at a Norwegian salmon farm found that particulate nitrogen and phosphorus concentrations were higher under cages and out to 550 m during the production cycle, compared to samples collected prior to fish stocking and distant (up to 3000 m away) reference sites (Kutti et al. 2007a). Sediment phosphorus levels were mostly above 1500µg/g dry weigh sediment near the farm, but less than 1000 µg/g dry weigh sediment further out. Particulate nitrogen accumulation in the sediments, however, was not evident. Recently, Norði et al. (2011) sampled nitrogen budgets at a rainbow trout farm in the Faroe Islands finding that sediment nitrogen doubled (from 0.2 up to 0.41 mmol/ gram dry weight sediment) during farming, mostly from fecal waste. A Scottish review of the environmental impacts of marine aquaculture concluded that while a few farm sites are nutrient enriched, most are not (Black et al. 2002). This was partially explained by improved feed efficiency, as less than 5% of feed is currently lost directly as waste, compared to earlier (prior to 1990) estimates of 20% (Black et al. 2008).

The release of large amounts of nitrogen and phosphorus is of concern due to the potential for eutrophication and large-scale ecological impacts.

Australasia

Cole (2002) summarized earlier studies in New Zealand which documented nutrient enrichment from salmon farms, but he notes that many fish farms in this area are in deep water.

SUB-TROPICAL REGIONS

North America

In Baja California, sampling at tuna sea cages found increased nitrogen levels in sediments ranging from 0.02-0.12% (Diaz-Castaneda and Valenzuela-Solano 2009). The highest levels were found in a more enclosed bay.

The Mediterranean

The last ten years have seen a great deal of research focusing on nutrient enrichment in the Mediterranean resulting from fish farming. The release of large amounts of nitrogen and phosphorus is of concern due to the potential for eutrophication and large-scale ecological impacts (Huntington et al. 2006, Cardia and Lovatelli 2007, International Union for Conservation of Nature 2007, Grigorakis and Rigos 2011).

In Spain, Aguado-Giminez and Garcia-Garcia (2004) found increased phosphorus beneath sea bream/sea bass cages, but similar increase in nitrogen was not detected presumably due to high current speeds and low stocking density. A follow up study using two sampling methods found significant differences in sediment nitrogen and phosphorus directly below and adjacent to cages, but the effects were not evident within 200-500 m of the cages (Aguado-Gimenez et al. 2007). Aguado-Gimenez et al. (2006) used bioenergetics modeling to estimate that Spanish tuna fattening farms release 26-49 mg nitrogen and 28-75 mg phosphorus per kg of fish per day. For particulate nitrogen these levels are comparable to output from sea bream and sea bass farms, but for phosphorus this is more than double. Further modeling comparisons of these three species and their nutrient output (Piedecausa et al. 2010) predict that tuna fattening releases the highest amounts of particulate nitrogen (up to

700 g nitrogen per day) and phosphorus (1000 g phosphorus per day), but this release is concentrated in a few months of the year. In contrast, sea bream and sea bass farms operate year round with continuous waste discharge. Dominguez et al. (2001) monitored sediments beneath sea bream cages in the Canary Islands and found little or no accumulation of nitrogen or phosphorus after the first year of farm operation.

In Italy, sediments in seagrass beds 20 or 100 m from fish farms were compared to beds at reference stations (Cancemi et al. 2000). Sediment pore water nitrogen (up to 10 times) and phosphorus (up to three times) concentrations were higher at farms compared to a reference sites. Nutrient accumulation was highest directly under the cages and decreased with distance from the farm. Similarly, total sediment phosphorus was very high beneath the cages, but decreased as a function of distance from the farm. Another Italian study found high levels of nutrient enrichment in sampling stations beneath cages with a clear pattern of nutrient decline out to 200 m (Porrello et al. 2005).

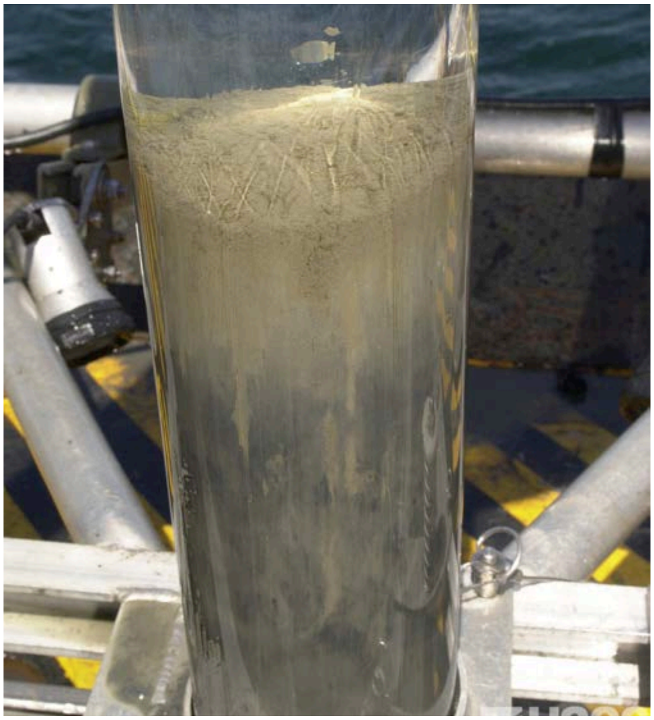


Photo courtesy of USGS.

Vizzini and Mazzola (2006) measured high levels of nitrogen isotopes in sediments taken off the coast of Sicily near fish farming operations, but could not separate farm effects from other anthropogenic sources of enrichment.

In the Adriatic Sea, Matijevic et al. (2008) found sediment phosphorus levels at tuna farms were up to five times higher than sites without farms. Similarly, Matijevic et al. (2009) and Kovac et al. (2001) reported increased phosphorus and nitrogen in sediments below sea bass and sea bream farms.

Using nitrogen isotope analysis of invertebrate tissue to differentiate between nitrogen enrichment caused by fish farm waste and sewage in the Adriatic, Dolenec et al. (2007) demonstrated that nitrogen from the farm was being assimilated into higher trophic levels in this ecosystem.

A study in Greece found increased phosphorus in sediments closest to farm stations, especially in the summer months (Mantzavrakos et al. 2005). Apostolaki et al. (2007) studied sediments in seagrass meadows in Greek, Spanish and Italian waters near sea bass and sea bream farms. While phosphorus levels declined with distance from farms, organic nitrogen levels were similar between stations.

Karakassis et al. (2005) used a simple model to estimate the amount of nitrogen and phosphorus released into the entire Mediterranean from fish farming in comparison to other human activities. They estimated that less than 5% of the annual waste discharge comes from fish farming, and conclude that this industry poses less of a long-term threat to the Mediterranean than other anthropogenic sources. Because sea bream and sea bass discharges an estimated 1.5 times more nitrogen and phosphorus into the environment than Atlantic salmon, the environmental effects of farming these two species in the Mediterranean concerns some researchers (Grigorakis and Rigos 2011).

Asia

Nitrogen flux in sediments at sea bream and yellowtail tuna *Thunnus albacores* net pen sites in a Japanese bay were 2.5 times higher than at reference sites outside of the farm, caused primarily because vertical mixing was minimal during the highest nutrient loading (Tsutsumi et al. 2006). Similarly, sampling at a Japanese sea bream farm found a nearly fourfold increase in sediment nitrogen flux at cage sites compared to background levels (Yokoyama et al. 2009).

TROPICAL REGION

Caribbean

Monitoring at cobia and mutton snapper cages in Puerto Rico concluded that 13% of nitrogen input as feed was released as solid waste, but there was no significant difference in sediment nitrogen levels compared to a control site (Alston et al. 2005).

Asia

In a nutrient enrichment study at a Chinese multi-species fish farming site, total nitrogen and phosphorus in sediments were 129% and 1316% higher than at reference stations (Gao et al. 2005). Sediments sampled in and around milkfish *Chanos chanos* pens in the Philippines were also significantly enriched with both nitrogen and phosphorus, but because these pens enclosed the seafloor they physically restricted water flow (Holmer et al. 2002).

Australasia

Monitoring at a barramundi farm in Queensland, Australia found no net accumulation of nitrogen under cage sites and the percent of nitrogen in sediments was within normal ranges for similar environments (McKinnon et al. 2008).

The deposition and accumulation of nitrogen and phosphorus in benthic sediments below marine fish cages is widely studied and highly variable (Table 3). Modern feed formulations and feeding practices have reduced the output of these nutrients to the environment. Siting of farms in deep areas with sufficient flushing and considering the cumulative effects of multiple farms are among the best tools for minimizing long-term harmful impacts. At most modern farm facilities, nitrogen and phosphorus enrichment in benthic sediments is minimal and restricted to the areas beneath and within 500 m of the cages.

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Carbon

Organic carbon is released from marine cages in the form of uneaten food and in fish feces. Reviews of the environmental effects of marine aquaculture often identify carbon deposition and accumulation as a major concern, because its microbial degradation can lead to oxygen depletion and other chemical changes in the sediment as discussed in the next section. Wu (1995) summarized that 80-84% of the carbon in feed is released to the environment, with around 23% accumulating in the sediments

Hydrodynamic processes . . . will tend to spread organic waste over larger areas, yet also provide a mechanism for aerobic assimilation of waste nutrients within the marine ecosystem.

beneath the cages. These values are similar to the range of 29-78% or 4.1–78 g carbon/m^2/day reported by Pearson and Black (2001). In contrast, Nash (2001) estimated that only about 8.8% of the carbon in feed is discharged from salmon pens to settle in sediments because of improvements in feed formulation and feeding efficiency. The accumulation of organic carbon in sediments below marine fish cages has been identified as a concern in the U.S. (Goldburg et al. 2001, Nash 2001, Stickney 2002, Nash et al. 2005, Pittenger et al.

SEDIMENT NITROGEN LOADING	REFERENCE	LOCATION	SPECIES CULTURED
9 kg/ton fish produced	Strain and Hargrave 2005	New Brunswick	Salmon
1.7 to 330% natural flux	Strain and Hargrave 2005	New Brunswick	Salmon
Double levels at control sites	Soto and Norambuena 2004	Chile	Salmon
13% lost from feed	Alston et al. 2005	Puerto Rico	Cobia
129% higher than control site	Gao et al. 2005	China	Sea bream
26-49 mg/kg fish/day	Aguado-Gimenez et al. 2006	Spain	Tuna
133 kg/ton fish produced	Islam 2005	Various	Various
2-48% lost from feed	Huntington et al. 2006	Europe	Various
SEDIMENT PHOSPHORUS LOADING	**REFERENCE**	**LOCATION**	**SPECIES CULTURED**
2.3 kg/ton fish produced	Strain and Hargrave 2005	New Brunswick	Salmon
6-9 times level at control sites	Soto and Norambuena 2004	Chile	Salmon
1316% higher than control site	Gao et al. 2005	China	Sea bream
28-75 mg/kg fish/day	Aguado-Gimenez et al. 2006	Spain	Tuna
5 times levels at control sites	Matijevic et al. 2008	Adriatic Sea	Tuna
36-74% lost from feed	Huntington et al. 2006	Europe	Various
25 kg/ton fish produced	Islam 2005	Various	Various

Table 3. *Nitrogen and phosphorus loading rates at marine fish farms. Values are presented in the units in the original reference.*

2007, Johnson et al. 2008), Canada (Hargrave 2003, Wildish et al. 2004, Holmer et al. 2005), South America (Costa-Pierce et al. 2007), Europe (International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Black et al. 2008, Holmer et al. 2008b), the Mediterranean (International Union for Conservation of Nature 2007, The Mediterranean Science Commission 2007, Grigorakis and Rigos 2011) and globally (Halwart et al. 2007, Holmer 2010).

TEMPERATE REGIONS

North America

Much research has been conducted in Canada to understand carbon release, accumulation and impacts at marine fish farms. In the Bay of Fundy, sampling in two intensive salmon aquaculture areas found increased organic carbon (about 8%) in sediments below cages compared to inlets with no farming (Pohle et al. 2001). All sites showed decreasing carbon sediment levels over a four year sampling period implying improved environmental conditions on a large scale. Similarly, Sutherland et al. (2001) deployed sediment traps at salmon net pens in British Columbia and found higher carbon flux (≈180 mg/m^2/hour) and concentrations (637 μg/mg) adjacent to pens compared to the control site (≈75 mg/m^2/hour and 442 μg/mg) 500 m away. Schendel et al. (2004) also studied carbon accumulation in sediments along horizontal and vertical transects away from a salmon farm. Surface sediment carbon concentration below the salmon farm was 4%, but quickly dropped to about 2% at 30 m and out to 300 m. Sediment carbon concentration decreased to 2.9% at 5-10 cm below the surface. Another study in New Brunswick also found increased carbon in sediments below salmon cages (Chou et al. 2004). In this study, the background organic carbon concentration was 1.6%, while farm sites ranged from 1.8-9.1% with the highest carbon concentration found in anoxic sediments. In an experiment to validate the use of acoustic detection technology to assess benthic enrichment, Wildish et al. (2004) measured sediment carbon at salmon farms and reference sites. Background carbon levels ranged from 2 -2.8%, while sediments beneath farms ranged from 13.7-25.7%, indicating highly enriched sediments. The backscatter profile from the cage site also indicated enrichment, but further validation and refinement of the methodologies is required. Using mass balance calculations, Strain and Hargrave (2005) estimated that 76 kg of waste carbon are released per ton of salmon produced during a full grow out cycle. Their results suggested that the sediment accumulated underneath farms represents a small fraction of the total discharged waste. Further modeling at a larger scale was used to predict the total amount of waste that could be generated by many farms in an inlet with multiple farms. Carbon flux was estimated to reach 160% that of natural levels in areas of intensive fish culture. Thus, the long-term, regional organic matter accumulation may be significant, especially in areas with intensive fish farming. This study highlights the need to consider impacts of aquaculture at multiple scales.

In the U.S., (Goldburg and Triplett 1997) cited studies conducted at fish farms in Maine where increased carbon deposition to the sediments was not measurable within 20 m of the cages. In contrast, they reported that increased deposition at a Puget Sound farm could be seen in the benthos out to about 150 m. Studies and data reviewed by Nash (2001, 2003) indicated that generally carbon was elevated in sediments around Pacific Northwest salmon farms to about 30 m beyond the cages, although effects could extend to over 200 m depending upon the degree of flushing. Therefore, the environmental impacts of settling and accumulation of bio-deposits, including organic carbon, were assessed as high risk compared to other environmental concerns posed by salmon farming. The sedimentation rate at salmon farms ranged from 15-100 g total volatile solids/m^2/day, about half of which would be deposited as carbon.

The question of the scale of carbon sedimentation impact and the ability to predict the capacity of larger systems to assimilate waste nutrients is addressed in an extensive review paper by Holmer et al. (2005). The high levels of sediment carbon accumulation documented at some fish farms are well above natural levels found in most coastal sediments. Carbon to nitrogen ratios may be useful in differentiating carbon derived from fish farms from other sources of loading (e.g., municipal waste). Improvements in feed formulation and feeding efficiency contribute to the management of sedimentation rate and extent of waste carbon. Wildish (2004) compiled near-field carbon sedimentation rates measured at salmon farms around the world. These ranged from 1-181 g/m^2/day, and other reviewed studies using mass balance approaches also fell within this range. Differences in values depended upon sampling methodology, farming practices and physical site characteristics. Far field effects, including carbon burial rates at larger scales, were reviewed by Hargrave (2003). Hydrodynamic processes at the sediment-water interface (i.e., benthic shear) can erode and resuspend carbon rich sediments and laterally transport carbon to locations remote from farm sites. This will tend to spread organic waste over larger areas, yet it also provides a mechanism for aerobic assimilation of waste nutrients within the marine ecosystem. Detailed information about site specific hydrology, bathymetry and local nutrient dynamics are needed to provide insight into long-term processes over large areas.

South America

An assessment of benthic conditions at salmon farms in two southern Chilean fjords reported organic carbon mineralization rates of 2.16-4.53 g carbon/m^2/day, calculated based upon measured oxygen flux (Mulsow et al. 2006). A large-scale study in southern Chile (Soto and Norambuena 2004) sampled two to five salmon farms in nine farming areas and found significant sediment carbon accumulation (413 mmol/kg) compared to control (192 mmol/kg) sites. However, other anthropogenic sources of carbon were thought to contribute to some of the carbon loading and variability among locations.

Northern Europe

Norði et al. (2011) reported a significant increase in sediment organic carbon from 1.9 mmol/g dry weight sediment prior to farming, up to 5.55 mmol/g dry weight sediment during production at a trout farm in the Faroe Islands. Effects were most prevalent within 30 m of the cages. During a two year study at a large Norwegian salmon farm Kutti et al. (2007a) found that organic carbon flux measured in sediment traps was nine times higher at the farm (365 g/m^2) than at a reference site 3 km away. Sedimentation rates were also higher in the second production year. However, no increase in particulate organic carbon was measured in the sediments and there was no evidence of accumulated organic waste, most likely due to high bottom current speeds. Although most of the particulate waste settled in traps within 250 m of the farm, carbon isotope analysis indicated that some waste could be found in traps up to 900 m away, possibly due to sediment resuspension. Mass balance equations, using the current feed and food conversion ratio data, for a hypothetical Norwegian salmon farm producing 1000 metric tons per year estimated benthic carbon loading of 2300 g/m^2/year (Olsen et al. 2008). After accounting for assimilation and respiration, carbon waste was calculated to be 24% of feed input. A study in Norway used four sampling techniques to quantify sediment enrichment at 80 sites near salmon cages (Carroll et al. 2003), including diver surveys, imagery, sediment chemistry and faunal analysis. The sediment survey found degraded conditions (based upon total organic carbon levels) under 32% of the cages. The study results showed that elevated sediment carbon levels measured at farms had dissipated at a distance of 50-100 m, even at sites with degraded sediments beneath cages. Further analysis indicated that fallowing and current speed correlated positively with environmental quality. Shakouri (2003) collected sediment samples below a salmon cage in an Icelandic fjord, finding only slight carbon enrichment (1.7% sediment dry weight) directly beneath the cage. At 95 m (1.2%) and 600 m (1.3%), no further effect was detected.

Photo courtesy of NOAA.

In Scotland, the use of a high energy diet formulation resulted in a 12% decrease in carbon levels in salmon feces (Chen et al. 2003). The Scottish Environmental Protection Agency (SEPA) has set 9% sediment carbon as the allowable criteria level (Black et al. 2008). Active salmon farms in Scotland reported organic matter concentrations ranging from 3.1-22.9% beneath cages with a decreasing trend out to 50 m with reference stations ranging from 0.9-13.5% (Black et al. 2012).

Australasia

Morrisey et al. (2000) sampled sediment traps beneath salmon farms in New Zealand finding carbon deposition rates from 463-967 mmol C/m^2/day compared to about 50 mmol C/m^2/day at control sites. This data was used in conjunction with water velocity data to model potential impact to sediments. At the lowest currents actually measured, this amount of carbon flux was predicted to cause impact with significant accumulation of carbon to the sea floor.

SUB-TROPICAL REGIONS

North America

A study at a tuna sea cage farm in Baja California, Mexico found that organic carbon sediment concentrations ranged from 0.2% to 2.53% with the highest levels in the area of the bay with the tuna pens (Diaz-Castaneda and Valenzuela-Solano 2009). Because the samples were taken 250 m from the cages, carbon deposition levels directly beneath the cages are unknown.

The Mediterranean

Many studies have been conducted in the last ten years in Italy to assess carbon enrichment at marine fish cages. La Rosa et al. (2001) measured an elevation of benthic carbon at sea bass cage sites (4949 µg/g) compared to control sites (3013 µg/g). Following removal of the cages, carbon levels dropped to concentrations comparable to control levels within a few months. Vezzulli et al. (2002) found higher levels of carbon (6327 µg/g) in benthic sediments at a sea bream farm that had been operational for 15 years compared to a control site (4596 µg/g) 200 m away. Studies such as these are important for assessing the potential cumulative effects of fish farming over longer periods. Carbon enrichment (up to 6275 µg/g) was reported at an Italian sea bream and sea bass farm, with sediment impact apparent within six weeks of fish stocking and was proportional to feeding rates (La Rosa et al. 2004). Sampling at a sea bream and drum *Argyrosomus regius* farm off Italy also found evidence of carbon loading (up to 6.32%) in sediments directly beneath the cages, but these effects declined steeply within 50 m of the cages (Porrello et al. 2005). Below a bluefin tuna fattening farm off Sicily, no significant differences were found in sediment carbon levels compared to a nearby control site (Vezzulli et al. 2008). The water depth at this open sea site was 46 m and average current was 6 cm/s, and these were considered to be the primary factors that minimized nutrient impacts despite high cultured fish biomass and feed inputs.

Modeling has been used in Italy to predict carbon loading to coastal sediments from fish farming. Doglioli et al. (2004) developed a three dimensional model, LAMP3D, to determine that a sea bream and sea bass farm in the Ligurian Sea would add about 0.085 g C/m^2/day — a level expected to have little negative environmental effect. The hypothetical site was 1.5 km offshore in 40 m of water, with strong wind and water currents. Similarly, the potential environmental impacts of a sea bass and sea bream farm expansion were modeled using the MERAMOD® model (Brambilla et al. 2007). Maximum carbon flux was estimated at 1350 g/m^2/year, with up to 150 g/m^2/year being added by the addition of four more cages. The impact area was projected to increase from 5.6 ha to 7.3 ha.

Work has also been done in the eastern Mediterranean to assess carbon loading, with mixed results. Belias et al. (2003) found organic carbon levels of 1.8, 1.9 and 7.2% at three Greek fish farms, compared to nearby reference levels around 1%. The farm with the highest enrichment level also had the highest production level of the three farms sampled. Similarly, Aksu et al. (2010) found variable carbon enrichment (0.03–10.65%) when sampling sediments at eight farms in the Aegean Sea. Again, the highest mean sediment carbon levels were found at the farms with high production and high carbon inputs to the environment. In the northern Adriatic Sea, Kovac et al. (2001) also found higher levels of carbon in sediments below sea bass cages. Apostolaki et al. (2007) tested sediments at three coastal Mediterranean fish farms. Percent total organic carbon tended to be higher beneath cages compared to controls, but there was variability between the farms and no site reached carbon levels higher than 2.6%. Sampling at a sea bass and sea bream farm in the middle Adriatic was unable to

Aquaculture likely represents only a small fraction of the anthropogenic carbon and other nutrients building up in coastal waters, and continued research, technological advancements and improved farm management will lead to further improvements.

detect any consistent differences in carbon sediment concentration between sites below the cages and a control site 1 km away (Matijevic et al. 2009). Similarly, Aksu et al. (2010) conducted a four year study of the nutrient loading impacts of a tuna fattening farm off Turkey and were unable to detect any carbon accumulation in the sediment. Water depth and strong currents were credited with the low measures of nutrient accumulation.

Asia

A study in western Japan estimated that carbon flux to the seafloor at a net pen site averaged 2.11 g C/m^2/day, which was 2.5 times higher than the natural flux outside of the fish farm (Tsutsumi et al. 2006). A feeding experiment in Japan calculated carbon flux at cage sites ranging from 0.13-3.1g C/m^2/day, compared to background levels ranging from 0.16-0.8g C/m^2/day (Yokoyama et al. 2009). The total organic carbon in the sediment at cage sites was 56–79 mg C/g dry sediment compared to 12–19 mg C/g at control sites. Reduction of overfeeding was successful in decreasing organic loading while maintaining fish production levels. Another Japanese study (Pawar et al. 2002) found that fish farm sediment quality was directly related to organic carbon input from farms. Here carbon input from fish feed ranged from 2-57 kg C/m^2/year.

TROPICAL REGION

Caribbean

Monitoring at a cobia farm in Puerto Rico found that total carbon content of sediment at cage and control sites ranged from 4-6% and were not significantly different, but the organic carbon fraction was not differentiated (Alston et al. 2005). Sediment sampling for nine months at the cage sites found carbon levels to be generally very consistent, with a spike in June that coincided with peak feeding rates and biomass. Continued monitoring was recommended to track sediment carbon levels especially if the farm expanded its operational capacity.

Asia

At fish farms in Hong Kong, sediment sampling found that carbon levels were 83% higher than at reference sites 600 m away, with samples taken at 100 m away being similar to reference sites (Gao et al. 2005). Following removal of mariculture operations in a small enclosed lagoon in Taiwan, the sediment C/N ratio increased from 7.3 to 8.1, but this was not statistically significant (Hung et al. 2008). Prior to cessation of farming, the enriched sediments were 4-9% organic carbon. Alongi et al. (2003) conducted a study of carbon flow from fish cage aquaculture in Malaysian mangrove estuaries. Although greater carbon levels were found in areas with fish cages, most of the variability was driven by tides and water depth. Resuspension of sediments by boat traffic was also proposed as a factor in benthic clearing. They estimated that the fish cages represented 2% of total carbon input, as these waters are heavily impacted by other sources of pollution. In the Philippines, Holmer et al. (2002) found that sediment carbon levels increased under milkfish pens throughout the growout production cycle, ranging from 1.8-0.95%. Sediment carbon was four times higher inside cages than outside, with concentrations decreasing with both horizontal distance (100 m) from the cage and vertical depth into the sediment layer.

Australasia

Monitoring at a barramundi farm in Queensland found that carbon was not accumulating beneath the cages (McKinnon et al. 2008). Here, the yearly farm carbon input represented only 9% of total carbon loading, with mangrove litter accounting for 85%.

Giles (2008) reports that carbon levels in sediments below fish farms range from 0.2–26.1% in 17 studies (including studies cited in our report) from around the world, reflecting the great variability of potential enrichment (Table 4). Background carbon levels in most coastal sediments is <5% (Holmer et al. 2005), so the accumulation and effect of organic carbon from fish farms continue to be an environmental concern for marine aquaculture. Improvements in feed formulation in the last decades have decreased nutrient loading (Soto and Norambuena 2004, Buschmann et al. 2009), as has siting in areas with sufficient flushing. Aquaculture likely represents only a small fraction of the anthropogenic carbon and other nutrients building up in coastal waters (Goldburg and Triplett 1997, Cloern 2001, Anderson et al. 2002, Pittenger et al. 2007), and continued research, technological advancements and improved farm management will lead to further improvements.

Technologies to capture solid waste on screens below fish cages are being developed but are not currently a viable alternative for waste management (Buryniuk et al. 2006, Heinig et al. 2006). Bioremediation techniques using bacterial augmentation of sediments below fish cages to mobilize carbon are also being investigated. An experiment at a commercial sea bass farm yielded significant reduction in carbon levels in sites treated with a mixture of microorganisms and oxygen releasing compounds (Vezzulli et al. 2004), providing promising results for further development of this approach to managing nutrient enrichment at the farm scale. At a sea bream farm in an enclosed Japanese bay, an experiment to assess bioremediation of benthic sediment by stocking artificially cultured *Capitella* polychaetes early in the production cycle was successful (Tsutsumi 2007). Organic carbon concentration in the sediments beneath the cage decreased from nearly 30 mg/g dry sediment to less than 10 mg/g dry sediment within a few months after stocking the polychaetes. This approach offers another potential avenue for ameliorating environmental impacts of carbon accumulation beneath fish cages, but likely has limited applicability in very deep or high current open ocean sites.

Sediment Biogeochemistry

The output of fish feed and feces from marine fish cages, their accumulation on the seabed and effects on natural biogeochemical processes are among the environmental concerns for the marine aquaculture industry. The potential impacts to benthic sediment and chemistry have been identified as an important issue for the U.S. (Goldburg et al. 2001, Stickney 2002, Clement and Janowicz 2003, Nash et al. 2005, Pittenger et al. 2007, Johnson et al. 2008), Canada (Hargrave 2003, Wildish et al. 2004), South America (Buschmann et al. 2009), Europe (Black et al. 2002, Gillibrand et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Braaten 2007, Olsen et al. 2008, Holmer 2010), the Mediterranean (International Union for Conservation of Nature 2007, The Mediterranean Science Commission 2007, Borg et al. 2011, Grigorakis and Rigos 2011) and globally (Halwart et al. 2007, Holmer et al. 2008b, Hall et al. 2011).

SEDIMENT CARBON LOADING	REFERENCE	LOCATION	SPECIES CULTURED
15-100 g TVS/m^2/day	Nash 2001	Pacific Northwest	Salmon
13.7 – 25.7% organic carbon	Wildish et al. 2004	Canada	Salmon
8% organic carbon	Pohle et al. 2001	Bay of Fundy	Salmon
1.8 – 9.1% organic carbon	Chou et al. 2004	New Brunswick	Salmon
180 mg/m^2/day	Sutherland et al. 2001	British Columbia	Salmon
2.16 – 4.53 g/ m^2/day	Mulsow et al. 2006	Chile	Salmon
365 g/ m^2	Kutti et al. 2007	Norway	Salmon
3.1 – 22.9% organic carbon	Black et al. 2012	Scotland	Salmon
463 – 967 mmol/ m^2/day	Morrisey et al. 2000	New Zealand	Salmon
6.32% organic carbon	Porrello et al. 2005	Italy	Sea bream & drum
1.8 – 7.2% organic carbon	Belias et al. 2003	Grece	Sea bream & bass
2.6% organic carbon	Apostolaki et al. 2007	Mediterranean	Sea bream & bass
2.11 g/ m^2/day	Tsutsumi et al. 2006	Japan	Sea bream
4-6% total carbon	Alston et al. 2005	Puerto Rico	Cobia
5.55 mmol/g dry weight	Norði et al. 2011	Faroe Islands	Trout
1.8 – 10.95% organic carbon	Holmer et al. 2002	Philippines	Milkfish
0.2-26.1% organic carbon	Giles 2008	17 studies worldwide	Various
4 – 9% organic carbon	Hung et al. 2008	Taiwan	Not reported

Table 4. *Reported organic carbon loading rates at marine fish farms. Values are presented in the units in the original reference.*

In response to these concerns a great deal of research has documented and quantified the changes to the benthic chemistry that are directly attributable to marine finfish cage culture. In this chapter, we first provide an overview of the natural biogeochemical processes that occur in most seafloor sediments involving the flux and reactivity of numerous chemicals. Next we review and summarize the current research on the biogeochemical impacts of fish farms to underlying marine sediments. We also present information about which sedimentation parameters or measurements are relatively easy and cheap to collect while also being reliably indicative of significant negative impacts. Different sampling methodologies are compared. The next chapter, **Marine Life**, addresses the ecological impacts that nutrient enrichment has on seafloor and pelagic biodiversity.

Marine Sediment Biogeochemistry

The following overview of marine sediment biogeochemistry is derived from reports by Schulz

(2000), Wildish et al. (2004), Holmer et al. (2005), Hargrave et al. (2008), and Valdemarsen et al. (2010) which provide more technical detail. Most marine benthic sediment processes are driven by the decomposition of organic matter and are mediated by a variety of bacteria. The organic waste beneath fish farms is primarily derived from particulate organic carbon from feed and fecal waste. Most of the carbon is labile (soluble and available for decomposition), although some portion may be refractory (bound up and relatively inert). Oxygen transport into benthic sediments occurs by direct diffusion from bottom water as well as biological processes such as bioturbation from benthic feeding activity and burrowing by benthic dwellers. The oxygen is used in a series of oxidation-reduction, or redox, reactions in the sediment. Redox reactions involve the exchange of electrons between products and reactants, resulting in either reduced or oxidized products. The direction of the redox reaction is driven by oxygen availability. As oxygen is consumed for microbial respiration and ultimately depleted vertically into the sediment depths, anaerobic bacteria prevail, causing the redox reactions to be driven toward the reduced state. This series of redox reactions results in carbon dioxide production, nitrification of ammonia, and reduction of manganese, iron and sulfur. In organically enriched sediments, sulfate reduction may account for all the carbon oxidation, resulting in toxic sulfide compounds with negative impacts to benthic organisms. At the greatest sediment depths, the redox reactions convert organic carbon into methane. In unimpacted sediments with overlying water currents, the aerobic layer may penetrate several centimeters. A well-defined intermediate zone with reduced oxygen extends down before reaching the deeper anoxic layers which are in a chemically reduced state. Table 5, adapted from Holmer et al. (2005), summarizes the predominant bacteria-mediated redox reactions occurring in benthic sediment profiles with organic carbon as the original energetic input.

Redox potential (Eh) is measured in millivolts (mV) using electrodes inserted directly into sediments. Oxidized sediments (dissolved oxygen >2 mg/L) tend to have redox values above 100 mV. As oxygen is depleted and hypoxic conditions become established (dissolved oxygen is 0-2 mg/L), Eh ranges between 100 and -150 mV. Under anoxic conditions (dissolved oxygen is 0 mg/L), Eh values are less than -150 mV. Redox reactions are correlated with pH. In normoxic sediments, pH tends to be around 8. Deoxygenated, reducing sediments may be around pH of 7. Under anoxic and fully reduced conditions, pH may be as low as 5.

Beneath poorly flushed or heavily stocked fish farms, the sedimentation rate may be increased and organic matter may accumulate followed quickly by increased microbial respiration. As microbial oxygen demand is increased, sediments may reach hypoxic (<2 mg/L of oxygen) or anoxic states. Oxygen uptake (+), carbon dioxide release (+), redox (-), pH (-), and sulfide (+) levels all change predictably as the oxidation/reduction reactions are driven toward the reduced state. Figure 1, adapted from Hargrave et al. (2008; Figure 5), summarizes the many interconnected biological and geochemical processes that can be measured in benthic sediments to assess the level of enrichment. This figure also summarizes ecological responses, which are addressed in the next chapter.

In heavily impacted sediments, even the surface may be completely anoxic and covered in heavily enriched organic matter which persists because there is minimal aerobically mediated decomposition. Bubbling of methane gas may be visible. Although the methane itself is relatively non-toxic, the bubbles also can transport hydrogen sulfide which is produced under anaerobic conditions and is toxic to fish and other marine life, into the water column above.

The hydrography and sediment type determine the biogeochemical processes beneath marine cages. For example, depositional sites are at greater risk of becoming enriched compared with net erosional areas. Depositional sites are generally characterized by higher silt/clay and overall organic content, compared to areas with net erosion where sediments

Sediment Depth	Reaction	Process	Product	Reaction	Process	Product
	$CH_2O + O^2$	Oxygen Respiration	$H_2O + CO_2$			
	$CH_2O + NO_3^-$	Denitrification	$N_2 + CO_2$	$NH_4^+ + O_2$	Nitrification	NO_3^-
	$CH_2O + Mn_4^+$	Manganese Reduction	$Mn^{2+} + O_2$	$Mn^{2+} + O_2$	Manganese Oxidation	Mn_4^+
	$CH_2O + Fe^{3+}$	Iron Reduction	$Fe^{2+} + CO_2$	$Fe^{2+} + O_2$	Iron Oxidation	Fe^{3+}
	$CH_2O + SO_4^{2-}$	Sulfate Reduction	$H_2S + CO_2$	$H_2S + O_2$	Sulfide Oxidation	SO_4^{2-}
	$CH_2O + CH_2O$	Methane Production	$CH_4 + CO_2$	$CH + O_2$	Methane Oxidation	CO_2

Table 5. Biogeochemical processes in marine sediments. Adapted from Holmer et al. (2005).

usually contain higher levels of sand and low organic matter. The concentrations of other minerals, notably iron, may also play an important role in sediment biogeochemical processes beneath fish farms and these dynamics are being investigated to aid in identification of sites with sediment compositions that may buffer organic enrichment effects (Valdemarsen et al. 2009, 2010). In general, redox and sulfide concentration are thought to be the most consistently reliable indicators of the enrichment level of sediments and are often selected as a sediment parameters for monitoring purposes. Both are relatively easy to measure in the field, even in deep water.

Sedimentation and Geochemical Effects

TEMPERATE REGIONS

North America

A great deal of research has been conducted in the last decade in Canada to address the biogeochemical impacts of marine farms to benthic sediments. Reviews of far-field (Hargrave 2003) and near-field (Wildish et al. 2004, Holmer et al. 2005) enrichment effects provide excellent summaries of sediment processes and impact data collected mostly in the 1970-90s. The best biochemical predictors of benthic enrichment at Canadian salmon farms include increased total sulfide, oxygen uptake, carbon dioxide release and decrease in redox potential. Improvements in feed formulation and feeding management have generally decreased organic loading at Canadian farms. The spatial and temporal severity of impact may be driven by hydrographic and nutrient dynamics at varying scales.

Efforts in Canada have expanded to focus on development of innovative imaging technology and refining the assessment and modeling of far-field impacts. For example, a study by Tlusty et al. (2000) compared the transport and solubility loss of fecal versus food waste from steelhead trout *Oncorhynchus mykiss* pens. They conclude that the impacts below the cages will be greater for food waste because organic matter from feed particles is dispersed less during sinking. The authors suggest that the observed bimodality for sinking rates and organic matter input potential for feed versus feces should be factored into mathematical models that seek to quantify organic input to benthic sediments below farms. This was supported by DEPOMOD model validation work which predicted that waste feed would settle out proportionally higher near cages (within ~50 m), whereas fecal waste would account for organic matter sedimentation more distant from farm sites (Chamberlain and Stucchi 2007). Wildish et al. (2001) compared chemical and biological approaches for monitoring organic enrichment near salmon farms in the Bay of Fundy. Chemical analysis found lower redox potential and higher sulfide concentrations beneath farm sites than at reference sites. The biological parameters also reflected an impacted sediment community. Thus, both sampling methods supported the conclusion that benthic sediments at the farm site were enriched and in a reducing state. However, the chemical analysis proved to be a much cheaper approach costing about 10 minutes of field time per sample taken compared to 22 minutes of field time plus 184.5 minutes of lab time per biological sample.

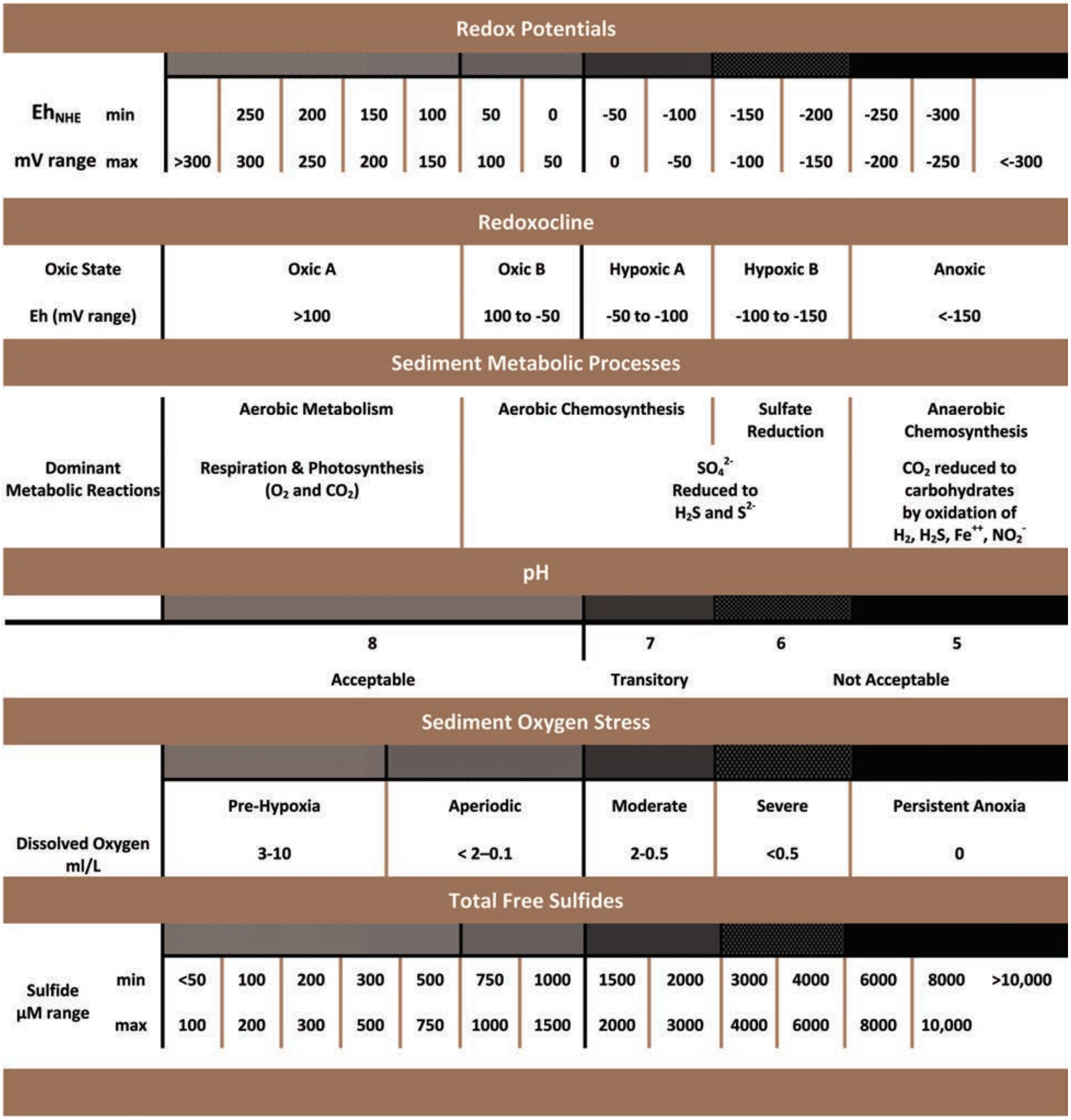
In British Columbia, vertical sediment flux at a fish farm was highest at the bottom edge of net pens (0.77 g/m^2/h) compared with control sites (0.48 g/m2/h; Sutherland et al. 2001). Additionally, the stable carbon isotope ($\delta^{13}C$) signature of the feed pellets, suspended particles and sediment trap materials was determined. A distinct signal from feed was observed in water column samples during feeding events and in the sediment traps nearest the net pens. These results are useful in the development of protocols for the use of stable isotopes as tracers of aquaculture waste products across larger scales.

Another comparative study by Wildish et al. (2003) found that sediment profile imaging (SPI) was able to detect organic enrichment. Sediments sampled from a New Brunswick farm site had average redox potentials of -148 mV and sulfide levels of 32,000 µM, compared to reference sites with redox potentials averaging 158 mV and sulfide levels of 1300 µM. The redox discontinuity layer (RPD), where anoxic conditions replace aerobic processes, was 0 cm at the farm sites compared to 9.9 cm at the reference sites, indicating anoxic conditions at the sediment surface. A digital camera was used to photograph the sediment cores and image analysis software was used to classify the geochemical state of each sample. The results of the two methodologies were in close agreement with each other as well as with biological classification conducted simultaneously. While image analysis may not be applicable in all sediment types, it does provide a less expensive alternative for assessing sediment impacts below farms located over soft sediments. The use of SPI to assess benthic enrichment has been verified by researchers in the Mediterranean as well (Holmer et al. 2002, Holmer et al. 2005) and acoustic assessment of organic enrichment has been conducted at salmon farms in the Bay of Fundy (Wildish et al. 2004). Backscatter images from multibeam and sidescan acoustic surveys were able to detect the footprints of sediment enrichment below active cages. Ground truthing from two years of surveys confirmed that sediment below the fish farms was enriched. Average redox potential was -148 mV (in 2001) and -111 mV (in 2002) compared to 158 and 100 mV at reference sites. Sulfide levels at the farm sites were 30,000 and 2500 µM compared to 1300 and 350 µM at reference sites. Abandoned cage sites were identifiable on the images by lower backscatter.

In general, redox and sulfide concentration are thought to be the most consistently reliable indicators of the enrichment level of sediments and are often selected as a sediment parameters for monitoring purposes.

Monitoring of benthic chemical remediation at intensive salmon farms in British Columbia demonstrated that high levels of sulfides (>6000 µmol) and decreased redox potential were ubiquitously measurable at the perimeter of the net pens (Brooks et al. 2003). However, sediment recovery occurred in a short period (six months or less) following harvest. These results suggest that, at adequately flushed sites, the effects of even high production farms may be relatively ephemeral with appropriate fallowing. In contrast, another remediation study (Brooks et al. 2004) conducted

Figure 1. Relationships between biogeochemical processes in marine sediments. Adapted from Hargrave et al. (2008).



at a nearby salmon farm, used regression analysis to estimate a remediation time of 65 months for that site. Average redox potential was -124 mV, sulfide level was 1349 µM, the total volatile solids was 13%, and RPD was initially only 1.2 cm. Collectively these indicate an enriched anaerobic benthos with effects generally confined to within 100 m of the pen sites. Repeated sampling indicated steady, but slow recovery. Yet, chemical remediation of this site took much longer compared with other salmon farms in the area. The explanation for this is uncertain, but the authors suggest that siting over depositional bottoms with high silt and clay content or other sediment geochemical processes could be contributing factors. Similarly, the fraction of small particle size sediments (<63 µm fines including silt and clay) was correlated with redox potential and anaerobic sediment condition as part of an effort by

Chou et al. (2004) to refine regression models used by the New Brunswick environmental monitoring program to assess sediment impacts from marine aquaculture sites.

Anderson et al. (2005) found correlations of lower redox potential and higher sulfides with organic enrichment under salmon farms in Newfoundland. However, these relationships were not consistently evident at reference sites and other shellfish aquaculture locations, possibly due to effects of low temperature on organic matter decomposition and sulfate reduction. Therefore, the authors concluded that in Newfoundland site-specific comparisons must account for wide variability in temperature dependent sediment characteristics if singular measurements of redox potential or sulfide levels are to be used as indicators of benthic enrichment.


Photo courtesy of Blythe Chang.

Other researchers found sediment sulfide concentrations to be good indicators of enrichment (Chamberlain and Stucchi 2007). In this study at fish farms in British Columbia, sulfide concentrations were consistently high at farm sites sampled over an entire production cycle. Sulfide levels rose from <200 µM near the edge of the farm at the outset of sampling, to a final level of 7870 µM beneath the cage site. In general, the highest impacts were measurable within 125 m of the farm.

The potential far-field effect of salmon aquaculture has been investigated in Canada. A study in the Letang Region of New Brunswick analyzed core and sediment samples from 1990–2002 from three interconnected bays with various degrees of bottom stress (Milligan and Law 2005). They found that the floc limit, an indicator of fine-grained particulate matter deposition, increased over the 10–20 year period when salmon farming expanded in the area. The researchers found that over large areas, local hydrodynamics may prevent accumulation of sediment directly beneath fish cages, yet may direct fine organic matter particulates to the surrounding environment.

In the U.S., much concern about benthic sediment impacts of salmon farms has been raised. Nash (2001, 2003) and Nash et al. (2005) identify the effects of bio-deposits on sediment chemistry, including redox and free sulfides, as one of the highest environmental risk issues for salmon cage culture. Sites with inadequate circulation and poor farm management practices are more likely to have depositional rates that exceed the ability of the sediment to break down organic matter. Nash reported sedimentation rates at salmon farms ranging from 15.1-100 g of total volatile solids/m^2/day, a measure of organic loading. At a multi-species fish farm in the Gulf of Maine, sediment sampling found no differences in redox potential measurements at the cage sites compared with intermediate and remote control sites (Langan 2007). Increased organic matter accumulation and benthic carbon flux were measured directly beneath cages at a salmon farm in Maine, but these effects were not measurable 10 m beyond the pen (Findlay et al. 1995). In this case, storm activity was thought to be an important contributor to re-suspension of sediments.

In the temperate waters of Baja California, redox potential of sediments sampled 250 m from a bluefin tuna ranching farm ranged between -110 to -302 mV (Diaz-Castaneda and Valenzuela-Solano 2009). This was the nearest to the pen that samples could be collected, so impacts at the cage sites are unknown. Feeding practices, which include the use of raw fish as the primary diet at the farm are thought to input large quantities of organic matter, and despite favorable hydrodynamics, sediment impacts appeared to be significant.

South America

Mulsow et al. (2006) used SPI analysis and micro-electrode technologies to assess the impact sediment geochemistry impacts at salmon farms in two fjords in southern Chile. Generally, both approaches led to

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similar conclusions regarding impact levels. At farms in the smaller, enclosed, depositional fjord site, the layer of uneaten food was 0.74 cm, the RPD depth was 0-4 cm, redox reached 0 between 4-7 mm below the sediment surface and hydrogen sulfide increased only a few millimeters below the surface. In comparison, at cage sites in the larger, better flushed fjord, the food layer was minimal even directly at the cages (.05-.07 cm), the RPD ranged from 1.7-7.87 cm, redox values decreased slowly with sediment depth and hydrogen sulfide levels never exceeded normal values. A large-scale comparison of 29 active salmon farm sites in Chile found few differences in sediment surface chemistry between farm and control sites (Soto and Norambuena 2004), including oxygen concentration, pH, and redox potential. However, change in redox potential between the water-sediment interface was found to be significantly different, with farm sites showing a -109.8 mV reduction in redox potential compared to a +2.6 mV change at control sites. Additionally, percent organic matter was higher at farm (4.41%) than control (2.09%) sites. The authors concluded that their findings suggested that salmon farming did impact sediment chemistry, but that generally enrichment from farms was a local phenomenon determined largely by site conditions, was confined to the cage shadow and had no broader ecosystem impact.

Northern Europe

Work in Europe is underway to improve monitoring and management of benthic sediments below fish farms. Sampling at a Norwegian salmon farm showed redox values down to -126 mV beneath the cages and out to 227 m (Kutti et al. 2007b). Redox values near the cages tended to decrease during the production cycle, while redox was always positive at reference stations. A comparative study was conducted in Norway (Carroll et al. 2003) to determine the ability of four different monitoring methods to detect benthic impacts at five farm sites. At all farms, sediment chemistry measurements including decreased redox potential (-125 to -184 mV) and pH (6.13-7.16) indicated significant enrichment below and within 20 m of the fish cages. At all sites, partial or full recovery was generally evident at 50 m, compared to samples from reference sites. The other sampling methodologies were faunal surveys, sediment profile image analysis and diver surveys including photographic data.

Results of all four methods agreed that the direct impact zone was adjacent to the cages, but some differences existed in defining more subtle effects. Another Norwegian study describes the integration of multiple parameters, including sediment chemistry, to monitor farm sediment conditions and promote long-term viability of fish farming sites (Hansen et al. 2001). Site condition was evaluated based upon a scoring system taking into account sedimentation rates, chemical analysis (redox potential, pH, and gas production) and biodiversity. Scores from all parameters were included in the final determination of benthic condition. In terms of geochemistry, sediment condition was rated as impacted once redox potential approached zero and pH went below 7.7. This integrated approach to an environmental monitoring system is part of the regulatory process, and continues to be evaluated with the goal of decreasing sampling cost and effort while maintain data quality and accuracy.

Using 15 years of Norwegian sampling data, Schaanning and Hansen (2005) determined that graphic plots of electrode measurements of redox potential versus pH or sulfide provide a reliable visual tool for the assessment of enrichment condition. This methodology is also cost effective and can be implemented in many types of benthic substrates. Their investigation found highly variable sediment conditions beneath farms. Mean redox potential below cages was -161 mV compared to +82 mV at reference sites, and pH was 7.22 compared to 7.85. Based upon plotted data the authors suggested that sediment redox potential above -100 mV in combination with pH above 7.1 represented acceptable sediment conditions. Methane gas ebullition was consistently present when sediment pH dropped below 7.1. At most farm sites, impacts were limited to the immediate vicinity (within 100 m) of the farms. Siting in high current speeds, deep water and maintaining space between cages were identified as factors to avoid long-term enrichment. Similarly, a study in Finland found that farms sited in a shallow bay with less water exchange were prone to organic sedimentation and hypoxia (Kraufvelin et al. 2001). In a Danish fjord, sediment sampling below estuarine rainbow trout *Oncorhynchus mykiss* farms found highly increased oxygen flux (300 mmol/m^2/day) due to organic matter loading (Christensen et al. 2000). Effects were limited to 100 m from the cage sites. Mineralization of food and waste was also documented, indicating that the organic matter was being broken down. This input of nitrogen and phosphorus to the water column from sediment efflux was noted as an important source of nutrients to this system, particularly during summer months when land-derived nutrient loading for primary production is decreased.

In Scotland, models are being refined to predict key biogeochemical processes and sediment recovery times at farm sites (Black et al. 2012). DEPOMOD is the model currently used to track organic waste dispersion from fish farms. Modeling output and monitoring data from five operational farms were used to first test a module for estimating sediment recovery times as a function of organic matter decomposition rates based upon organic matter accumulation, microbial oxygen demand and water column oxygen supply ratios (using a Findlay-Watling approach). Although this method accurately modeled impacts during the operational phase, it did not adequately predict recovery time. Next the Respiratory Quotient (RQ) box model was implemented which, in addition to oxygen demand, accounted for background levels and resuspension of organic matter, and sulfide production and oxygen demand from reductive processes. This model better predicted recovery rates of sediments at the five farms, and modeled recovery rates correlated well with biological indices.

Australasia

A study in New Zealand recently analyzed 12 years of monitoring data at five salmon farms in low and high flow regimes to evaluate the reliability of several indicators as predictors of benthic enrichment (Keeley et al. 2012). Both decreasing redox and increasing sulfide correlated well with progressive enrichment and anoxia, especially under low flow conditions. Also in New Zealand, sediments from active farms, abandoned sites and control areas were sampled as part of a larger project validating a benthic impact model (Morrisey et al. 2000). Sedimentation rates at the active farm site were up to 63 g/m^2/day, compared to <13.5 g/m^2/day at control sites. Benthic flux of oxygen, nitrogen and sulfur indicated that sediments were in an enriched state. Sediment profiles at the disused sites suggested extended recovery time (3.3-12 years), because low current velocities limited recovery to *in situ* decomposition with little resuspension or hydrodynamic dispersal. Similarly, sedimentation rates at a South Australian tuna ranch ranged between 8-92 g dry weight/m^2/day at farm sites, compared to control sites with lower sedimentation rates between 7-28 g dry weight/m^2/day (Lauer et al. 2009). Ammonium and phosphate fluxes were also significantly increased reflecting mineralization rates consistent with benthic nutrient enrichment. Because these benthic impacts lessened after harvest, the results support continuation of government fallowing requirements.

Wildish et al. (2003) validated the use of sediment profile imaging (SPI) at fish farms in Tasmania. Here redox potential was decreased from 311 mV at reference locations to -7 mV below cages and sulfide was increased from 0.01 µM to 49 µM. The benthic enrichment index values derived from the SPI results were similar to the geochemical monitoring method for reference sites and acceptable for most monitoring applications in soft sediments. However, SPI was thought to be less useful in benthic habitats in course sediments or rocky substrates. Sediment condition tested at a Tasmanian salmon farm was degraded with elevated sulfide levels >350 µM and organic matter enrichment directly beneath cages (Macleod et al. 2004). Effects dissipated with increasing distance from the cage and over a 36 month recovery period. Similar results were reported at a nearby farm where redox potential beneath salmon cages was significantly lower than at reference sites (Edgar et al. 2005). Impacted sediments (down to 40 mm) had redox values below -100 mV while reference sites measured around 200 mV at the sediment surface. This effect was generally limited to within 35 m of the cages. A follow up study of 42 sites (Edgar et al. 2010) confirmed that decreased sediment redox potential was measured in sediments below cages at the sediment surface (about 100 mV decrease) and down 40 mm (about 60 mV decrease). Sediment redox potential measurements at sites at least 35 m distant from the farms were intermediate between the impacted and reference sites.

SUB-TROPICAL REGIONS

The Mediterranean

Since 2000, a great deal of research has been done on benthic impacts at Mediterranean fish farms. Vita et al. (2004) measured increased organic content in the sediments from a Spanish sea bream and sea bass farm with nearly 6% beneath cages compared to 3% at control sites. Sediment sulfide was increased at the cage sites (about 750 mg/kg) compared to control sites (500 mg/kg). The experiment at this site excluded wild fish from feeding on the bottom. The results revealed that without fish feeding on the waste particulates, benthic organic matter content was about 7.5% and sulfides were 1500 mg/kg, indicating that wild fishes may be an important contributor to the degradation of farm waste. In fact, this study estimated that about 80% of the sinking particles were consumed by wild fish within 4 m below the net pen.

Another study at fish farms along the Spanish Mediterranean coast did not discern any differences in sediment organic matter levels (Maldonado et al. 2005). The authors suggest this was due to a combination of moderate farm size and siting in semi-exposed environments. In contrast, results reported by Aguado-Giménez and García-García (2004) from a one year pilot study at an offshore sea bream and sea bass farm found an increase of organic matter levels of just below 5% out to 500 m from the farm site, compared to values around 3% for control sites. An intensive study at a sea bream and meagre *Argyrosomus regius* farm in Spain compared two monitoring techniques, diver sampling versus grab sampling (Aguado-Gimenez et al. 2007). The two methods provided similar results for all but one of the geochemical parameters tested. The only exception was redox potential which was always less electronegative and had greater variability in sediments collected with the grab sampler, possibly due to inadvertent mixing of the sediment layers during collection. The diver-collected samples showed redox potential of nearly -300 mV under the cages, increasing with distance out to 500 m from the cage. Sediment sulfide levels of 0.5-0.6 ppm were found at the cage sites compared to levels near 0 ppm at 100-550 m from the cages. The cost-effectiveness analysis found that staff and equipment costs for the diver surveys were 6 and 1.2 times higher, respectively, than for the grab sampling method.

Studies in Italy have also provided a variety of information about benthic impacts in Mediterranean fish farms. For example, LaRosa et al. (2001) measured the sediment RPD below fish farms off western Italy. RPD below cages was around 2 cm at control sites, but only 0.2 cm during farm operations. Following harvest, RPD increased to 1.9 cm within a few months indicating quick recovery from enrichment. Sampling at this same farm as part of a different project found similar RPD impacts (Mirto et al. 2002). At a more northerly sea bream farm site, Vezzulli e al. (2003) found reducing conditions in surface sediments below the farm while positive redox potential values were found at control sites.

Redox potential measured at farm sites off Sicily was around +200 mV compared with control site values of +500 mV (Vezzulli et al. 2004). A study at sea bass and sea bream farms off Corsica found organic matter content of 21-24% at farm sites (to 100 m from the cages) compared to 2% at a nearby control site. Accumulation of organic farm waste was attributed to poor flushing. Sara et al. (2004) used stable isotope analysis to study sediment nutrient inputs including fish farming off the coast of Sicily. Samples were collected beneath sea bream and sea bass cages, up to 1000 m away and at control sites. The carbon ($\delta^{13}C$) signal was not significantly different along the distance gradient. However, the nitrogen ($\delta^{15}N$) isotope signature from the farm wastes was evident in the sediment and particulates up to at least 300 m away. The authors proposed that resuspension of sediment and feeding by wild fishes may play a role in the wider distribution of nutrients away from the immediate cage area. Another study off western Italy evaluated which geochemical and hydrodynamic parameters were most useful in assessing environmental impacts

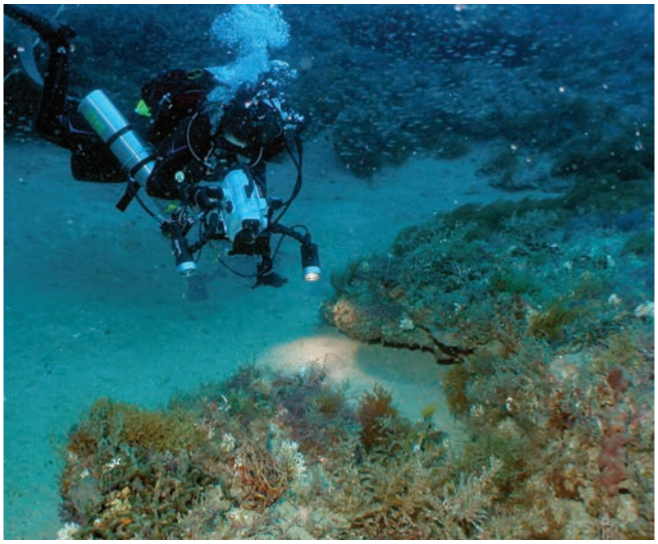

Photo courtesy of NOAA.

of fish farms (Porrello et al. 2005). Redox potential and sulfide levels were among the most useful for detecting enrichment through time and along distance gradients. The analysis also found that most geochemical effects were confined to within 50 m of cages. Vezzulli et al. (2008) reported lower redox potential values (-70 mV) in the upper (0-2 cm) sediment layer beneath a tuna fattening farm compared to samples from a control site (90 mV).

Studies in the eastern Mediterranean report findings similar to the western portion. Sediment profiling imagery data collected beneath a fish farm in the Ionian Sea was compared to geochemical analysis by Karakassis et al. (2002). The SPI results were well coordinated with the geochemical ones, validating the use of this methodology for enrichment assessments. This study did not report actual values for the geochemical parameters but the authors confirmed that enrichment, measured with both methods, was confined to within 10 m of the cages. Because of the lower cost and rapidity of image analysis associated with using SPI, it is seen as a viable alternative to traditional benthic monitoring techniques.

Belias et al. (2005) reported particulate matter sedimentation rates below Greek fish cages to be five times greater than at control sites. Despite good circulation at this site, about 30 cm of loose organic matter was observed at the sediment surface. It was reported that about half of the food at the farms is lost as particulate waste. Neofitou et al. (2010) found that organic matter concentration was higher at two semi-enclosed sea bream and sea bass farm sites in the Greek Aegean Sea (7.2 and 16.8%) than at control sites (2.6 and 10.1%). In both cases, sampling 50 m away found intermediate concentrations. Benthic sampling at seven Greek fish farms over 16 months resulted in consistently negative redox potential (around -150 mV) just beneath cages, but showed an increasing trend toward positive values within 25 m at most farms (Lampadariou et al. 2008).

After 70 days of allowing gray mullet in small bottom pens to feed on waste below sea bream cages, several indicators of enrichment showed that the detritivores had a positive impact.

As part of a waste dispersal model validation study, Jusup et al. (2009) measured sedimentation below sea bass and sea bream farms in Croatia. The sedimentation rate was around 50 g dry weight/m^2/day directly under the cages and decreased gradually to around 9 g dry weight/m^2/day at 40 m from the cages. At a nearby Slovenian sea bass farm, Kovac et al. (2004) measured somewhat lower sedimentation rates of 31 g dry weight/m^2/day, compared with 3 g dry weight/m^2/day at local controls sites.

In contrast to the above Mediterranean studies, Apostolaki et al. (2007) analyzed sediments at farm sites off Greece and Italy finding only positive redox potential values and no difference in redox potential compared to control sites. Similarly, Matijevic et al. (2009) did not find significant changes in sediment redox potential, organic matter or sediment grain size beneath sea bass and sea bream farms in the Adriatic Sea. The use of enclosed fish to reduce benthic impacts was assessed in Israel (Katz et al. 2002). After 70 days of allowing gray mullet in small bottom pens to feed on waste below sea bream cages, several indicators of enrichment showed that the detritivores had a positive impact. Sediment sulfide levels and sediment oxygen demand decreased by 85% and 31%. The enriched sediment layer was dramatically reduced by 5 cm within the enclosures due to ingestion and resuspension by the mullet. These results have promising implications for both remediation of enriched sediments and development of commercially viable integrated multi-trophic aquaculture practices.

At gilthead sea bream farms in the Canary Islands, no difference in organic matter concentrations were detected between farm and reference sites (Molina Dominguez et al. 2001) with considerable season variability at all sites. Similar results were found by Riera et al. (2011) at other sea bream and sea bass farms. Organic matter concentrations were similarly low at both farm (0.45%) and control (0.38%) stations. Farm areas in both studies are characterized by good currents (6 and 12 cm/sec, respectively).

Asia

In Japan, Pawar et al. (2002) collected sediments from sea bream and sea bass farms to study the correlation between organic farm input, sediment quality, seasonal variation and hydrographic conditions. At all sites the organic matter (up to 12%) and sulfide levels (up to 1.8 mg dry weight/g) increased, and redox potential decreased (to <-175) with increasing organic loading from farms. This trend was consistent between the two farm areas surveyed and variation was attributed primarily to seasonal changes in feed input and temperature, rather than background sedimentation processes. Another Japanese study investigated sediment impacts at 22 sea bream and yellowtail farms (Yokoyama 2003). Elevated sulfide levels up to 2 mg/g dry weight were measured in sediments directly beneath the cages, dropping to 0.75 mg/g at 100-500 m from the cages. This level of enrichment was still below the critical value of 2.5 mg/g established as a regulatory threshold.

TROPICAL REGIONS

Pacific Islands and the Caribbean

Lee et al. (2006) measured sediment changes at Pacific threadfin *Polydactylus sexfilis* cages in Hawaii. Sediment grain size, an indication of siltation, did not appear to differ between farm and control sites, but redox values at cage sites were consistently lower than controls. Collectors discerned sulfidic odors at the cage site, suggesting reduced conditions. Benthic sampling over three years at a Hawaiian yellowtail farm documented negative redox potential readings only once (Sarver 2009). Following improvements in feeding techniques, organic matter input was reduced and redox levels rose steadily over the next year and eventually reached levels of nearby control stations.

Benthic sampling at a cobia farm in deep water with good flushing in Puerto Rico also found no difference in sediment organic matter (ranging from 4-6.2%) between cage and control sites suggesting there was no enrichment at this farm (Alston et al. 2005).

Asia

In the Philippines, organic matter from a milkfish net pen farm resulted in significantly increased sedimentation beneath the cages over a production cycle (Holmer et al. 2002). Enrichment at these shallow pens was higher compared to nearby cage farms at greater depths.

META ANALYSES

Two comprehensive reviews include analyses of the enrichment effects below marine fish cages. Kalantzi and Karakassis (2006) reviewed 41 papers covering a wide range of cultured species, habitats, site characteristics and farm management practices. This paper contains a great deal of information about the relationships between enrichment sediment variables resulting from nutrient and particle input from farms. The overarching conclusions from this work were that: 1) the most popular geochemical variables studied (e.g., organic material content, sedimentation rates, oxygen consumption and redox potential) show consistent patterns along enrichment gradients regardless of site and farm characteristics, 2) increase in water depth below the farm allows for greater dispersion of waste and improved sediment quality, 3) latitudinal differences in background productivity and sedimentation must be considered for monitoring and evaluation, and 4) the sediment type under the farm is a major contributing factor in determining the extent and severity of impacts. The authors state that applying common standards over large geographic areas is challenging due to the complex interplay of site characteristics. In general, however, their analysis suggests that the impact radius at fish farms decreases with high depth, at low latitudes and over fine sediment.

Giles (2008) developed a Bayesian network based upon 64 studies conducted at fish farms in temperate regions to quantitatively assess the relationships between environmental impact parameters, site characteristics and farm production measures. This study provides a useful analysis of the interconnectedness of farm management practices and potential impacts to the benthic environment. Sediment sulfide, redox potential, sediment oxygen consumption and nitrogen mineralization were determined to be among the most consistent and sensitive geochemical measures of benthic impacts. These parameters have the added benefit of being relatively inexpensive and applicable in multiple sediment types. The analysis found that impacts were usually confined to within 40-70 m of the farms and further confirmed that well-flushed sites in deep water tend to have significantly less impact than shallow, low-current farms. The analysis was not intended to predict the exact environmental responses, but Giles provides suggestions for its use as a decision making support tool.

Benthic enrichment impacts are often identified as the most significant and concerning environmental impact of marine aquaculture because the geochemical consequences of enrichment in the sediment can be long lasting. The trends observed worldwide reflect recurring impact patterns in benthic sediments beneath marine fish cages. In the absence of sufficient flushing or under high fish densities organic matter accumulation leads to increased microbial activity, decreasing oxygen, a shift toward reducing conditions and increase in sulfide and mineralization levels. Generally, these impacts are confined to within 100 m of the cage or farm area. A few studies are illuminating the potential far-field impacts in areas that have experienced high levels of marine aquaculture development. Research focusing upon larger scales will likely become a priority, especially in coastal areas with multiple concerned user groups. Monitoring and research to quantify downstream, far-field and long-term effects of fish farms beyond the immediate cage perimeter will continue to be important. The use of stable isotopes as tracers of farm waste output at larger spatial and temporal scales is a promising tool to help in this area. Continued effort to build upon recent work comparing different monitoring technologies and protocols to provide reliable, accurate and cost effective methods of assessing enrichment and biogeochemical impacts will be benefical.

Lacking are monitoring and assessment methods for hard bottom marine habitats, as collection of sediment may not be possible. There is little information available about marine fish farm organic discharge over hard bottom habitats. These are generally more dispersive areas with high currents and high benthic shear, and are thus less likely to exhibit accumulation of organic matter. In these cases, minimal effects may be evident immediately beneath fish cages. As marine aquaculture operations move offshore into the open ocean it is expected that organic waste will be more rapidly and broadly dispersed compared to sites in nearshore waters (Holmer 2010). Impacts in deep sediments will certainly be an area for future research as the industry expands.

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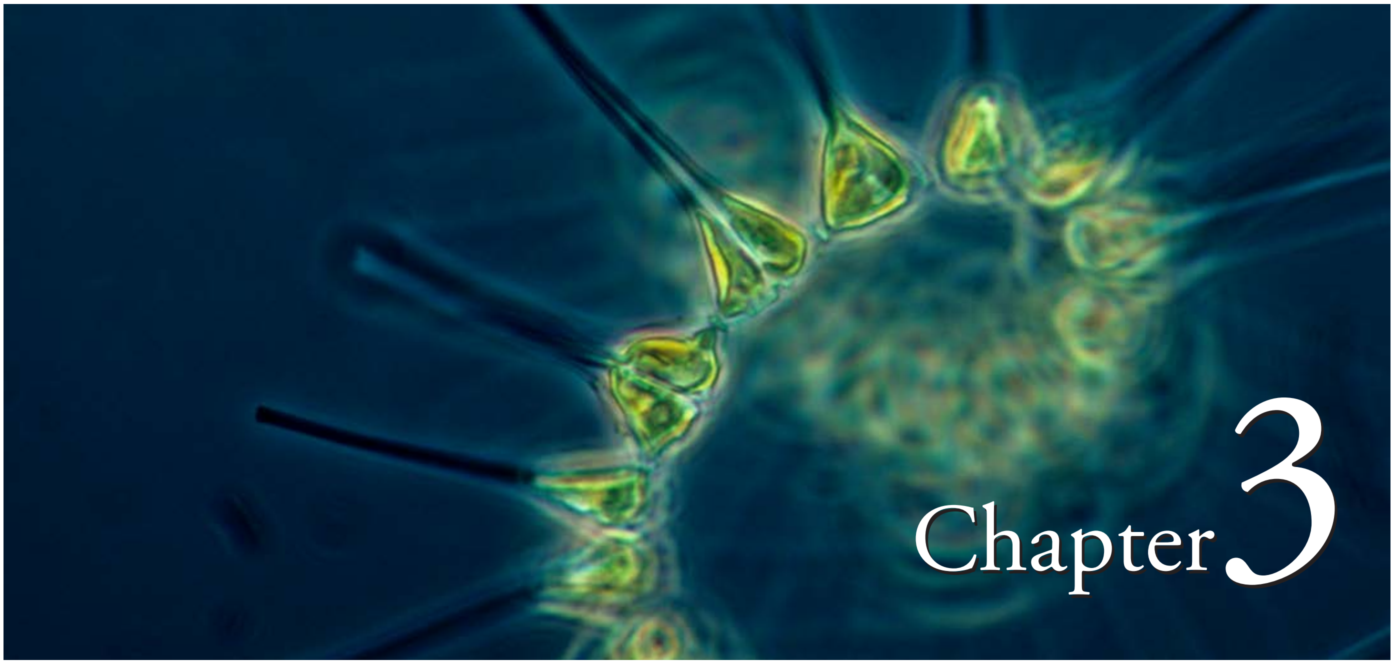


Photo courtesy of NOAA.

MARINE LIFE

The previous chapters addressed a wide range of the possible physical and chemical effects of cage aquaculture on the marine environment. While some of those may have direct effects to the surrounding waters, another predominant concern is the secondary impacts to local marine life resulting from the nutrient rich effluents released from the farms. Most often, it is the benthic community directly below cages that reflects the greatest alteration. The potential impacts to other marine life near fish cages — including plants, wild fish, sharks, sea turtles, marine mammals and sea birds — are also of interest. Another area of concern is possible impacts to sensitive marine ecosystems like seagrass beds, coral reefs and mangrove forests. Research is also emerging about sites where moderate levels of nutrient discharge from fish farms may be having a beneficial effect on surrounding biodiversity particularly in nutrient limited aquatic ecosystems. In this chapter we review recent studies that address these issues.

The potential to cause severe and long-term damage to benthic and pelagic marine life is often identified as a concern of marine managers, scientists and regulatory entities. This topic has been identified as a priority in the U.S. (Goldburg et al. 2001, Stickney 2002, Nash et al. 2005, Pittenger et al. 2007, Johnson et al. 2008, Ocean Conservancy 2011), Canada (Hargrave 2003, Wildish et al. 2004a, Strain and Hargrave 2005), South America (Buschmann et al. 2009), Europe (Black et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Holmer et al. 2008, Tett 2008, Holmer 2010), the Mediterranean (International Union for Conservation of Nature 2007, Borg et al. 2011, Grigorakis and Rigos 2011) and globally (Beveridge 2004, Halwart et al. 2007, Tucker and Hargreaves 2008, Hall et al. 2011).

Primary Producers

In the **Water Quality** chapter recent research on the release of dissolved nutrients, predominantly nitrogen and phosphorus, from marine fish farms into the water column was summarized. Increases in nutrients have been documented at some farm sites, but not at others. At sites with increases, elevated nitrogen and phosphorus are generally measurable less than 100 m from the farm. The primary determining factor affecting such nutrient increases are farm management practices which optimize feeding and siting the farms in well flushed areas. Farms in enclosed bays and shallow water are more likely to contribute to nutrification of nearby waters. Strong currents quickly dilute the nutrients and disperse them into the surrounding environment. The potential secondary effects of these nutrients to primary production are of interest. Because marine waters are often nutrient limited, it is possible that elevated nitrogen and phosphorus may contribute to increases in phytoplankton and macroalgal production (Cloern 2001). In most marine waters, nitrogen is the limiting nutrient, but there are waters (some estuarine and tropical waters, for example) where phosphorus or abiotic seasonal factors like light are more influential on driving primary productivity.

In this section we review current research investigating the potential links between aquaculture effluent and increased primary production. Special attention is given to the issue of harmful algal blooms (HABs), both potential causes of HABs by fish farms as well as potential impacts on fish farms of HABs. Nutrient enrichment and potential eutrophication related to marine fish farm effluent are an important concern raised in the U.S. (Goldburg et al. 2001, Nash 2001, Nash et al. 2005, Pittenger et al. 2007, Johnson et al. 2008), Canada (Hargrave 2003, Strain and Hargrave 2005), South America (Costa-Pierce et al. 2007, Buschmann et al. 2009), Europe (Black et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Holmer et al. 2008, Olsen et al. 2008, Tett 2008, Holmer 2010), the Mediterranean (International Union for Conservation of Nature 2007, The Mediterranean Science Commission 2007, Borg et al. 2011) and globally (Beveridge 2004, Halwart et al. 2007, Tucker and Hargreaves 2008).

The rise in nutrification and eutrophication from anthropogenic sources has been documented around the world, but it is difficult to parse out the relative contributions from specific activities such as aquaculture (Wu 1995, Pearson and Black 2001). There are few long-term data series of nutrient levels and primary productivity in coastal waters, but there are data indicating that nitrogen and phosphorus fluxes in coastal waters have increased by an estimated 2-14 times the natural rates (Cloern 2001). Only a small portion of that can be attributed to marine cage culture, the dominant sources being terrestrial. While fish farms may contribute to coastal seas eutrophication, the nutrient budgets of open oceans are difficult and complex systems to quantify and there is a lack of inventory of contributing factors in most locations worldwide. Questions remain about the types and levels of risk that cage culture poses for water column enrichment and eutrophication (Olsen et al. 2008). There are cases in which primary production increases near marine cages, but many studies have not detected a chlorophyll response tied to nutrient loading from farms, perhaps due to dispersion or rapid assimilation of nitrogen and phosphorus into the food web, especially in oligotrophic waters (Braaten 2007, Holmer et al. 2008, Holmer 2010). In this section we first review studies which documented impacts to primary production, followed by cases in where no effects were found.

There is evidence that nutrification at fish farms can lead to increased primary productivity.

TEMPERATE REGIONS

Robinson et al. (2005) studied the far-field effects to primary production of salmon farm effluent in the Bay of Fundy. Here, eutrophication linked to farm effluent (1 km from the intertidal zone) resulted in the growth of extensive algal mats along the shoreline, threatening a native soft clam fishery. The estimated economic direct loss of clams at one site was calculated at $168,000 (Canadian dollars).

The appearance of these algal mats in the mid-1990s coincided with the development of salmon farming in nearby waters. Elevated zinc levels in shoreline sediment cores supported the hypothesis that nutrients from the farm were being transported near the shore. Aerial photography showed that at times the mats covered up to 40% of the beach for an estimated algal biomass production of 58.6 tons. Rensel and Forster (2007) documented over 29 species of algae growing on net pens, floats and anchor lines at a salmon farm in Puget Sound. Algal growth was linked to the farm effluent by nitrogen and carbon isotope analysis. The authors consider such bio-colonization an environmental benefit to the marine ecosystem. Some colonizing algae could have commercial value.

Honkanen and Helminen (2000), Nordvarg and Johansson (2002) found increased levels of planktonic chlorophyll-*a* near seven fish farms in two Finnish straits. Samples collected from the water column and growth plates showed increased algal productivity nearest the farms. Interestingly, neither dissolved nitrogen nor phosphorus varied consistently with distance from the cages. In the Baltic Sea, Nordvarg and Johansson (2002) sampled water quality and deployed algal growth plates at ten salmon farm areas and four control areas to assess farm nutrification and primary productivity response. The presence of fish farms increased both chlorophyll-a levels and periphyton growth at only a few locations. Local hydrology was thought to be the most influential factor in determining whether an effect on primary production occurred. Affected sites were semi-enclosed, shallow bays. The data were further used to develop and validate a model to predict nutrient and chlorophyll-*a* dynamics in the area.


Photo courtesy of NOAA.

SUB-TROPICAL REGIONS

A study in Sicily found that chlorophyll-*a* levels in water as far as 1000m from fish cages were up to 25 times higher than at five control sites (Modica et al. 2006). However, all the chlorophyll levels measured were well below the eutrophication threshold for that area and the researchers concluded that the organic enrichment from the farm was not likely to result in undesirable biological consequences.
A carbon isotope analysis of seagrass and brown algae collected near the outfall of an Italian land-based fish farm and non-impacted control areas found that plants closest to the outfall sequestered significantly more $\delta^{15}N$ associated with the farm effluent than did plants up to 2 km away (Vizzini et al. 2005). However, differences in the $\delta^{13}C$ isotope signature were not as clearly evident. While this study was not conducted at a cage farm, it provides insight into nearshore nutrient processes and also provided information for a follow up study. Vizzini and Mazzola (2006) used stable isotope ratios to compare the impact of anthropogenic organic matter from onshore and offshore fish farming and a sewage outfall on seagrass and two green algae. As in the previous study, $\delta^{15}N$ was the better tracer for nutrification, showing a distinct pattern of increased isotope uptake near the fish and sewage effluent sources compared to control sites two and six km away. The effluent isotope signature was also evident at higher trophic levels, indicating local nutrient assimilation into the ecosystem. This methodology was not able to discriminate the exact anthropogenic source of enrichment in the sampled plants.
In the eastern Mediterranean, Pitta et al (2005) analyzed sites near (2-3 nautical miles) and distant from (20 nautical miles) fish farms to determine if nutrient enrichment from them caused large-scale effects on water quality and plankton assemblages. Chlorophyll-*a* was significantly and consistently

increased at the near sites, but significant seasonal and regional variability was also observed. The authors suggest that there was rapid utilization of nutrients by plankton organisms, coupled with a transfer of these nutrients up the food web without leaving behind significant traces of eutrophication. There was evidence of increased chlorophyll-*a* production below the thermocline, suggesting that resuspension of nutrients, especially phosphorus in this area, was an important process. Given the large area sampled, it appears that nutrient flux out of these farms was evident at scales larger than many impact studies. Later, Pitta et al. (2009) used dialysis bag experiments to demonstrate that nutrients from sea bass and sea bream farms were being transferred up the food chain by phytoplankton grazers. In bags containing water filtered to remove grazers, chlorophyll-*a* and nitrogen levels were higher near the farms, and decreased out to 500 m. In bags with grazers, chlorophyll-*a* was lower, presumably due to planktivory. The authors suggest that in oligotrophic waters, the quick transfer of nutrients to higher trophic levels is possible. Such fertilization by fish farms is sometimes seen as a positive contribution of fish farms to nutrient poor marine environments.

The rise in nutrification and eutrophication from anthropogenic sources has been documented around the world, but it is difficult to parse out the relative contributions from specific activities such as aquaculture.

Apostolaki et al. (2007) found varying effects of effluent on chlorophyll-*a* at three Mediterranean sea bream and sea bass farms – only one farm showed increasing productivity while the other two showed a negative influence or no effect. This suggests that the site-specific interplay of a variety of water column characteristics is important in determining ecological outcomes.

TROPICAL REGION

A water quality study in the South China Sea found that the highest chlorophyll-*a* levels in a semi-enclosed bay were in the area of high cage aquaculture with an average of 11.74 mg/m^3 compared with levels as low as 3.81 mg/m^3 elsewhere in the bay (Song et al. 2004). In Taiwan, Huang et al. (2011) found chlorophyll-*a* levels ranging from 1.46-1.75 µg/l in a semi-enclosed bay with well-established small scale fish cage culture compared to 1.0-1.37 µg/l at a nearby reference site. Macroalgae coverage at farm sites was 2-10 times higher than at reference locations. Nutrient measurements were above eutrophication threshold values. Hydrological conditions and the use of raw fish as feed were cited as the main causative factors.

TEMPERATE REGIONS

Two years of extensive sampling near salmon farms in three New Brunswick bays found no increase in chlorophyll concentrations compared with control sites (Harrison et al. 2005). This was explained by the strong tidal mixing in this area. It is possible that light, rather than nutrient loading, is the limiting factor driving primary production in this bay. Likewise, monitoring in Blue Hill Bay, Maine also did not show increased chlorophyll concentrations in proximity to fish farms (Sowles 2005).
An evaluation of 43 salmon farm sites in Chile did not detect any effect of farm effluent on chlorophyll levels (Soto and Norambuena 2004) compared to control sites. This analysis included farms at nine locations of varying ages and production levels. The farms are located in deep water (15-94 m) and rapid flushing of nutrients likely explained the lack of an effect to primary production.

Water sampling at a salmon farm in Scotland detected increased nutrient levels at the farm, but no difference in chlorophyll-*a* (Navarro et al. 2008) compared to a control site 650 m away. These results supported conclusions from previous studies of no clear effect of farm nutrient enrichment on primary productivity. In fact, fish farming is considered to pose little risk of increased primary production in most Scottish waters, apart from a few heavily loaded sea lochs (Black et al. 2002). Heath et al. (2003) applied the European Regional Seas Ecosystem model (ERSEM) to identify areas of Scotland's maritime regions that may be at risk of eutrophication, with special focus on the contribution of salmon farms to nutrient loading. They concluded that the nutrients from aquaculture had no discernible eutrophication impacts on the west and north coastal and offshore waters. Recently, Tett et al. (2011) tested a computational physical-biological model, ACExR-LESV, for estimating the aquaculture carrying and assimilative capacities of Scottish fjords. Modeling output from a simulated loch was compared to water quality indicators and standards to decide how many fish farms the loch could support sustainably. The modeled carrying capacity was strongly driven by light penetration and circulation patterns that minimized chlorophyll production. This model requires further refinement before it can be reliably applied.

SUB-TROPICAL REGIONS

A study in Spain compared chlorophyll-*a* levels in the sediment below five sea bass and sea bream fish farms (Maldonado et al. 2005). Overall chlorophyll levels remained low (<2 μ/g) and, while some variability between farms was evident, there were no detectable differences between farm and reference sites. Vezzulli et al. (2008) tested chlorophyll-*a* levels in the water and sediments at a bluefin tuna farm in Italy. Only seasonal differences in concentrations were detected and the authors conclude that the water currents and depth at the farm site were adequate for preventing impacts to primary production. No eutrophication effect was found at a sea bass and sea bream farm in Greece (Belias et al. 2003), possibly due to overall low nutrient levels. However, the authors note that the alga *Ulva lactuca* has recently been found in several parts of the Astakos Gulf, possibly signaling increased nutrient loading. Demirak et al. (2006) found no difference in chlorophyll-*a* level at seven Turkish fish farm sites compared to reference sites. Basaran et al. (2010) did not detect a significant difference in chlorophyll levels at eight sea bream and sea bass farms off Turkey compared to a control station. Likewise, long-term monitoring at a tuna farm in Turkey exhibited no differences in chlorophyll-*a* at the farm site compared with reference sites (Aksu et al. 2010).

TROPICAL REGION

In the U.S., monitoring at a cobia farm off Puerto Rico found no differences in chlorophyll-*a* concentrations at the cage versus control sites (Alston et al. 2005). Similar monitoring results were reported at an experimental cage in the Bahamas (Benetti et al. 2005) and a Hawaiian moi *Polydactylus sexfilis* farm (Helsley 2007).

Harmful Algal Blooms

Harmful algal blooms (HABs) are concentrated densities of phytoplankton that produce compounds harmful to humans or marine life. Because of the potential harm to public health and fisheries, the possibility that marine fish farm effluent could induce HABs in coastal waters has been raised. When HABs occur near fish farms, fish may die of direct poisoning, incur gill damage or show decreased growth and vigor (Beveridge 2004, Davidson et al. 2009, Borg et al. 2011).

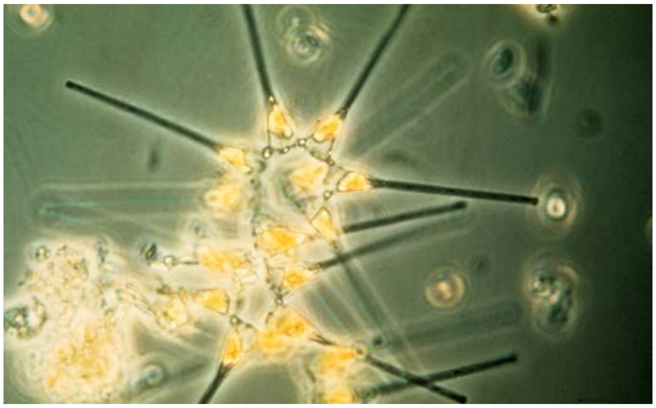


Photo courtesy of NOAA.

There is little research to date supporting a link between nutrient discharge from fish farms and the occurrence of HABs (Nash 2001, Silvert 2001, Black et al. 2002, Cole 2002, Huntington et al.

2006, Halwart et al. 2007). Similar to other algae species, the nutrient fluxes that influence HAB population dynamics are complex and vary for different species (Anderson et al. 2002, Anderson et al. 2008, Vargo 2009, Lewitus et al. 2012). Environmental factors other than nutrient loading also contribute to HABs. For example, in the Pacific Northwest, river discharge appears to drive HABs near many salmon farming areas (Rensel et al. 2010). As a best management practice, siting fish farms outside of nutrient sensitive habitats is encouraged (Nash 2003, Nash et al. 2005).

There are only a few studies which indicate that aquaculture effluents may contribute to occurrence of HABs. In a major aquaculture area in Guangdong province, China, the occurrence of algal blooms more than tripled from 1994-2004 compared to the previous decade (Yu et al. 2007). This included the occurrence of HABs near fish farms (Song et al. 2004), but industrial, agricultural and nuclear

Photo courtesy of NOAA.

facilities in the same area also contributed heavily to eutrophication and warming of the semi-enclosed bay's water. In a lab study Bodennec et al. (2002) found that exposure to dead fish and fish feed elutriates could increase the growth and toxicity of ichthyotoxic algal species.

To avoid any potential negative interactions — either stimulation of HABs from aquaculture discharge or harm to cultured fish from naturally occurring HABs — it is recommended that farms be sited away from areas with a history of recurring HABs, or in marine areas with low water exchange rates and high nutrient loads where blooms may thrive (Beveridge 2004, Borg et al. 2011).

In summary, while there is evidence that effluent from fish farms may result in increased primary productivity, most studies have failed to demonstrate a clear effect (Table 6). When effects are found, hydrological conditions or farm management practices may contribute. Siting farms in deep, well-flushed waters will help disperse dissolved nutrients and avoiding areas where effluent will be washed onshore will also help avoid eutrophication.

Because a change in primary productivity linked to fish farm effluents would have to be detected against the background of natural variability, it is difficult to discern effects unless they are of great magnitude (as high as a 50% increase in productivity) and duration (Huntington et al. 2006). Many farms conduct routine water sampling as part of their regulatory requirements. Given the difficulty in correlating nutrient enrichment directly to increased primary production, it is suggested that sampling include direct measurements of chlorophyll-*a*, or other metrics of productivity (Pittenger et al. 2007). Because nutrients may be flushed away from the immediate cage area and dispersed into the surrounding water body, it is difficult to assess whether far-field primary production is being affected over large areas and at longer time scales. This is further complicated by the occurrence of many anthropogenically derived nutrients in coastal marine waters, making it difficult to attribute nutrification to any one source, including aquaculture.

Benthic Community

The impact of marine finfish cage culture to the benthic community is an environmental concern. The accumulation of fish and feed waste below cages and the associated geochemical changes can induce changes to the micro and macrofauna that live on and in the sediments. Early reviews of environmental impacts by Wu (1995) and

IMPACT LEVEL	REFERENCE	LOCATION	SPECIES CULTURED
NONE DETECTED	Alston et al. 2005	Puerto Rico	Cobia
	Benetti et al. 2005	Hawaii	Moi
	Sowles 2005	Maine	Salmon
	Harrison et al. 2005	New Brunswick	Salmon
	Soto and Norambuena 2004	Chile	Salmon
	Navarro et al. 2008	Scotland	Salmon
	Maldonado et al. 2005	Spain	Sea bass & sea bream
	Basaran et al. 2010	Turkey	Sea bass & sea bream
	Demirak et al. 2006	Turkey	Sea bass & sea bream
	Belias et al. 2003	Greece	Sea bass & sea bream
	Vezzulli et al. 2008	Italy	Tuna
SIGNIFICANT	Robinson et al. 2005	Bay of Fundy	Salmon
	Rensel and Forster 2007	Puget Sound	Salmon
	Honkanen and Helminen 2000	Finland	Salmon
	Modica et al. 2006	Sicily	Sea bass & sea bream
	Vizzini and Mazzola 2006	Mediterranean	Sea bass & sea bream
	Huang et al. 2011	South China Sea	Various

Table 6. *Summary of primary production effects reported and modeled at fish cage sites in response to farm nutrient discharge.*

Pearson and Black (2001) address changes in benthic communities directly attributable to fish farming as an issue warranting additional attention. Benthic community impacts are identified as being one of the most critical areas requiring systematic examination and further research in the U.S. (Goldburg et al. 2001, Nash 2001, Stickney 2002, Nash 2003, Nash et al. 2005, Pittenger et al. 2007, Johnson et al. 2008, Ocean Conservancy 2011), Canada (Hargrave 2003, Wildish et al. 2004a, Hargrave 2005), Europe (Black et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006, The Mediterranean Science Commission 2007, Holmer et al. 2008, Olsen et al. 2008, Holmer 2010), the Mediterranean (International Union for Conservation of Nature 2007, Borg et al. 2011), Asia (Xue et al. 2004, Pan 2005), Australasia (Cole 2002, Crawford 2003) and globally (Beveridge 2004, Halwart et al. 2007, Tucker and Hargreaves

2008, Hall et al. 2011). Many countries require regular benthic community monitoring at fish farms as part of their regulatory process.

A great deal of recent research has increased our knowledge of how farm effluents affect benthic biogeochemistry and the resulting impacts to benthic biodiversity. We have expanded our understanding of how farm and site characteristics influence the degree, extent and duration of benthic community impacts, and work has progressed toward refining site and habitat specific indicators of perturbation (Black et al. 2008). The interplay of biotic and abiotic sediment processes is well understood and this chapter summarizes recent research which specifically targets the impacts of marine fish farms to the benthic community.

Microbial Communities

Excess fish food and waste can be a rich source of nutrient input to the marine environment. As organic matter accumulates on the seabed, the bacterial community is stimulated. Increased bacterial respiration rate depletes oxygen and may transform the sediment into an anoxic environment. A parallel shift in the bacterial community away from aerobic species and toward anaerobic species can occur, with mats of sulfide oxidizing bacteria like *Beggiatoa* as the only visible organism present. This process is generally well understood in marine sediments, but there has been relatively little work to more closely examine the effects of fish farm nutrients on specific components of the benthic microbial communities.

Studies conducted at Italian fish farms provide insight into the microbial processes occurring in enriched sediments. Vezzulli et al. (2002) studied the bacterial community beneath a 15 year old sea bream farm where sediment samples indicated an organically enriched benthos under reducing conditions. Bacteria levels below the farm were up to three times higher than at a reference site. There was a shift toward gram negative species at impacted locations and occurrence of pathogenic *Vibrio* (species was not reported) also increased. Danovaro et al. (2003) reported similar results from a study comparing benthic bacterial response at three fish farms. At impacted sites, the majority of culturable bacteria were facultative anaerobes, confirming hypoxic to anoxic conditions. Again, gram negative species predominated at farm sites, but gram positive species were prevalent in control site sediment. Farm sediments showed a 3-10 fold increase in bacterial biomass. Fifteen days after cage removal bacterial levels returned to levels similar to control sites. A study conducted by La Rosa et al. (2004) showed that after rapid organic accumulation following installation of a fish cage, the benthic bacterial community increased rapidly (within a few weeks) in response. As carbon levels in the sediment increased over the growout period, so did the bacterial biomass. Beneath the study cages there was a 13% decrease in eukaryotic species and a rise in cyanobacteria.

The use of commercial bacterial products to aid in the recovery of sediments beneath a fish farm was investigated by Vezzulli et al. (2004). In field trials, a blend of indigenous microbial strains (BIO-VASE) was added to enriched (high organic carbon and

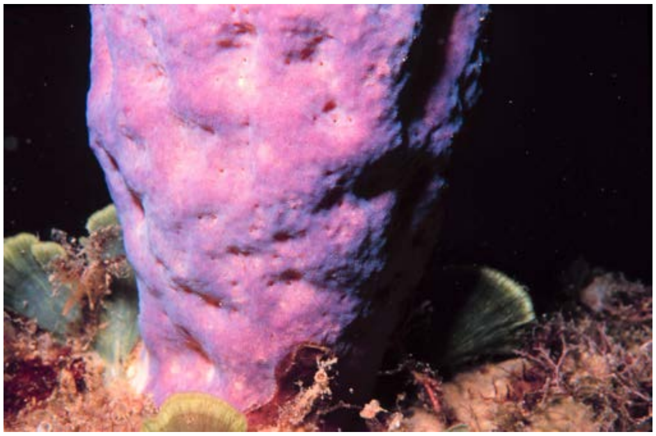


Photo courtesy of NOAA.

decreased redox potential) experimental plots below cages. This bioaugmentation stimulated carbon mobilization and enhanced extracellular enzymatic activity rates. The use of cultured bacterial products to mitigate environmental enrichment at marine fish farms is a relatively new field requiring additional research to evaluate its potential.

Meio- and Macrofauna Assemblages

The changes in the benthic faunal community resulting from marine fish farm nutrient enrichment and changes in sediment chemistry have been well documented for many years (Pearson and Rosenberg 1978). In stressed sediments, the benthic species composition and diversity shift toward tolerant generalists. The polychaete community is perhaps the most studied taxonomic group and it is widely accepted that the abundance of capitellid polychaetes and other generalist species is increased beneath impacted sites. Recent work is focused on defining additional species that can serve as consistent indicators of enrichment. There is a high cost associated with conducting benthic faunal sampling and it requires time and taxonomic expertise to process samples. Therefore, scientists and the industry are interested in identifying cheaper monitoring tools that provide reliable indication of environmental perturbation or degradation. Complex computer simulation models already used to track organic waste dispersion from fish farms are being expanded to include benthic components which predict benthic macrofaunal community response (Cromey et al. 2002).


Photo courtesy of NOAA.

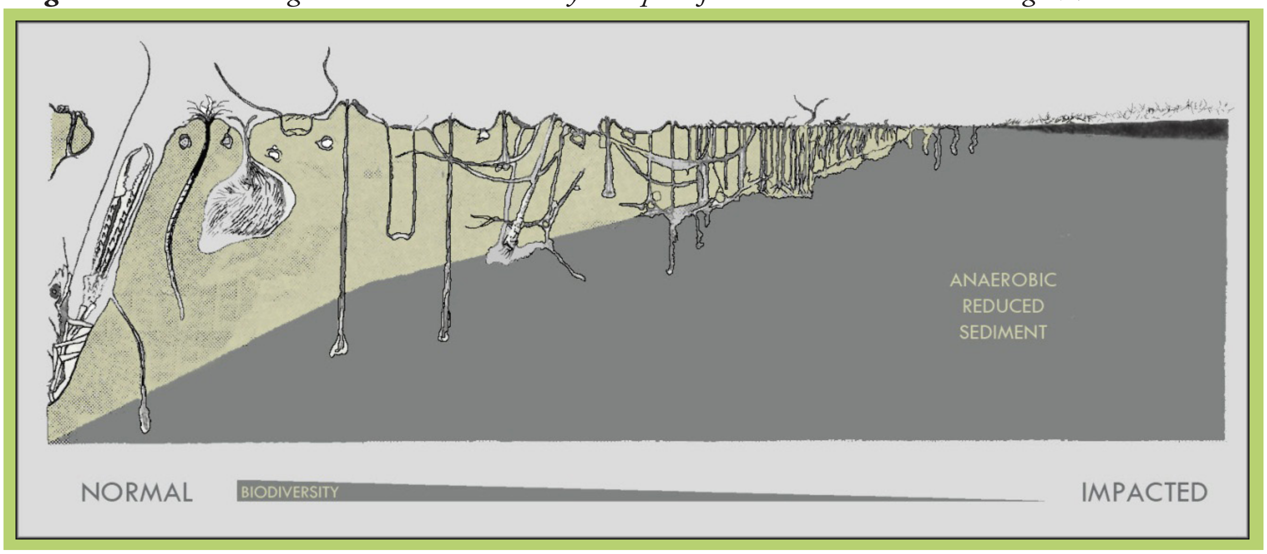
The following sections reference several biodiversity indices, quantitative tools used to assess the community structure, which reflect the biological community in sediments below fish farms and at reference stations. These indices are calculated from matrices of species data to estimate biological variability and compare communities. Some of the indices mentioned here are k-dominance curves, Shannon or Shannon-Wiener Index, Pielou's Index, Infaunal Trophic Index, Simpson's Index and others. Each differs in how it is calculated and what it reflects about biodiversity, so often researchers will calculate several indices for a data set. Some indices score or rank species according to whether they are generalist species that are relatively tolerant of a range of environmental conditions or more specialized species with narrower requirements. Quantitative indices are useful for comparing two locations with different species compositions, or for assessing the community structure of a location through time as species composition shifts. Heip et al. (1998) provide a useful overview of common indices, how they are calculated and how each may be interpreted and applied.

The question of benthic community changes and how best to monitor them at fish farm sites was addressed in two chapters of *The Environmental Effects of Finfish Aquaculture* (Hargrave 2005). Holmer et al. (2005) provides a broad overview of the interconnectedness of benthic sediment conditions and the benthic macrofauna. Sediment conditions, including enrichment from farm wastes, are among the factors driving the composition of the benthic community. Likewise, feeding and burrowing behaviors can also impact sediment conditions. While there is considerable research indicating that enrichment alters benthic faunal communities, the relative roles of natural variability and site-specific determinants are less well understood. Studies which can account for these factors separate from fish farm effects are needed to be able to refine our understanding of the benthic impacts directly attributable to farm organic matter enrichment. The chapter by Wildish and Pohle (2005) reviews the benthic macrofaunal changes typically associated with marine finfish cage culture. Most of the well-documented effects pertain to near-field scales. The far-field effects of aquaculture to the ecological functionality of food webs and secondary production have not been studied and are difficult to ascertain. Many studies used the classic enrichment gradients of Pearson and Rosenburg (1978) to classify sediment and faunal conditions (Figure 2).

Building upon this older model, Wildish and Pohle (2005) developed a summary table which compares value range of several specific chemical and biological parameter ranges (Table 7). These measures were used to broadly categorize the state of the benthic sediments and community. However, as research progressed it has become evident that there are cases in which this simplistic successional stage model is inadequate. For example, the use of this model may not be adequate when the initial conditions are not 'Normal,' if one is comparing species guilds across regions, when there are seasonal macrofaunal community fluxes or if farms are located above some types of unstable marine sediments that do not adhere to the standard geochemical model. The authors suggested that additional indices should be developed to address some of these deficits.

A tool to enhance our understanding of the interplay between biogeochemistry and benthic community structure was developed by Hargrave et al. (2008). They provides an in-depth summary of the current knowledge of the geochemical conditions resulting from organic enrichment and a review of the response of various benthic organisms, with the purpose of providing guidance for cost-effective monitoring of organic waste discharge from aquaculture. As sediments become enriched and deoxygenation ensues, sulfate metabolism becomes the major metabolic pathway driving the shifts in bacterial and macrofaunal communities. Hypoxia and sulfide toxicity inhibit the persistence of most sensitive taxa like mollusks and crustaceans. Diversity indices reflect the prevalence of opportunistic species like *C. capitata* and tolerant nematodes. Under extremely poor conditions, only tolerant species such as *Beggiatoa* (mat-forming chemoautotrophic filamentous bacteria) are found. The authors developed a nomogram which classifies marine sediments along an enrichment gradient with respect to a range of measurable biological and chemical variables (Figure 3).

Figure 2. *Enrichment gradient and biodiversity. Adapted from Pearson and Rosenburg 1978.*



This chart offers an improvement over older classifications as more chemical and biological indices with specific ranges of indicative values are included. This tool can be used by managers in developing monitoring plans at farm sites to track benthic effects. The interplay between sediment chemistry and benthic communities is widely studied (Nilsson and Rosenburg 2000, Valdemarsen et al. 2010) and research at fish farms sites will

INDICATOR	VALUE RANGE			
Geochemical	**Normal**	**Oxic**	**Hypoxic**	**Anoxic**
Redox	>100	0 – 100	-100 – 0	<-100
Sulfide	<300	300 – 1300	1300-6000	>6000
Biological				
Microbial	Normal	Oxic	Hypoxic	Anoxic
Macrofauna	Normal	Transitory	Polluted	Grossly Polluted
Sediment Profile Imaging				
OSI (Organism-sediment index)	III	II	I	Azoic
BHQ (Benthic habitat quality index)	>10	5 – 10	2 – 4	<2

Table 7. *Value ranges of geochemical, biological and image-derived indicators of enrichment and biological effects at marine fish cages. Adapted from Wildish and Pohle 2005.*

continue to add to our knowledge of these complex ecological processes.

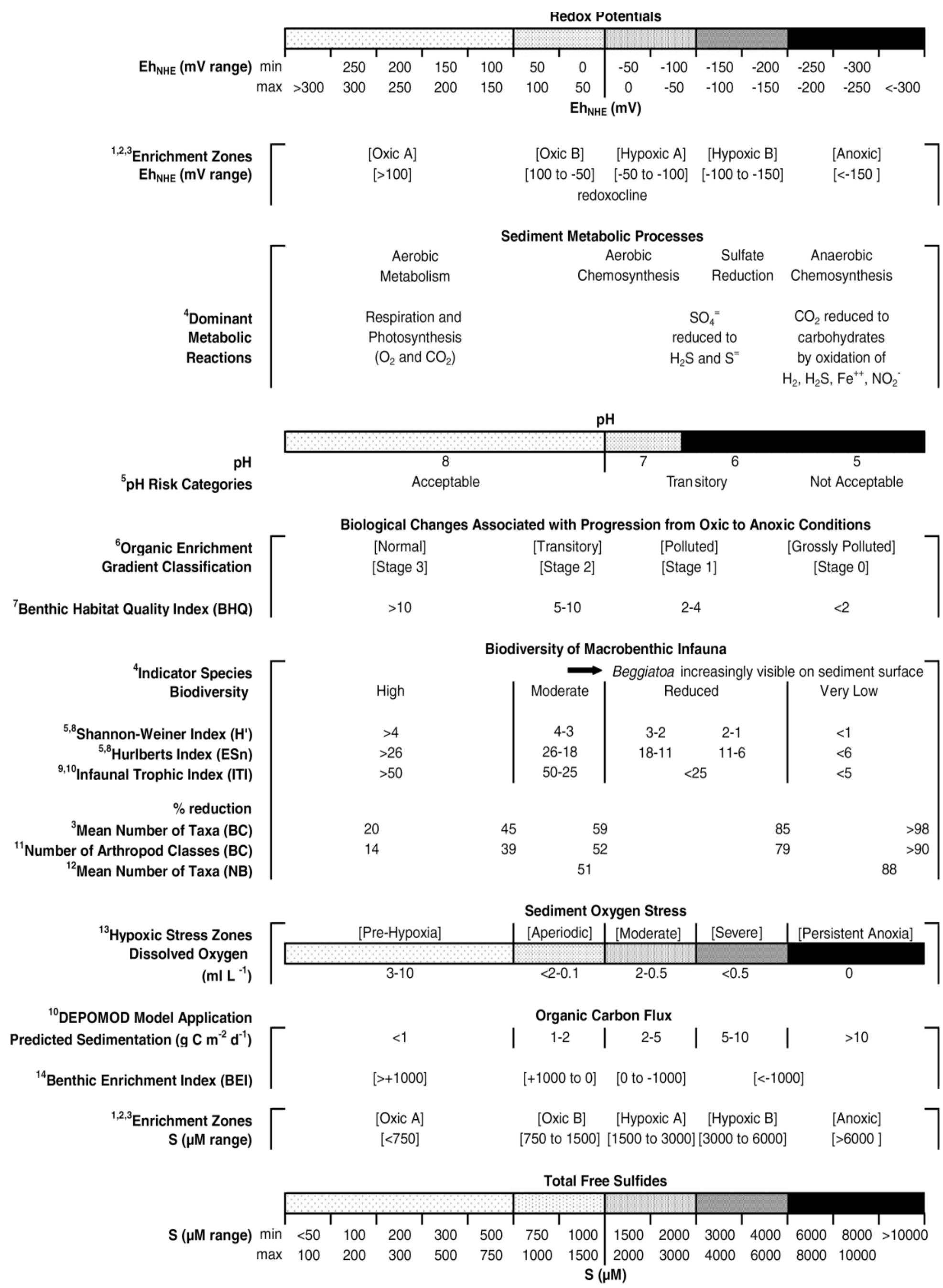
TEMPERATE REGIONS

North America

Much Canadian research has addressed benthic infaunal community impacts and the development of effective monitoring protocols. Wildish et al. (2001) compared the scientific results and cost effectiveness of two methods of benthic monitoring techniques — one based upon sediment geochemical analysis and one on macrofaunal analysis. The study was conducted at a salmon farm in the Bay of Fundy. Both methods found significant differences in sediment chemistry and community structure between farm and control sites, with abundance, diversity and evenness indices significantly reduced at the farm sites. *Capitella capitata* was the only species found in farm sediments. All of the geochemical tests could be conducted aboard a sampling boat, while faunal samples required extensive follow up work in the laboratory. Thus, 22 geochemical samples could be processed for every macrofaunal sampling, greatly decreasing the time cost. The training to conduct faunal identification further increases costs. Although both methods reached the same scientifically-based conclusion that the benthos was enriched, faunal sampling was found to be considerably more expensive.

A study of benthic effects at two salmon farm sites in the Letang Inlet, Bay of Fundy conducted in the late 1990's found significant enrichment (as reflected in percent organic matter) and benthic community effects compared to a nearby reference location with no aquaculture activities (Pohle et al. 2001). At the most heavily impacted site in Lime Kiln Bay, species diversity indices remained depressed and k-dominance curves (plots illustrating the relative abundance of all species in a community) elevated throughout the

Figure 3. *Nomogram depicting relationships between common geochemical and biological indicators of marine sediment condition below marine fish farms. Copied with permission from Hargrave et al. 2008.*



study period reflecting negative impacts to the benthic community. This effect persisted despite the cessation of farming one year prior to the final sampling. At the less impacted farm site, benthic community indices and k-dominance curves reflected initial degradation, but showed recovery in the last three years of surveys. Local benthic indicator species included polychaetes, bivalves and crustaceans. Enrichment tolerant species increased at impacted sites with a concomitant decrease in disturbance sensitive species.

In order to validate the use of sediment profiling imagery as a methodology for assessing benthic enrichment in Limekiln Bay, Bay of Fundy, Wildish et al. (2003) compared sediment geochemistry and faunal indicators to photographic analysis results. Both methods characterized the benthic conditions at the 20+ year old fish farming site as significantly impacted. The sediments were visually and chemically determined to be anoxic and highly reduced and only a few *C. capitata* were found. Both methods resulted in similar assessments for a nearby healthy reference site. The agreement between the two methods indicates that image technology, which is much cheaper and faster than faunal and geochemical sampling, is suitable for assessing benthic conditions beneath fish farms. Wildish et al. (2004b) also validated the use of acoustic technology to detect organic enrichment by comparing backscatter images to macrofaunal and geochemical samples collected at fish farm sites. This preliminary study confirmed that all three methods detected enriched benthic conditions at the cages. The total number of macrofaunal species was decreased and *C. capitata* numbers were elevated compared to reference sites. Additional work is needed to refine the use of acoustic mapping for benthic assessments, and this is a promising cheaper alternative to intensive sampling techniques.

...the response of benthic communities to marine aquaculture enrichment is a function of site specific environmental factors, which should be considered when studying the cumulative impacts of existing farms and for selection of future farm locations.

Brooks et al. (2003) employed a comprehensive set of chemical and biological indicators to evaluate remediation efforts at large commercial salmon farms in British Columbia. A variety of local, benthic fauna was used in the assessment. Indices including sulfide levels, total organic carbon and redox potential followed patterns typical for an enriched benthos. Effects were greatest within 30 m of the cages, but were measurable 105-185 m downstream. Following the initiation of harvest, chemical remediation of the benthic sediments was complete prior to the cessation of harvest (about nine months) and beginning of fallowing. Changes in the macrobenthos were most pronounced within 50 m of the cages, but were evident up to 225 m from the farm during peak production. Opportunistic polychaetes thrived and increased in abundance during fish grow out, but decreased as organic loading declined. Similar patterns were observed for generalist mollusk species. Shannon's Index values increased following harvest and initiation of fallowing, with distant sampling sites (>150 m) reflecting the earliest recovery. Biological remediation was defined as a return to macrofaunal diversity comparable to reference conditions and was completed with six months of fallowing. This work also includes a description of three distinct communities of local invertebrates associated with high, moderate and low concentration of sediment organic carbon.

In contrast, a second comprehensive study at a set of farms near the previous study site found remediation periods of several years (Brooks et al.

2004). Again, chemical and biological indices were used to evaluate the recovery of heavily enriched and degraded benthic conditions following harvest in 1997. By 2002, chemical remediation was nearly complete out to distances greater than 80 m from the cages. However, biological remediation did not progress as quickly and, even after four years of fallowing, community structure beneath the cages had not fully recovered. Recruitment of benthic invertebrates was slow and included few species. The authors note that many previous studies have documented a coupled chemical and biological benthic recovery process. As burrowing infauna

Photo courtesy of NOAA.

and epifauna recolonize enriched sediments, their burrowing and feeding activities resuspend organic matter and oxygenate the benthos, aiding in chemical remediation. This process was not, however, observed during this study. This farm site represented a worst case scenario for the authors who note that such a lengthy remediation is uncharacteristic of salmon farms in that area. Siting over depositional sediments in an area with poor dispersion was the likely explanatory factor.

Hargrave (2003) summarized the current research on the far field effects to benthic communities and food webs from aquaculture enrichment. These are more difficult to assess as there are multiple sources of enrichment in most water bodies with aquaculture operations and because there are few large-scale, long-term data sets. In New Brunswick, studies have found indications of far field impacts in terms of benthic community structure which may take greater than five years to manifest themselves. The potential food web disruptions at larger scales could be significant and could negatively impact Canada's demersal commercial fisheries, including groundfishes, scallops, lobsters and sea urchins (Wildish et al. 2004a).

Benthic faunal impacts are identified as an environmental issue of concern for the U.S. aquaculture industry (Nash 2001, Tlusty 2001, Nash et al. 2005, Pittenger et al. 2007). Nash (2003) identifies the potential effects to benthic faunal abundance and diversity as a high risk issue for salmon aquaculture in the U.S., especially if cages are placed in poorly flushed areas. He suggests that proper siting, appropriate production levels and fallowing will likely restrict harmful impacts to within less than 15 m of the cages. At well-flushed sites where accumulation of organic matter is not a factor, there may even be a net increase in benthic biomass from slight increases of carbon.

Nash (2001) summarized the benthic community effects from studies in the 1990s at North American salmon farms. Invertebrate infauna consistently responded to enrichment in terms of abundance and taxonomic diversity. Enhanced production was sometimes documented in the early phases of production, but usually adverse impacts were associated with increase in farm biomass. Polychaete, crustacean and mollusk abundance and diversity tended to decrease within 75 m of fish cages, with tolerant generalist species prevailing. Nash et al. (2005) later suggested that as the number of farms increases, there will be greater potential for far-field benthic effects from cumulative nutrient loading. They note that the scale of benthic impact will depend upon the degree of flushing in and around a facility and the biomass of the animals cultured. Appropriate siting of intensive aquaculture facilities is critical to the management of benthic effects. The high cost of monitoring of benthic community impacts may be reduced by using video techniques in combination with less expensive assessments of total volatile solids, redox potential and free sulfides.

Heinig (2001) reported on the results of long-term monitoring during the 1990s at salmon farms in Maine as part of that state's Finfish Aquaculture Monitoring Program (FAMP). Infaunal analysis indicated that net pen effects on the abundance and diversity of benthic community tended to be most pronounced directly beneath fish cages and within a 30 m radius. Impacts were typically not measurable beyond 60-80 m. Abundance and dominance by *C. capitata* was highly variable, ranging from 0-100%, but generally decreased with distances from the cages. This report urged the use of multiple indices to assess the benthic community because site-specific conditions and variability may be significant factors.

Similar conclusions were reached following nematode sampling conducted in the Gulf of Maine at two fish cage demonstration sites to collect baseline monitoring data (Abebe et al. 2004). A survey of the pre-stocking population status found low similarity in the nematode composition between the sites, even though sediment characteristics were similar. These results highlight the need to document site-specific changes in biodiversity before and after deployment of cages to be able to understand long-term effects. Goldburg and Triplett (1997) summarized reports from the 1990s of degraded benthic community conditions at Maine salmon farms. However, voluntarily fallowing and other mitigation measures were successfully implemented.

A study by Rensel and Forster (2007) points to the beneficial effect of nutrient loading to the colonizing organisms found at marine fish farms. This study did not examine the benthic community, but did find over 100 algae and invertebrate species populating the cages, lines and floats at a salmon farm in Puget Sound. Marine birds, fish, shrimp and crab were observed near the farms but not at reference areas nearby without farms. Such data supports the idea that limited nutrient input from fish farms in well flushed areas can have an overall enhancing effect on marine biomass (especially substrate colonizing organisms) and food webs.

South America

Sediment profile imaging (SPI) was used to examine sediment cores collected beneath salmon farms in two Chilean fjords (Mulsow et al. 2006). Image analysis and geochemical parameters reflected high levels of ecological degradation in the more enclosed Pillan Fjord where the benthos was largely azoic. The organism sediment index (OSI) values ranged from -4 to -2 at the most impacted sampling areas and the benthic habitat quality (BHQ) index from 0.67 to 1.3 at the most degraded sites and from 3.6 to 10 at the least impacted sites. In the more exposed fjord, there was less perturbation, but still evidence of impacts. Though no sites were devoid of benthic fauna, some areas had low OSI (2.7) and BHQ (5) scores compared to reference locations where OSI was 11 and BHQ was up to 12.7. The researchers concluded that SPI alone might have underestimated the impacts of fish farming and recommended this technology to be coupled with biogeochemical analysis for environmental assessments.

A large scale comparative study in Chile found impacts of 29 salmon farms on the benthic communities (Soto and Norambuena 2004). Shannon index and evenness values (how the individuals are spread among the species present) were significantly higher at reference sites compared to farm sites. Hardy, tolerant species were more common at impacted sites. Significant latitudinal differences in taxonomic representation were also found reflecting the need for regional knowledge about benthic fauna and identification of local species to serve as indicators of disturbance. A consistent relationship of decreasing species richness with high sediment phosphorus concentrations was detected. As the aquaculture industry expands in Chile, the potential environmental impact to benthic communities has been identified as a concern (Buschmann et al. 2009).

Northern Europe

A great deal of research has been conducted in Europe to understand effects of fish farming on benthic communities. Shifts in community dynamics beneath cages were already being documented in the 1990s (Lu and Wu 1998, Mazzola et al. 1999). Work has continued to further understand these impacts at multiple scales and develop effective monitoring and remediation strategies and techniques (Holmer 2010). A study in Finland was not able to detect consistent patterns of eutrophication effects to the benthic community with respect to geographical location or distance from fish cages (Honkanen and Helminen 2000). Here, plankton chlorophyll-*a* was a better indicator of enrichment, likely due to water circulation and mixing or high degrees of spatial variability in benthic community structure. In Norway, benthic sampling is a core component of the monitoring system (MOM) used to track environmental impacts of marine fish farms (Hansen et al. 2001). Impacts are assessed at the cage site, in the surrounding waters and regionally. Investigations of environmental conditions include monitoring of organic sedimentation rates, geochemical and sediment condition parameters and benthic macrofauna. Combined results are used to score overall impacts at farm sites. A trial test of this monitoring program at 44 farms found that sediment chemistry analysis was as definitive as more expensive and time consuming faunal sampling in detecting unacceptable sediment conditions. Most samples were categorized as showing little impacts. The polychaete *Malcoceros fuliginosus* was identified as an indicator species in enriched sediments.

Kutti et al. (2007) examined the temporal and spatial variations in infaunal communities for two years near a Norwegian salmon farm sited in very deep water (230 m). At peak farm production, infaunal abundance was 10 times and biomass was 35 times higher within 250 m of the farm, compared to a reference site 3 km away. Species richness was highest 550-900 m from the farm. Sediment parameters (visual observations and redox) indicated degraded sediment conditions in the immediate farm footprint (< 250 m) but the researchers concluded that overall the benthic capacity to decompose farm waste was not exceeded at this site. The organic wastes released from the farm served as a readily utilized food source for opportunistic polychaetes, bivalves and echinoderms. The researchers noted that effects at deep water sites may be spread over larger spatial scales than farms in shallower areas.

Benthic community structure was used to assess the recovery of sediments in two farming areas in the North Baltic Sea impacted by long term organic pollution (Kraufvelin et al. 2001). Historical monitoring data (1982-1991) showed that 12-18 species of opportunistic chironomid, oligochaete and bivalve species characterized early samples. Samples collected over seven years following pollution abatement found varying results. At one site, increase in abundance and species diversity indicated slow, but partial recovery. The other farm site, however, reflected continuing deterioration. Differences in topography and water exchange patterns were suggested as explanatory factors. Carroll et al. (2003) compared four common monitoring techniques — diver surveys, faunal analysis, sediment chemistry and sediment profile imagery — for evaluating sediment enrichment at five Norwegian salmon cage farm sites. They found that beneath the cages, faunal abundance and diversity indices were negatively impacted with effects decreasing out to 50 m. The four monitoring methods generally gave similar results with respect to assigning sediment condition. While faunal analysis is a very sensitive indicator of ecological impacts, it is time consuming and costly. Image analysis and sediment chemistry provide cheaper alternatives, but may underestimate the spatial extent of impacts.

A benthic recovery project in Scotland compared recovery time predicted using DEPOMOD (a model which tracks waste nutrient dispersion from fish farms) to actual recovery at five salmon farms (Black et al. 2012). The sites either had high initial impacts and recovered within a year or had low impacts but were further from recovery after two years, thus reflecting the site-specific nature of benthic recovery processes. At both sites, a suite of biodiversity indices, including Shannon's H´, AMBI, Pielou J´ and ITI, were compiled from benthic faunal samples used to compare site conditions over time. At peak biomass, all sites showed decreased

Photo courtesy of NOAA.

indices values out to 50 m, with recovery times of 251-774 days. A new index, the Brooks Recovery Index (BRI), was also developed which evaluated the persistence of individual benthic taxa from grow out through recovery. A recent study by Wilding (2011) focused on the abundance of the sea pen *Pennatula phophorea* near Scottish salmon farms finding that most transects within 30 m contained no sea pens. Sea pen numbers increased at intermediate distances (to 50 m). Interestingly, peripheral transects were highly variable with some transects containing no sea pens while others had relatively high densities. This variability was potentially explained as a protective effect of sea cages at some sites where the presence of cages deterred trawling activity.

Recently, a large-scale study was undertaken by Borja et al. (2009) to: 1) identify the suitability of selected quantitative indicators to assess the effects of aquaculture on benthic communities, 2) assess their applicability over a range of ecosystems and production systems, and 3) investigate the factors to which the indicators respond across Europe. Ten study sites from differing latitudes, water depths, sediment types and cultured species were included in the analysis. Macrofaunal abundance, biomass, species diversity indices and species richness were inversely related to the sampling distance from the farm. The influence of and relationships with other environmental variables such as depth and current speed were also analyzed and found to account for 53.2% of the variability in macrofaunal parameters. Thus, this study concludes that the response of benthic communities to marine aquaculture enrichment is a function of site-specific environmental factors, which should be considered when studying the cumulative impacts of existing farms and for selection of future farm locations.

SUB-TROPICAL REGIONS

North America

The impacts of a tuna sea cage operation in Baja California, Mexico, on the local benthic fauna (including mollusk, crustaceans, polychaetes and echinoderms) were investigated by Diaz-Castaneda and Valenzuela-Solano (2009). Sampling was conducted over two years at 18 stations in the bay surrounding the farm with the closest samples being taken 250 m from the cages. Shannon diversity index values varied only slightly over the study (2.26-3.40) and were distributed around the bay. An analysis of environmental condition base upon diversity and evenness index scores suggested that most sites were in favorable or stable condition. Polychaete diversity remained high and *C. capitata* represented only about 9% of polychaete abundance. Overall, the authors concluded that this area hosted a rich benthic invertebrate community, but because sampling at the cages was not possible they were unable to test for near-field impacts.

The Mediterranean

Many studies have been conducted throughout the Mediterranean in the last decade to investigate the impacts of marine fish culture, primarily of sea bass and sea bream, to benthic biodiversity. A study conducted at five farms in Spain (Maldonado et al. 2005) was able to detect significant benthic community impacts at only one site, though trends indicated biodiversity reduction at farm sites. The authors reported that poor statistical power was likely an experimental factor, but even so, the effect of fish farming seemed to be relatively weak based upon the results of clustering and ordination analyses. Opportunistic capitellid polychaetes and nassarid gastropods were the most common taxa collected at the impacted farm. Another Spanish study compared chemical and biological parameters tested in sediments from a single fish farm (Aguado-Gimenez et al. 2007). Here, only sulfide levels correlated well with the effects to the indices of macrobenthic community condition. Two methods of grab sampling, Van Veen grabs and diver sampling, were also compared. Both sampling methods found that effects to biotic indices were

Photo courtesy of NOAA.

most evident directly beneath the cage and within 100 m of the cage. Cost effectiveness analysis concluded that at this farm, faunal sampling was necessary to assess ecological impacts and that grab sampling was less costly than using divers.

In Italy, La Rosa et al. (2001) studied the response of meoifauna to fish farm sediment impacts and subsequent cage removal. Both total abundance and biomass of meiofauna and nematode were decreased under the cages compared to a control site in response to organic loading from the farm. Within a few months of cage removal, the nematode population began to increase suggesting a relatively quick onset of sediment and benthic community recovery. A follow up study at the same farm (Mirto et al. 2002) focused on the nematode assemblage response to organic farm deposition. Again, nematode abundance and biomass were decreased below the cage compared to a control site. Individual nematode body weight was higher at the cage site, however. Community structure of the nematode assemblage differed beneath the cage. For example, four of the dominant genera found below the cage were negligible in control sediments. *Setosabateria* characterized the control site and *Pierrickia* the cage station. Within a few months of farm deployment, k-dominance curves from cage samples were above control sites.

Impacts to meiofauna were examined by Vezzuli et al. (2003) at an established (15 years of continuous production) fish farm. Total meiofauna abundance and density increased below cages, with nematodes accounting for more than 85% of the abundance at cages, compared to 67% at the control site. Copepods were more abundant (26%) at control sites, compared to the cages (4%). Several minor taxa were absent below cages. Sampling of macrofauna at an intensive sea bream and sea bass farm in Trieste (Aleffi et al. 2005) also found increased biomass beneath the cages. However, the number of species declined under cages with opportunistic polychaetes *Neanthes caudata* and the mollusk *Mytilus galloprovincialis* dominating. K-dominance curves reflected disturbed communities beneath the cages. Overall, the severity of impact was considered low compared with other studies and impacts were confined to within 100m of the cages. Vezzulli et al. (2008) investigated the meiofaunal assemblage below a bluefin tuna fattening farm off the southwest coast of Italy. Due to good flushing at this site, environmental impacts were generally not detectable, but slight differences in the meiofaunal community were evident. The total number of species decreased and nematode composition differed beneath cage stations. Limited sampling and seasonal flux may have masked farm effects. A more intensive study at an Italian sea bass and meagre farm found significant differences in the benthic (Aguado-Gimenez et al. 2007) community. The overall number of species was lower beneath cages and increased with distance. Shannon diversity index was lower and opportunistic polychaetes prevailed beneath and near cages. Cluster analysis clearly differentiated between cage and control sites. AMBI (AZTI Marine Biotic Index) values were also calculated and confirmed progressively degraded conditions below the cages over the 18 months of increasing biomass during grow out.

Italian sea grass meadows near fish cages have also demonstrated changes in their macrofaunal assemblages. Terlizzi et al. (2010) found that seagrass beds 100-500 m downstream of a sea bass and sea bream farm showed increased organic loading compared to control sites. Benthic communities closest to the farms had fewer individuals, decreased evenness and diversity index scores, and increased k-dominance curves. The 500 m site values were intermediate between the 100 m site and controls, but statistically similar to control sites. At the impacted sites, a few opportunistic species tolerant of stressed habitats with high organic matter represented most of the faunal abundance. Impacts to Mediterranean seagrass meadows macrofauna were compared for three farm sites in Spain, Italy and Greece (Apostolaki et al. 2007). Enrichment was negligible at the seagrass meadows according to geochemical analysis. Species number and abundance showed little variability between the farm and reference stations at all sites. Interestingly, macrofaunal biomass peaked at the intermediate sampling locations between the farm and control stations for all sites. Overall, the meadows displayed high diversity and contained the expected species arrays, resulting in the conclusion that effects to the seagrass at these farms were mild. These two studies highlight the need to examine benthic effects of marine aquaculture in sensitive habitats.

In the last ten years many studies were conducted in Greece to understand the effects of fish farms on benthic communities. For example, Karakassis et al. (2002) used sediment profiling image analysis to characterize macrofaunal assemblages for comparison with traditional core samples and geochemical analysis. The two methods showed a high degree of correlation, validating the use of image analysis as a cheap monitoring alternative. The stations directly below the stations became heavily degraded over the 10 month study, with stations out to 50 m from cages more closely resembling conditions at a control site. Lampadariou et al. (2005) found increased meiofaunal abundance 25 m from cages at three Greek fish farms compared to control sites, mostly due to increased nematode and copepod densities. Diversity indices decreased significantly at only one of the farms. Meiofaunal response was in agreement with redox and organic matter levels which indicated enriched sediment conditions. Similarly, Klaoudatos et al. (2006) found significant increases in abundance, but decreased species number, diversity and richness during a year of sampling at floating cages off eastern Greece. The polychaetes *Nereis diversicolor* dominated (35% abundance) at farm sites compared to controls (12%). Other opportunistic polychaete species were also abundant at farm sites. K-dominance curves indicated that the highest impacts to benthic assemblages occurred in October, reflecting the importance of seasonal variability in faunal abundance.

Lampadariou et al. (2008) developed a biomass fractionation index (BFI) to rapidly assess benthic organic enrichment. A quick sieving method is used to quantify the biomass fraction >0.5 mm and <1.0 mm as a proportion of total biomass in each sample. This technique was tested at seven Greek farm sites sited in varying conditions by comparing assessments to geochemical analysis and full macrofaunal identification. Impacted sediments and changes in macrofaunal assemblages, primarily due to the prevalence of *C. capitata*, were evident up to 25 m from the cages. The BFI values were elevated (up to 0.8) below and near cages (out to 10-25 m), and decreased (down to < 0.1) out to 50 m from the cages. This was largely due to increased total biomass contributed by large macrofauna such as mollusks and echinoderms further away from the cage areas. Recently, Neofitou et al. (2010) studied the spatial and temporal benthic community effects at two Greek fish farms in a semi-enclosed gulf. Spatial, but not seasonal, differences in enrichment were detected; the greatest impacts were within 10 m of the cages and decreased closer to control levels by 50 m. Total abundance and biomass were variable with regard to distance from the cage, season and farm. However, the number of species, species richness, evenness and the Shannon-Wiener index were all lower within 10 m of the cages, with an increasing trend out to the control station 300 m away. The 50 m sampling stations were often intermediate between the high impact area under the cage and the controls. K-dominance curves followed a similar pattern and, as in other studies, opportunistic polychaetes *C. capitata* principally accounted for the dissimilarities in benthic communities between farm and control sites.

A recent study used six sea bream and sea bass sites in the eastern Mediterranean to test a computer simulation model, MERAMOD, which tracks waste nutrient particles and predicts benthic impacts from fish farm discharge (Cromey et al. 2012). The abundance and biomass of opportunistic species including *C. capitata* (representing over 85% of total abundance near the cages) increased significantly beneath cages. The Shannon-Wiener diversity index and species richness decreased 10-25 m from the cage and increased 50 m away and at the references stations. Statistical comparison indicated that the relationship between the field data and the model's predicted values for benthic biodiversity impacts (abundance, Shannon-Wiener H´ and Simpson's index) were classified as excellent, demonstrating the usefulness of tools like MERAMOD for understanding the ecological impacts of fish farms in the marine environment. In this study, 25 m was the greatest distance at which benthic impacts were detected according to modeled and observed measures of biodiversity and sediment flux.

In the Adriatic Sea, Kovac et al. (2004) reported meiofaunal changes beneath a sea bass farm where species diversity was impoverished and several groups (Gastropoda, Acarina, Ostracda and Ophiuroidea) were completely absent. Effects were evident up to 200 m from the cages. Najdek et al. (2007) reported a localized (20 m) impact to benthic communities in enriched sediments below a sea bass and sea bream farm site. Relative abundance of nematodes at the cages was up to 92%, compared to 69% at a control site 1 km away, while total density and species diversity decreased. Stable isotope analysis was used to detect fish farm derived nitrogen in sessile benthic invertebrates (Dolenec et al. 2007). Enrichment of $\delta^{15}N$ up to 5.2-6.8 ‰ in

Photo courtesy of NOAA.

organisms collected from the perimeter of fish farms compared to reference locations with values close to zero. This study was able to distinguish invertebrate nitrogen uptake in sponges, anemones and barnacles from farm and municipal waste sources, providing insight into the use of this tool for assessing near and far field impacts in areas with multiple sources of enrichment.

In Israel, the benthic foraminiferal community was studied in relation to organic enrichment gradients associated with a commercial sea bream farm (Angel et al. 2000). These taxa are used to study anthropogenic effects in marine sediments as their abundance, calcium carbonate test formation and community composition may be altered in response to perturbations. Over 50 species of foraminifera were found around the farms with highest abundance in the enriched sediments associated with the farms compared to control sites. Species richness was generally low in the vicinity of the farms, but lack of historical data in this area made it impossible to draw a conclusion about changes in diversity due to enrichment. Eden et al. (2003) studied the response of the mud snail *Nassarius sinusigerus* to changes in sediment biogeochemistry beneath an Israeli sea bream farm. The peak in snail abundance occurred with moderately impacted sediments 20-80 m from the farm's center. Highly deteriorated sediment conditions caused the snails to move further away, but they returned following recovery.

A broad scale, comparative study looked at the influence of marine cage culture on the development of sublittoral fouling communities on identical artificial structures in Scotland, Crete, Slovenia and Israel (Cook et al. 2006, Tsemel et al. 2006). The results provide information about the nutrient availability to food webs and epibiotic recruitment around fish farms compared to reference locations. After six months, biomass was higher at the Scottish and Israeli fish farm structures, but the opposite was true for the site in Slovenia. Community composition varied between the sites with 26-73 colonizing species recorded and algal production also differing among the sites. It is likely that in oligotrophic waters, nutrients released from fish farms may increase the biomass of fouling organisms, possibly reducing other environmental impacts of cage culture.

Photo courtesy of Blythe Chang.

Recently, the AZTI Marine Biotic Index (AMBI) was developed to provide a tool to assess the benthic biotic condition in a wide range of European coastal sediments (Muxika et al. 2005). This index can be used to determine the ecological quality of benthic habitat impacted by a wide range of human activities including marine fish aquaculture. The proportions of benthic species, ranging from very sensitive to disturbance tolerant to opportunistic, are used to calculate a location's AMBI value, with higher values reflecting heavily disturbed conditions. This type of index is valuable in making comparisons of impacts across wide geographical areas. A case study at three Greek fish farms found AMBI scores increased directly below the cages, but decreasing out to 25 m. This index has been applied in Atlantic and Mediterranean regions.

Studies in the Canary Islands have found significant changes in benthic communities below fish farms. Boyra et al. (2004) used image analysis to show an increase in sea anemone coverage at a sea bream and sea bass farm (1.1-2.3% seafloor coverage) compared to reference sites (0.3-1.2%). A six year study of meiofaunal community dynamics under fish farms in Tenerife found significant shifts in impacted sediments toward nematode dominated communities. Overall meiofaunal abundance was greatly increased below cage sites compared to control and intermediate stations, and seasonal and yearly effects were also significant. Harpacticoid copepod abundance and presence were also affected by the presence of farms, while polychaete abundance was low (less than 5%) in all samples.

Asia

Japanese regulatory requirements for sustainable aquaculture include benthic community monitoring. Yokoyama (2003) describes the relationships between macrofaunal communities, degree of embayment of farm sites, farm production and sediment chemical parameters to provide additional information for evaluating environmental criteria. Six indicator groups of macrofaunal species were derived based upon sampling at 22 fish farms. Results suggested that topography (depth and width of a bay) is the primary factor affecting the benthic communities under cages, with farm production as a secondary driver. This information was combined into a simple graph which can be used to guide production or siting decisions based upon predicted benthic community impacts. The relationship between benthic fauna, topography and current velocity as indicators to assess the assimilative capacity of fish farms was further examined by Yokoyama et al. (2007). An index based upon water depth and current velocity was refined and a graph similar to the one described above was developed to guide siting and production. They also included a table of critical threshold values of biotic and abiotic parameters typically collected during monitoring. Similar research was conducted in Korea (Kim et al. 1998, Park et al. 2000) and other Asian countries, but it is often difficult to obtain translated research articles.

Australasia

A benthic fish exclusion study conducted by Felsing et al. (2005) additionally analyzed changes in the benthic community. Sedimentation and enrichment were highest under cages with restricted wild fish access, as feeding activity greatly ameliorated farm effects. Macrobenthic community structure was also most affected when fish were excluded. Capitellid and spionid polychaete abundances were predominantly present in the more degraded sediment inside the exclusion nets. Shannon diversity index values were lower beneath cages with and without fish exclusion nets compared to reference site values.

TROPICAL REGIONS

Caribbean

Several U.S. marine fish farms have conducted benthic fauna sampling as part of their monitoring regimes. Benthic macroinvertebrate sampling at a mutton snapper and cobia farm in Puerto Rico found no differences for the Shannon diversity index, species evenness index, or species richness index at the cage site versus the control site (Alston et al. 2005). Contrast analysis, however, showed that abundance of macroinvertebrates in the sediments at the control site was significantly higher when compared to stations beneath the cages, especially at the snapper cage. Seasonal differences in abundance related to maximum feeding loads were also noted. Overall, impacts were confined to the area directly beneath the cages.

Pacific Islands

Benthic sampling at a Hawaiian yellowtail farm found a high proportion of gastropods and few bivalve species (Family Lucinidae) known to occur in anaerobic and high sulfide conditions (Sarver 2009). The report concluded that two years of sampling indicated only a low impact of the farm to the benthic fauna. An increase in the number of dorvilleid polychaetes was related to increased feed amounts and fish size at a moi farm in Hawaii (Bybee 2001). This opportunistic group of polychaetes was possibly an indicator of enrichment, even though crustacean and nematode abundance were not affected. After harvest, the dorvelleid polychaete numbers returned to pre-stocking values. A follow up study sampled the polychaete infaunal community at the same sites a few years later under increased production (Lee et al. 2006). This study found chemical measurements indicative of an enriched benthos, and Shannon-Weiner diversity index values of the polychaete community decreased both over time and in relation to distance from the cages. Pielou's evenness levels were lower at cage than control sites and opportunistic species *C. capitata* and *Ophryotrocha adherens* were more abundant at impacted sites. Polychaete communities at control sites were unchanged over time. Following a six month fallowing period, polychaete diversity and community structure at the affected sites began to resemble communities at reference sites (Lin and Bailey-Brock 2008). Enrichment indicator species declined sharply, but the study concluded that full recovery had not yet been achieved as significant differences in community structure still existed.

Asia

Research is being conducted in India to assess benthic impacts as mariculture expands in that country. A survey of the macrobenthos in the Bay of Bengal, India found significant changes in the assemblages there compared to surveys conducted 50 years ago (Raut et al. 2005). Yet, two taxonomic distinctness indices still reflected an overall healthy level of biodiversity and a taxonomically stable community structure. Increased human activities, including aquaculture, were identified as factors affecting this region. A pilot study of the culture of sea bass in small open cages (hapa) on the west coast of India monitored benthic macrofauna (Imelda-Joseph et al. 2010). During the four month culture period the macrofaunal abundance increased nearly fourfold due to high organic loading from the trash fish used as feed.

In China, Gao et al. (2005) report that fish farm activities near Hong Kong had adverse impacts to the macroinvertebrate assemblage. A one year field study was conducted in a semi-enclosed bay with grouper, snapper and sea bream mariculture operations. Changes in polychaete, brittle star and bivalve abundance were evident beneath fish cages and at intermediate (100 m away) stations compared to controls (600 m away). Shannon-Wiener index value significantly decreased beneath fish cages and at intermediate sites, and K-dominance curves reflected similar patterns of perturbation.

Australasia

An Australian study examined sediment and macrobenthos condition to assess recovery at a high production salmon farm in operation for 14 years (Macleod et al. 2004). Sulfide levels at the cage and out to 35 m returned to reference site values within six months and sediment organic matter at the cage site had decreased by 30-40% after two years. Benthic faunal recovery, however, was slower. Even after three years, Shannon diversity values remained lower at the cage site (1.6) than at the reference station (2.0) although stations beyond 10 m were recovered within a few months. The farm was situated in a depositional environment, which tended to localize impacts to within 10m but also slowed recovery.

A comparison of sediments and macrobenthos at 20 fish farms in Tasmania showed an increase in opportunistic polychaetes and decreased species diversity correlated to the degree of farm waste (Edgar et al. 2005). Species richness of crustaceans and gastropods and biomass of bivalves were lower at cage than less-impacted sites. Sites 20 m from the cages and 35 m from farm boundaries showed community effects intermediate between cage sites and reference sites 1-2 km distant. A recent follow up study in the same area (Edgar et al. 2010) found similar results. Redox potential, the proportional abundance of capitellid polychaetes, and bivalve/mollusk ratio were determined to be the most useful environmental indicators of fish farm impacts for this region. The study also attempted to discern large scale, regional environmental impacts from fish farming. However, even though 42 farm sites were sampled, there was insufficient statistical replication and power to make definitive inferences about long-term impacts. Nonetheless, background changes through time suggested to the authors that organic matter, faunal abundance and proportion of introduced taxa increased in Tasmania during the six year monitoring period, while redox potential, sediment particle size and abundance of capitellids decreased.

A recent study used 12 years of sediment data collected at five New Zealand salmon farms to evaluate five benthic indicators (abundance, number of taxa, redox potential, total sulfides and total organic matter) and 10 biotic indices (Margalef's d, Peilou's J′, Shannon H′, AMBI, M-AMBI, MEDOCC, BENTIX, BOPA, ITI and BQI) under low and high flow regimes to identify those that best define organic enrichment gradients (Keeley et al. 2012). Though most of the indices performed well, none was able to consistently discriminate biotic impacts over the full range of enrichment gradient for both flow regimes. Overall, redox potential and the M-AMBI index performed well for both flow regimes across the enrichment range. At the upper end of the enrichment scale, however, the M-AMBI showed increased variability, while redox had lower correlation with enrichment at higher flows. At very high enrichment, redox, sulfides, number of taxa and abundance were relatively clear, but some of the more complex biotic indices were less discerning. Of the ten indices, BQI (Benthic Quality Index) performed best for higher enrichment levels. At the lower end of the enrichment scale geochemical parameters were less sensitive, and biotic indices were better at reflecting early impacts to the community. Perhaps one of the most important findings of this study was that it was difficult to discriminate biotic impacts at high levels of enrichment especially when trying to determine the threshold point at which opportunistic macrofauna can no longer survive and the benthos become azoic. The researchers concluded that a combination of geochemical parameters and regionally validated indexes will be useful to assess benthic community conditions at fish farms, but caution that expert judgment must be applied to weight indicator variables appropriately, identify spurious results and to provide an integrated approach to the assessment process.

Advances in image analyses and acoustic technology are being evaluated to develop quicker and cheaper sampling methods.

In his summary, Phillips (2005) reports that benthic community impacts are generally confined to within 50 m of fish cages. Flushing and feed management are two factors which determine the radius of impact. Highly variable fallowing periods range from a few months to greater than 10 years. Two other studies have summarized global trends in benthic impacts of fish farms. Kalantzi and Karakassis (2006) conducted a meta-analysis of benthic impacts drawing on data from 41 studies covering a range of farmed species, geographic areas, management practices and site characteristics. Benthic faunal parameters included as dependent variables were Shannon diversity index, Pielou's evenness index, number of species, abundance and biomass. Stepwise regression found that most biological variables were determined by distance from the farm, water depth and latitude. For example, 68% of the variance associated with Shannon-Wiener diversity index was explained by these three factors. Results were also presented for analyses done with respect to three sediment types, providing further insight into site-specific characteristics which may influence the severity of benthic impacts from fish waste. Giles (2008) accessed data from 64 studies and used Bayesian networks to quantitatively assess the relationships between impact parameters and farm characteristics. Macrofaunal abundance and biomass, and Shannon diversity index were used to quantify benthic diversity effects. These were significantly correlated to sediment nitrogen, sediment organic matter and redox potential, as well as to farm characteristics including farm volume, current speed and sediment type.

These types of comprehensive data analyses are possible because of increased monitoring and recent research incorporating repeated measurement of biological and geochemical parameters at farm and reference sites. Such tools will be useful to the marine aquaculture industry and regulatory agencies for making decisions regarding siting of new farms and setting environmental impact thresholds. The need for improving the power of benthic surveys to detect trends in offshore marine sediments impacted by aquaculture or other human activities is addressed by Rogers et al. (2008). This work describes the resource and sampling requirements necessary to effectively assess ecosystem status in benthic sediments, concluding that large numbers of

relatively expensive repeated samples will generally be required to detect impacts. Overall, megafaunal sampling provided the best tradeoff between sufficient power of detection and costs.
Research has continued to document previously reported effects to the benthic community and build upon this research in terms of improving our knowledge of the interactions of biotic and abiotic components of the benthic environment (Table 8). Improvements in farm management, proper siting and fallowing are consistently reported to substantially decrease and minimize the impacts of marine fish farm waste to benthic communities. Advances in image analyses and acoustic technology are being evaluated to develop quicker and cheaper sampling methods. Continued monitoring of benthic communities at farm sites is imperative, as is site specific reference data establishing baseline faunal conditions. Future research to gain understanding about regional and far-field impacts of marine fish farming to benthic communities is needed. This will require long-term data sets and repeated sampling over large areas and refinement of techniques that can differentiate between aquaculture waste and other natural and human sources of nutrients. Methods to measure impacts to hard bottom sites are needed to assess impacts to those habitats.

When wild fish were excluded from areas of the sediment below the cages the organic content, nitrogen and sulfide levels, and Capitellid polychaete and macrofauna numbers increased significantly.

Fish

The excess food and waste released from fish cages may be a food source for wild fishes, especially benthic feeders (International Council for the Exploration of the Seas 2002, International Union for Conservation of Nature 2007, Grigorakis and Rigos 2011). Cages may also provide shelter and foraging habitat for fish. These characteristics may be considered a benefit to the local and regional environment because of increased production of local fish and potential benefits to the benthic environment.

On-Site Effects

A study in Israel (Katz et al. 2002) found that bottom-feeding gray mullet stocked in enclosures beneath a sea bream farm increased sediment oxygen levels and decreased organic loading and sulfide levels as a result of increased bioturbation during mullet feeding. In this study, wild demersal fishes were excluded from portions of the sediment resulting in degraded conditions demonstrating the positive effects of sediment resuspension. Planktivorous damselfish and snails were also attracted to the area beneath fish cages, with the latter being present in higher numbers in the mullet cages (3970 snails/m^2) compared to unstocked enclosures (457 snails/m^2).

Similarly, Vita et al. (2004) found a beneficial effect of fish at sea bream and sea bass farms in Spain during an exclusion experiment. When wild fish were excluded from areas of the sediment below the cages the organic content, nitrogen and sulfide levels, and *Capitellid* polychaete and macrofauna numbers increased significantly. Analysis of sedimentation showed about 80% of the organic waste was consumed within 4 m of the cage bottom, thus reducing its accumulation on the bottom. Additional bioturbation of sediment during fish foraging activity greatly improved sediment quality. Likewise, wild fish exclusion experiments at a marine rainbow trout farm in Australia estimated that wild fish consumed 40-60% of the sedimented nutrients from the fish cages (Felsing et al. 2005). Carbon deposition under cages without fish was 4.5 g carbon/m^2/day compared to only 0.7 g carbon/

COMMUNITY EFFECT	REFERENCE	LOCATION
Increase in anaerobic microbes in sediment	Vezzulli et al. 2002	Mediterranean
	Danovaro et al. 2003	Mediterranean
	La Rosa et al. 2004	Mediterranean
MACROFAUNA		
Decreased abundance or species diversity and/or increase in opportunistic species	Nash 2001	North America
	Wildish et al. 2001	Bay of Fundy
	Pohle et al. 2001	Bay of Fundy
	Lee et al. 2006	Hawaii
	Brooks et al. 2003, 2004	British Columbia
	Hargrave 2005	Canada
	Soto and Norambuena 2004	Chile
	Kraufvelin et al. 2001	Baltic Sea
	Carroll et al. 2003	Baltic Sea
	Borja et al. 2009	Europe
	Aguado-Giminez et al. 2007	Spain
	Vezzuli et al. 2003	Italy
	Terlizzi et al. 2010	Italy
	Neofitou et al. 2010	Greece
	Gao et al. 2005	China
	Imelda-Joseph et al. 2010	India
	Macleod et al. 2004	Australia
	Edgar et al. 2005	Tasmania
	Kalantzi and Karakassis 2006	Global
	Giles 2008	Global
Minimal effects on species diversity; increased abundance or biomass	Diaz-Castenada and Valenzuela-Solano 2009	Mexico
	Alston et al. 2005	Puerto Rico
	Sarver 2009	Hawaii
	Rensel and Forster 2007	Puget Sound

Table 8. *Effects to the benthic community at marine fish farms.*

m^2/day under cages open to benthic foraging. After 62 days, conditions beneath cages excluding fish had deteriorated as reflected by both geochemical measurements of nutrient enrichment and a shift in the benthic community towards *Capitellid* and *Spionid* polychaetes.

Fish aggregation devices (FADs) are structures deployed in aquatic environments to attract fish communities, and marine cages have been called 'super-FADs' because of the large numbers of wild fish attracted to these structures (Dempster et al. 2005).

TEMPERATE REGIONS

Three fish species were recorded being attracted to a salmon farm in Puget Sound (Rensel and Forster 2007), but this fish data was incidental within the larger context of the study which focused on invertebrate fouling organisms. Nash (2001) also states that salmon cages act as fish attractants.

SUB-TROPICAL REGIONS

From diver surveys, Oakes and Pondella (2009) found much higher fish abundance, density and diversity below cages stocked with white sea bass *Atractoscion nobilis* off Catalina Island (10,234 fish, 142 fish/100m2, and H´ = 2.29) compared to adjacent (8452 fishes, 117 fish/100m2, and H´ = 1.45) and distant (500 m away, 8958 fishes, 124 fish/100m2, and H´ = 1.13) reference reefs. Tuya et al. (2006) found that cages continued to attract wild fish even after the cages had been emptied and farm feeding activity ceased. Prior to harvest, wild fish abundance was about 50 times greater at cages than at control sites; after harvest wild fish abundance was double control levels. Fish that fed on particulate organic matter, large benthic chondrichthyid rays and *Pagellus* spp. declined at the fish farm after the cessation of farming, but herbivores and mid-sized benthic carnivores remained. Dempster et al. (2005) concluded it is difficult to predict the fish community structure response to the presences of fish cages. Their comparison among fish assemblages at cages in Spain and the Canary Islands, found no pattern of fish distribution vertically in the water column around the cages or with respect to size classes present. Their results suggest that it may be difficult to predict *a priori* at which sites demersal fish foraging and bioturbation might be expected to contribute to assimilating or dispersing farm waste. However, wild fish abundance and species richness were ubiquitously high near cages, with planktivores and pellet eaters consistently being numerically dominant. Recently, a computer model, MERAMOD, which tracks waste particle flux from fish farms was used to assess environmental impacts in the eastern Mediterranean Sea (Cromey et al. 2012). The researchers incorporated a module to account for site-specific rates of wild fish feeding on waste particulates and found this improved model performance. This was confirmed by direct diver observations which also indicated that removal of particulates by wild fish can be an important part of the nutrient flux process. Most nutrient dispersal models do not explicitly incorporate the ecological roles of wild fish into their simulations, either as direct consumers of particulate waste or as ultimate consumers benefitting from farm nutrient transfer up the food web (Pitta et al. 2009). This approach appears to be a valuable addition to these quantitative tools, especially for modeling areas with fish communities rich in demersal species.

TROPICAL REGION

Alston et al. (2005) monitored a diverse fish assemblage around a cobia sea cage in Puerto Rico. While species richness indices fluctuated throughout the year with no definitive pattern, the fish community at the cage site was always more diverse and about 40 times more abundant than at control sites. Both reef and pelagic species were present and Carangids were the most numerous fish representing 92% of the fish censused. In Indonesia, Sudirman et al. (2009) found 29 species of mostly small reef fishes aggregating around small marine cage farms, only five of which were observed directly feeding on waste pellets, consuming around 27%. The fish appeared to be permanent residents using the cages as shelter and for foraging on the fouling communities. In Queensland, researchers made incidental observations of wild fish aggregating near a barramundi farm, and concluded that most of the fish there were Siganid herbivores seeking shelter and feeding on fouling organisms (McKinnon et al. 2008).

Negative interactions with wild fishes have also been observed. For example, bluefish are reported to seasonally aggregate around and invade fish cages in the Mediterranean (Sanchez-Jerez et al. 2008). Of the 23 farms surveyed, bluefish aggregations were detected at 16, but only four farms reported significant impacts to the cultured fish. In addition to direct predation on the cultured fish, these four farms reported decreased productivity due to stress and additional costs associated with removal of bluefish and net repair. While marine cages primarily provide a habitat and foraging opportunity for fish, Nash et al. (2005) suggest

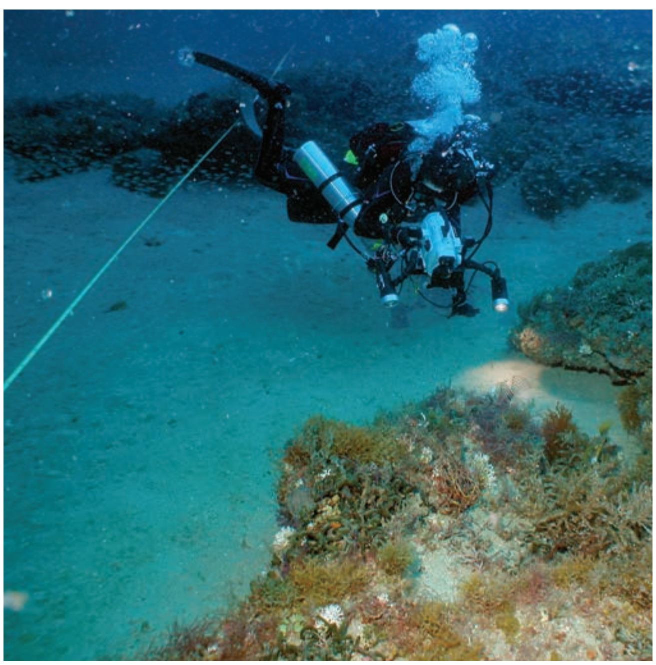


Photo courtesy of NOAA.

that lights used at salmon cages to extend the photoperiod for growth enhancement may attract fish at night, possibly interfering with juvenile migratory fishes. Other documented negative interactions include entanglement of wild fish (Huntington et al. 2006) and exposure to antibiotics and other chemicals (Fortt and Buschmann 2007, for example). The potential for wild fish to consume medicated feed and then be captured for human consumption, and the possibility of disease transfer from farmed fish (Braaten 2007) may also be important issues to consider.

Fish Community Effects

The effect to fish communities has been investigated at larger scales. Machias et al. (2004) studied the species composition of demersal fish assemblages in the Aegean Sea prior to and 12 years after the deployment of commercial fish cages. Fish abundance increased by a factor of four within the bay, the number of species caught increased from 37 to 42 and the trophic level value increased from 3.59 to 3.79 after the onset of marine cage culture. Traditional diversity indices showed that despite some differences in species composition, the overall fish community structure after the establishment of fish farming was not phylogenetically impoverished. The average lengths and weights of several fish species were also compared and fish were found to be either similar in size or larger after the farm was established. The results were thought to reflect an overall benefit to the local fish community at a regional scale, most likely due to nutrient driven increases in primary production. In another study, Machias et al. (2005) conducted trawls near (within three nautical miles) and far from (> 20 nautical miles) Greek fish farms. They found that the abundance and biomass of wild fish was greatest close to the fish farms compared to nearby reference sites without cages and at the distant sites. Although seasonal and substrate differences in fish abundance were evident, the Shannon-Wiener diversity indices showed no deleterious effect due to fish farms. Increased abundance of several important commercial fish species was also documented. These observations were bolstered by an analysis of the relationships between 18 years of data fish farming activity and fish landings (Machias et al. 2006) throughout Greece. The researchers found no negative correlations between farming activity and fisheries landings, and there were strong indications of increased fisheries production in areas with farms (presumably as a result of nutrient discharge).

The secondary role of fish cages as FADs, especially near reef habitat and in the open ocean, warrants further research (Holmer 2010) and keeping track of wild fish aggregates at open ocean cage facilities is recommended as part of standard environmental impact monitoring procedures (Lee and O'Bryen 2007, Holmer et al. 2008). Dempster et al. (2006) point out that the unintentional role of sea cages as FADs may have significant conservation impact to marine fisheries and they encourage banning commercial and recreational fishing activities around farms and the designation of these areas as Marine Protected Areas. A similar recommendation was made by researchers in Turkey (Akyol and Ertosluk 2010) as a result of their study of fish farmers who set traps near fish cages. This lucrative, but illegal, harvest of aggregating fish has been the basis of conflict with local artisanal fishers who are not allowed to fish near the cages.

Sharks

There is little published information about the interactions of sharks and marine cage farms, but they have been documented as being attracted to fish cages in the Pacific Northwest (Nash et al. 2005), Puerto Rico (Alston et al. 2005), The Bahamas (Benetti et al. 2005), Latin America (Rojas and Wadsworth 2007) and Australia (Australian Government 2009). Because sharks pose a threat to the stocked fish and potentially divers, dangerous species may be destroyed. In Australia, an estimated 20 great white sharks a year are killed at marine aquaculture farms (Australian Government 2009). Siting of a salmon farm off South Africa within an ecologically significant great white shark congregation area and eco-tourist destination elicited major negative public response (Scholl and Pade 2005) and the farm was later closed. A recent telemetry study of sand and tiger sharks near fish cages off Hawaii found that sharks did aggregate near the cages with some individuals being recorded for the entire term of the 2.5 year study (Papastimatiou et al. 2010). These animals were considered to pose minimal threat to humans. The economic and ecological potential risk of large scale fish releases due to sharks tearing nets may be a concern as the industry moves into offshore sites (Holmer 2010) depending on the types of nets and locations used.

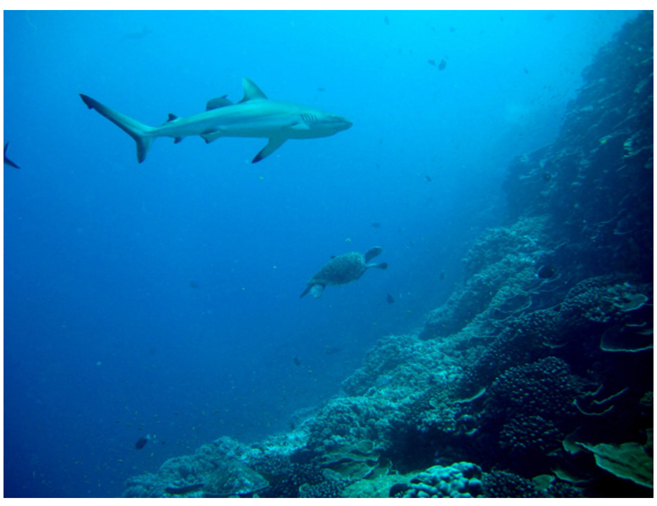


Photo courtesy of NOAA.

Deterring shark predation at marine cage sites can likely be accomplished by the use of tear-resistant nets. Sharks guards are small rigid mesh nets installed at the bottom of a fish cage to prevent sharks from damaging nets while attempting to feed on dead fish that have fallen to the bottom (Jamieson and Olesiuk 2002). Good husbandry practices such as removing sick or dead fish promptly from cages is also an effective predator deterrent. Given the recent global interest in shark population declines and the need to implement conservation efforts, the potential impacts of marine cage culture to sharks is likely a fruitful area for research.

Marine Mammals

The interactions of marine mammals with marine fish cages and efforts to minimize potential problems are recognized, but there is little recent published, peer-reviewed literature that specifically addresses the issue. Marine mammals such as seals, sea lions, cetaceans and otters at fish cages can represent a threat to cultured fish of direct predation, injury, stress mediated increased susceptibility to disease, decreased growth due to stress, and escapement loss through torn nets (Nash et al. 2000, Jamieson and Olesiuk 2002, Würsig and Gailey 2002, Rojas and Wadsworth 2007, Belle and Nash 2008). Reciprocally, marine aquaculture operations may displace marine mammals from their foraging habitats (Markowitz et al. 2004, Cañadas and Hammond 2008) or cause other disruptions to their behavior (Early 2001). Entanglement in nets or lines around fish farms may cause injury, stress or death to marine mammals.

Nash et al. (2000) provide a summary of information to assess the risk associated with aquaculture and marine mammal interactions in the Pacific Northwest salmon industry. Loss due to direct predation, fish injury or stress and escapement can account for losses of up to 10% in terms of fish and represents significant financial loss. Pinniped attacks on cage divers have also been reported. The authors conclude that physical barriers including rigid netting around cages are the best management options to decrease harm along with siting of cages offshore far away from haul out sites and rookeries.

A report by Jamieson and Olesiuk (2002) provides a thorough review of pinniped interactions with salmon farms in Canada, the financial impacts to the industry, methods for non-lethal intervention and the ecological implications of lethal deterrents to the seal and sea lion populations. The authors summarize estimates from the 1980-90s for damages caused by pinnipeds at salmon farms around the world. Losses range from a few thousand fish up to 10% of the stocked fish. Damages may be only a few thousand dollars for an individual farm, but can total millions of dollars for a single country in a year. The growth of the fish farming industry and concomitant expansion of pinniped populations has tended to increase the number of interactions, but lethal control methods are less viable than previously due to ecosystem conservation objectives and regulatory protection. Typically, only single individuals may be killed and only after multiple forays into the farm with repeated attempts to deter the animal. They note that the U.S. has even stricter regulations with respect to lethal removal. Nonlethal interventions include harassment by boat or with noise (such as underwater seal firecrackers), aversive conditioning, predator (killer whales) models or sounds, and the use of acoustic devices and relocation. Often, harassment techniques are effective in the short term, but may be less efficacious over time as animals become habituated. Acoustic deterrent devices (ADD and AHDs) are designed to cause auditory discomfort to pinnipeds by emitting sound underwater at a range of frequencies. However, these devices have also been shown to deleteriously impact non-target marine mammals.

Würsig and Gailey (2002) provide useful information on the conflicts between aquaculture and marine mammals and potential resolutions. They report on the damage and financial loss that marine mammals, especially pinnipeds, may inflict on commercial fish farms. The need for non-lethal management options to reduce conflicts is recognized, with the goal of decreasing impacts to non-target animals and preventing the killing, both licensed and illegal, of pinnipeds. Six options for reducing marine mammal impacts are discussed: harassment, aversive condition, exclusion, non-lethal removal, lethal removal and population control. Harassment by chasing, explosives, and ADDs has been found to be only somewhat effective and generally only in the short term until animals become habituated. In fact it is possible that over time noise harassment devices may actually become attractants to habituated individuals who come to recognize the sound as an unpleasant dinner bell. Predator models and sound devices (imitating killer whales for example) are also not very effective.

Good husbandry practices such as removing sick or dead fish promptly from cages is also an effective predator deterrent.

The dangers that these harassment techniques pose toward target and non-target marine life are discussed. Aversive conditioning refers to feeding with poisoned (with lithium chloride for example), but not deadly, bait to sicken the offending animals. This has also proved to be only ephemerally useful. Non-lethal capture and relocation of problematic individual animals is feasible, but very expensive, time-consuming and minimally effective. Relocated animals often return quickly to the farm area. Lethal removal and large scale population control (or culling) are generally not very effective, popular or legal options. Removing problem animals may help in some instances where an individual is causing damage, but typically more animals will just move in.

Photo courtesy of NOAA.

Furthermore, there is a segment of the public which opposes the killing of marine mammals, especially for private gain. Likewise, large-scale population control methods like culling are unlikely to be supported. Wursig and Gailey (2002) conclude that exclusion is the most effective measure. Also, siting is noted as being an important tool. For example, farms located distantly (> 20 km) from haul out sites tend to have fewer interactions with pinnipeds.

Research results support the views and conclusions in the foregoing three review papers. At 11 out of 25 sea bass and sea bream fish farms surveyed in the Turkish Aegean, individual monk seals were documented taking fish and damaging nets, mostly at nighttime feedings during the winter months (Guecluesoy and Savas 2003). A range of non-lethal deterrents was ineffective and only the installation of anti-predator nets was successful in avoiding fish losses. Aerial and ship surveys conducted in New Brunswick by Jacobs and Terhune (2000) suggested that harbor seals do not congregate in salmon farming areas, but nor do the farms seem to disrupt the mammals normal movement patterns. A later study by Terhune et al. (2002) found that ADDs near aquaculture facilities in the Bay of Fundy did not elicit startle responses, measurable avoidance behavior or changes in haul out behavior in pinnipeds that had been exposed to ADDs for many years. Surveys of salmon farm managers in Scotland (Northridge et al. 2010) indicated that seal predation has declined over the past decade and that less than a quarter of salmon farms reported major problems with seals despite nearly daily siting of seals near farms. Rogue individuals were thought to cause the most damage and individual recognition techniques are being improved as a potential management tool. ADDs were not in use at all farms and they were not thought to be very effective, while farm management strategies including net tensioning, removing mortalities, lower stocking densities and seal blinds at the bottom of the nets deterred predation.

The most damaging marine mammal interactions are with pinnipeds while dolphins, porpoises and whales are viewed as a minor threat to fish cages. Dolphins have been documented feeding on wild fish attracted to marine fish farms off Italy, but were not reported to predate caged fish (Diaz Lopez et al. 2005). In a recent five year study at Italian sea bass, sea bream and meagre cages Díaz López (2012) observed individually identified dolphins to assess patterns of habitat use and farm fidelity. Dolphin occurrence near the farm varied with time of day, season and year. Individual animals fell within four farm fidelity categories: farmers (occurrence rates > 50%; 20% of individuals), and frequent (occurrence rates 0.25-49%; 10% of individuals), occasional (seasonal occurrence rates < 25%, yearly occurrence > 0.25; 20% of individuals) or sporadic visitors (occurrence rates < 25%; 50% of individuals). Dolphins near farms were typically foraging on wild fish concentrated in the farm, but also fed on discarded or escaping fish during harvesting operations. Annual dolphin mortality was 1.5 per year and five animals were found entangled in nets during the study period. The potential for marine mammals to become entangled and drown in farm structures or lines is a predominant concern because many are protected in the U.S. under the Marine Mammal Protection Act (Würsig and Gailey 2002). From surveys at marine fish farms off Italy, Diaz Lopez and Shirai (2007) estimated one bottlenose dolphin mortality per month due to entanglement with farm nets. This risk can be minimized by siting farms in areas away from known migration routes, using rigid net materials or secondary rigid anti-predator nets, and keeping mooring lines taut. In Scotland detectors were placed at salmon farms and reference sights to monitor porpoise activity and response to ADDs (Northridge et al. 2010). Generally porpoises avoided farm areas when ADDs were turned on but returned quickly when they were deactivated. Some animals were observed foraging near farms with active ADDs, especially in areas where the devices had been deployed for some time.


Photo courtesy of NOAA.

Concerns are raised about the impacts of the noise pollution caused by ADDs to non-target marine mammals which pose no predation threat. For example, in British Columbia, harbor porpoises avoided areas during times when ADDs were activated (Olesiuk et al. 2002). A study in New Zealand (Stone et al. 2000) found that Hector's dolphins, a rare species, avoided acoustic gillnet pingers, suggesting that use of similar devices at salmon farms to deter pinnipeds could also impact non-target mammals. Early (2001) notes that killer whales in British Columbia will avoid marine farm areas where ADDs are in use. This is confirmed by another study in the Broughton Archipelago where killer whales avoided marine areas near salmon farms with ADDs installed to deter pinnipeds (Morton 2002). Following removal of the devices six years after deployment, the whale numbers rose to levels similar to previous levels. Killer whale numbers in a nearby farm area without ADDs remained stable during this same time period. To date, there are no available reports on the impacts of marine fish cage culture to manatees and dugongs, yet potential impacts to these animals should be considered at sites within their habitat range (Würsig and Gailey 2002).

The greatest success in deterring pinniped predation is the use of rigid net materials for fish cages or the installation of rigid exclusionary nets around salmon farms. These may be expensive to install, require follow up maintenance and cleaning and, in the case of secondary nets, may decrease water flow through the fish cage. Exclusion nets must be strong enough to resist chewing or tearing. Lines made of stiff materials will help prevent entanglement. Best management practices to deter predators include siting away from marine mammal aggregations, installing predator nets and other barriers, varying farm routines, using olfactory deterrents, and dogs where appropriate (Belle and Nash 2008), and installing electrical fencing around cage perimeters (Rojas and Wadsworth 2007). In the U.S., marine mammals are protected by either or both the Marine Mammal Protection Act of 1972 or the Endangered Species Act of 1973. Permitting to authorize fish farms in U.S. waters must include impact assessments to evaluate the threat, if any, posed by a marine aquaculture operation. These measures determine the allowable impacts to marine mammals and regulators may impose monitoring requirements or other farm operation and management measures to eliminate or reduce negative interactions.

Sea Birds and Turtles

At marine fish farms, entanglement in the cage nets poses the biggest threat to sea birds, especially those that may dive to feed on fish or fouling organisms (Belle and Nash 2008). Sea birds are reported to congregate near marine fish farms but are typically considered a low risk in terms of predatory threat, though they may scavenge mortalities or pick off fish during transfer or harvest (Pearson and Black 2001, Nash et al. 2005, Huntington et al. 2006, Rensel and Forster 2007). In contrast, the often significant impacts to freshwater aquaculture (Goldburg and Triplett 1997, Belant et al. 2000, Snow et al. 2005) and fisheries (Karpouzi et al. 2007) by piscivorous birds like cormorants and pelicans are better understood.

Permits are available to implement non-lethal predator controls to frighten birds away from cages and, because birds become habituated to noise harassment, farms often use overhead netting or screens to exclude sea birds from cage areas.

Permits are available to implement non-lethal predator controls to frighten birds away from cages and, because birds become habituated to noise harassment, farms often use overhead netting or screens to exclude sea birds from cage areas (Nash 2001, Huntington et al. 2006, Halwart et al. 2007). Siting of fish farms away from important sea bird habitats is encouraged or required in many countries (Bridger and Neal 2004, Borg et al. 2011) to minimize conflicts. Overviews of environmental impacts of marine aquaculture often refer to sea birds as species of concern, but contain few specific examples of measures implemented to aid in sea bird conservation (Halwart et al. 2007, International Union for Conservation of Nature 2007).

Like sea birds, sea turtles are generally perceived as incidental visitors at sea cages and not as predatory threats (Nash et al. 2005, Helsley 2007). Because these animals are protected in the U.S. and elsewhere as threatened or endangered species, potential impacts to sea turtles are an environmental concern associated with marine cage culture (Bridger and Neal 2004, Huntington et al. 2006, International Union for Conservation of Nature 2007, Borg et al. 2011), yet relatively little is known about how sea turtles may be impacted by such facilities. The primary concern with respect to these animals and marine cage culture tends to be the threat to the animals of entanglement with nets, mooring lines or other floating equipment. Management recommendations to reduce negative interactions include the use of rigid netting material for the cage, keeping mooring lines taut and removing any loose lines or floating equipment around the farm. Lines made of stiff materials will help prevent entanglement. Additionally, the proper disposal of all trash will reduce the risk that sea turtles will ingest plastic or other trash associated with farm operations. A recent study investigating hearing capabilities in sea turtles indicates they hear best at frequencies <1,000 Hz (Piniak et al. 2012), which is outside the range typically used for marine mammal ADDs.

Sensitive Habitats

The potential impacts of marine cage culture to sensitive habitats like corals, seagrass beds and mangrove forests are of concern to resource managers and scientists. Because they are nutrient sensitive, siting of fish farms near these habitats may have long-term consequences.

Corals

Eutrophication and sedimentation are known stressors on corals and reef communities, including those in U.S. marine waters (Torres 2001, Smith et al. 2008). There is interest regarding the potential impacts of marine fish farm effluent on sensitive coral reefs (Holmer et al. 2005) and within the last ten years research efforts have been focused upon this issue. A series of reports published in 2003 provided conflicting conclusions about the impacts of sea bream farms on the north shore of the Gulf of Eilat in the Red Sea. Bongiorni et al. (2003a, 2003b) and Rinkevich et al. (2003) presented data suggesting that coral exposed to fish farm effluent showed enhanced growth and reproduction. However, their study design and conclusions were criticized by Loya and Kramarsky-Winter (2003), who presented their own data which indicated the opposite effect – that fish farm effluent had deleterious impacts to coral growth and reproduction. Additional studies seem largely to bear out the latter conclusion. Villanueva et al. (2006) examined the survival, growth, physiology and reproduction of different life stages of reef-building coral in the Philippines. After 81 days of exposure to enriched conditions at a milkfish farm site, the survival, growth rate, photosynthesis to respiration ratio, and larval output were significantly lower than corals at intermediate and reference sites. Kramarsky-Winter et al. (2009) examined 15 cellular markers to assess potential physiological differences in corals and their algal symbionts growing near fish farms (the same Gulf of Eilat site as above) or at reference locations. Their results indicated significant differences in the physiological status between corals at impacted versus control sites for many of the markers tested. Two heat shock proteins (indicators of stress) were elevated in both corals and symbionts at the farm sites; five oxidative stress proteins (important for maintaining oxidation-reduction reactions and cellular signaling) were decreased in corals but increased for symbionts; three metabolic proteins (indicators of metabolic condition) showed varying differences; two cytochrome P450 (metabolic and xenobiotic response proteins) values differed, one being elevated and the other decreased. For stress proteins several of the biomarker showed no site-specific significant differences. These studies indicate that fish farm effluents can affect coral physiology and highlight the need for a better understanding of the effects to coral communities at multiple scales. A study of corals in the Philippines (Garren et al. 2009) revealed that the microbial communities on transplanted corals were altered within five days of exposure to milkfish farm effluents. This included increases of microorganisms pathogenic to coral, as well as humans. After 22 days of exposure, the microbial communities on the corals at effluent exposed sites, intermediate and references sites appeared to be transitioning back to pre-study composition. However, levels of the coral pathogen *Desulfovibrio* remained high at the sites nearest the fish farm. Stable carbon isotope analysis has been used to quantify the effect to coral skeletal growth from

Photo courtesy of NOAA.

long-term exposure to the heightened nutrient loads associated with two decades of mariculture operations (Levy et al. 2010). Corals growing near fish farms showed a growth rate of 9.28 mm/year while samples collected at two sites away from the farms grew at slightly higher rates of 10.28-12.2 mm/year.

The impacts of marine fish farming to sensitive red corraline algae gravel habitats, also known as maerl, are being investigated. Hall-Spencer et al. (2006) documented major effects of Scottish salmon farms on this habitat of high conservation importance. Diver surveys found a build-up of organic waste beneath the farms and out to 100 m. Scavenging fauna increased 10-100 fold and live maerl cover was significantly reduced beneath the cages. The benthic infana community was shifted toward enrichment tolerant species. Similar results have been found at other maerl sites in the Mediterranean (Borg et al. 2011). Maerl (Wilding 2011) and reef (Tett 2008) habitats are sensitive to salmon farming, but additional investigation was recommended.

The European Union made the following recommendations with respect to environmental quality standards regarding corals: deviation from mean ambient nitrogen concentrations should not exceed 5%; deviation from mean ambient phosphorus concentrations should not exceed 5%; no increase in mean ambient levels of suspended solids; changes in salinity levels from seasonal ambient state not to exceed 5 ppt (Huntington et al. 2006). The potential impacts of aquaculture operations to sensitive reefs in U.S. waters has been identified as a concern, especially for nearshore reefs which already experience considerable stress from anthropogenic sources including terrigenous sediments and nutrients (Torres 2001, Smith et al. 2008, Otero 2009), and sewage outfall (Kaczmarsky et al. 2005, Nagelkerken 2006, Sutherland et al. 2011).

Seagrasses

Seagrasses are an important marine habitat and provide a range of ecological services, and are under threat from a variety of anthropogenic influences like sedimentation and nutrient loading (Orth et al. 2006). The effects of marine fish farming on seagrasses have been investigated, notably in the Mediterranean, where seagrasses are considered a sensitive habitat. Seagrass beds are often found in clear water with high rates of advective exchange, which are also good areas for farming fish. Potential negative impacts of fish farms on seagrasses include reduced water clarity due to sedimentation and nutrient loading (Cancemi et al. 2003, Dolenec et al. 2006). Organic loading can result in anaerobic sediment conditions and the accumulation of sulfides in the root zones, both of which may be toxic to the seagrass (Holmer et al. 2003, 2005). Increased primary production in seagrasses may occur at low levels of nutrient input, but a possible secondary increase in herbivore (such as sea urchins) pressure may lead to an overall decrease in seagrass biomass.

Photo courtesy of NOAA.

Changes in the macrofaunal assemblages in seagrass meadows due to fish farm effluent were recently investigated by Terlizzi et al. (2010). Meadows heavily impacted by the study farm saw a shift toward mollusk, gastropod amphipod and polychaete species associated with muddy and high organic content sediment and stressed habitats. A review of impacts to seagrass beds by Pergent-Martini et al. (2006) found that fish farms contributed to a decrease in seagrass meadow surface area and cover, shoot density and size, leaf and rhizome growth and photosynthetic capacity, as well as increases in epiphyte biomass and leaf size. Their recommendations to minimize such impacts include siting at least 200 m away in deep, well-flushed waters and careful monitoring of the community to enable early response. This recommendation is somewhat supported by a recent study which found only minimal community responses in a seagrass meadow to effluent from a large offshore fish farm 3 km away (Ruiz et al. 2010).

The European Union made the following recommendations with respect to environmental quality standards regarding seagrass: no increase in mean seasonal levels of suspended solids; light levels at 2 m depth should not normally fall below 10% of surface incident light; total Kjeldahl N not to exceed 140 µg/L; mean total N not to exceed 500 µg/L (Huntington et al. 2006).

Mangroves

Alongi (2002) summarized the status and threats to mangrove habitats, including aquaculture operations. The harmful effects of marine aquaculture to mangrove habitat are primarily associated with near or onshore operations including pond construction for growing milkfish and shrimp (Barbier 2003). However, this tropical habitat could be impacted by fish net pen operations in shallow coastal waters with onshore currents. For example, a preliminary study at a sea bass farm in Malaysia suggests that nutrient enrichment from farm effluent may affect primary production in mangroves (Alongi et al. 2003), but more research is needed to fully understand the impacts of aquaculture within the larger context of human impacts.

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Photo courtesy of NOAA.

CHEMICALS

Chemicals used at marine cage culture sites may be released into the surrounding environment. Some of these chemicals pose only a short-term hazard because they are relatively benign, are diluted before being released into ocean waters, degrade quickly in water or do not accumulate in sediments. Other chemicals may persist and pose short or long-term risks to marine biodiversity near farms. The potential effects of antibiotics, therapeutants and antifoulants are often identified as being a concern. Antibiotics and therapeutants are administered to recover sick fish. Antibiotic and chemical use has declined in marine aquaculture in many countries and is limited in the U.S. Antifoulants are chemical treatments used on nets and other marine farm equipment to prevent the settling of marine fouling organisms. Heavy metals, especially zinc and copper, may be released from fish farms in feed or antifouling treatments. In this chapter we review current literature addressing the effects that these chemicals may have on the surrounding marine environment.

Antibiotics

The environmental impact of antibiotics used in marine aquaculture has been identified as an area of concern and was addressed in early review documents (Wu 1995, Stickney 2002). More recently the known and potential effects of antibiotics have been considered in summary reports for marine aquaculture globally (Beveridge 2004, Nash et al. 2005, Halwart et al. 2007), in the Pacific Northwest (Nash 2001, Nash and Waknitz 2003), in the Mediterranean (International Council for the Exploration of the Seas 2002, The Mediterranean Science Commission 2007), in Europe (International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Braaten 2007), in the U.S. (Goldburg et al. 2001, Nash 2001, Benbrook 2002, Boyd et al. 2005, Lee and O'Bryen 2007, Pittenger et al. 2007), for Canadian salmon farming (Scott 2004, Phillips 2005), and for salmon farming in general (Burridge 2003, Armstrong et al. 2005).

Antibiotics are administered in medicated feed, by injection or by immersion, with the latter resulting in the largest amounts released into natural waters. Commercial medicated feed is readily available and is commonly used at farms in response to disease outbreaks. However, the amount of antibiotics released depends upon the fish species, amount of feeding activity and absorption in the fish digestive tract. Studies estimate that as much as 75-99% of the antibiotic administered is released into the environment (Goldburg and Triplett 1997, Scott 2004, Armstrong et al. 2005, Pittenger et al. 2007).

The most common antibiotics in use around the world in marine aquaculture operations include oxytetracycline, sulfamerazine, amoxicillin, florfenicol, sulphonamides, quinolones, nitrofurans, and erythromycin (Benbrook 2002, International Council for the Exploration of the Seas 2002, Burridge 2003, Armstrong et al. 2005, Huntington et al. 2006). ICES (2002) summarized which antibiotics are used in the UK, Norway, Ireland and Canada. Burridge (2008) includes a recent list of antibiotics in use in Norway, Chile, the U.K. and Canada. According to the Food and Drug Administration (FDA) website antibiotics are infrequently used in U.S. marine fish farms, in part because only three antibiotics are approved for use in the U.S. according to the—oxytetracycline, florfenicol, and sulfadimethoxine/ormetoprim — and these are only allowed for specific indications in fresh water (www.fda.gov/AnimalVeterinary/DevelopmentApprovalProcess/Aquaculture/default.htm; visited 07 February 2011). Application in marine aquaculture requires extra-label approval by a licensed veterinarian or under an investigational new animal drug (INAD) approval through the FDA, generally with direct oversight by a veterinarian. Benbrook (2002) has compiled a summary of antibiotic drug use in U.S. aquaculture, but this report focuses largely upon catfish production.

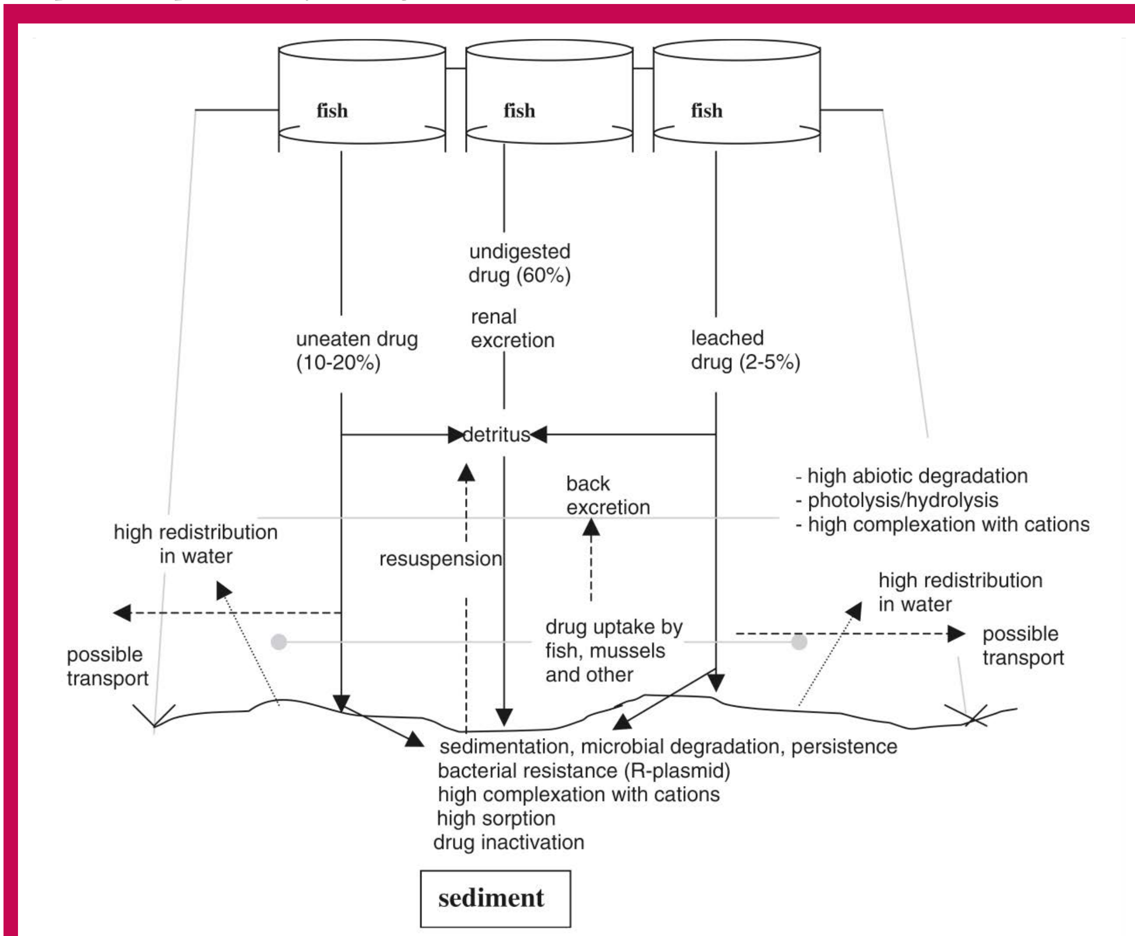
Antibiotics which are administered, but not assimilated by the fish, are released into the environment where they either become dissolved in the water column or settle to the sea floor and accumulate in the sediment.

Antibiotics which are administered, but not assimilated by the fish, are released into the environment where they either become dissolved in the water column or settle to the sea floor and accumulate in the sediment (Capone et al. 1996, Lalumera 2004, Rigos et al. 2004). Some antibiotics have relatively short residence times in marine sediment, while others may remain at measurable levels for longer periods. Laboratory and field studies have found that antibiotic persistence in sediment ranges from a few days to years depending on the drug in question and the geophysical properties (including light level, oxygen levels, pH, temperature, and sediment type) of the water or sediment (Scott 2004, Armstrong et al. 2005, Rigos and Troisi 2005).

Rigos and Troisi (2005) have developed a model to illustrate the transport and environmental fate of orally administered antibiotics (Figure 4) at Mediterranean fish farms. This model is useful for visualizing pathways by which antibiotics may become available for uptake in the water column or sediment, and how they may impact marine food webs. The authors review environmental concerns about the potential impacts from antibiotics released from cage aquaculture including the emergence of resistant bacteria, impacts to marine biodiversity and risks to human health.

Exposure to antibiotics in the environment allows bacteria to adapt and become resistant to them (Kummerer 2004). This is true for both the targeted disease pathogens and for other microbes occurring naturally in the ecosystem. Both have been affected

Figure 4. The transport and environmental fate of orally administered antibiotics. Copied with permission from Rigos and Troisi (2005).



by exposure to antibiotics. The occurrence of resistant strains of fish pathogens has been reported in Spain (Zorrilla 2003), Washington state (Nash 2001), Finland and Chile (as cited in Armstrong et al. 2005), and Denmark (Schmidt et al. 2000, Bruun et al. 2003). Questions remain about the relative risk posed to the marine ecosystem by antibiotic use at marine fish farms due to the relatively low doses that may actually be entering the ecosystem, the high solubility and short half-life of many antibiotics, and uncertainty about the level of selective pressure that is exerted on target pathogens or non-target resident microbes (Alday et al. 2006).

Non-target sedimentary microbes may be exposed to antibiotics released from marine farms, raising concerns about the impacts to benthic microbial biodiversity (Burridge 2003). Chelossi et al. (2003) found a higher fraction of antibiotic resistant bacteria isolated from sediments beneath Mediterranean fish farms than from control sites. Similarly, microcosm studies conducted by Kerry et al. (1996) found that oxytetracyline-resistant bacterial colonies were present in 6-90% of replicates depending upon dosage. Review papers by Armstrong et al. (2005) and Scott (2004) reference numerous studies in Canada, Chile, Denmark, Asia, Norway, and the U.S., which report antibiotic resistance in bacteria from sediments underneath freshwater and marine fish farms. The authors suggest that the antibiotics released may create sedimentary reservoirs for resistant bacteria.

The toxicity of antibiotics to marine plants is a concern as they are known to be toxic to some phytoplankton (Halling-Sorensen et al. 1998). For example, when Oh et al. (2005) tested the effects of six antibiotics commonly used in finfish aquaculture on seaweed, they found a dose-dependent decrease in photosynthetic efficiency and ammonium uptake.

Antibiotics thought to originate from marine aquaculture operations have been isolated in wild fauna collected near farm sites (Beveridge 2004). Capone et al. (1996) found oxytetracycline in Dungeness and red rock crabs collected near salmon farms in Puget Sound during and up to 12 days after treatment, but samples collected 41 and 75 days after treatment showed only trace residues. Migliore et al. (1997) compared the toxicity of five antibiotics to *Artemia* nauplii. Mortality rates ranged from 0–100 % depending upon exposure time and dose. The most toxic antibiotic, bacitracin, was found to significantly decrease hatching rates, and flumequine altered nauplii pigmentation. Additional studies in the field would be useful to determine if antibiotic exposure doses that might be measured at a fish farm are sufficient to cause ecological effects.

In general, improved husbandry in marine cage culture over the last 10-20 years has resulted in a tremendous decline in the use of antibiotics.

Studies have found antibiotics present in wild fish feeding on feces and food originating from marine farms (Fortt and Buschmann 2007). This may serve as a pathway for development of antibacterial resistance within wild populations (Rigos et al. 2004). Armstrong et al. (2005) and Scott (2004) document the accumulation of antibiotics in marine fish and invertebrates near farms, but these were studies conducted during years of higher antibiotic use. In their assessment of the environmental impacts of antibiotics to the Mediterranean, Rigos and Troisi (2005) reviewed a range of potential impacts of antibiotic exposure to marine biodiversity, but state that there is a need for studies that directly address the levels of and environmental impacts of antibiotics under sea cages. Burridge et al. (2008) suggest that continued research into the accumulation of antibiotics from fish farms to the flesh of other organisms, including humans, is needed. To protect human health, most governments require a withdrawal period of days to months before fish treated with antibiotics may be harvested (Burridge 2003). He also notes that aquaculture workers may be exposed to antibiotics in the dust aerosols associated with feed production and distribution.

In general, improved husbandry in marine cage culture over the last 10-20 years has resulted in a tremendous decline in the use of antibiotics in Scandinavia, Canada, the U.S. and Europe (International Council for the Exploration of the Seas 2002, Cardia and Lovatelli 2007, Pittenger et al. 2007, Holmer et al. 2008). For example, data from Norway (Tveterås 2002) and British Columbia, are representative of the general decline in antibiotic use in the marine aquaculture industry since the 1980s (Figure 5). Nash (2001) concludes that antibiotics used in marine aquaculture are safe and effective, stating that over 40 years of salmon culture in the Pacific Northwest has not resulted in adverse impacts to wild salmon. Phillips (2005) also suggests there is little risk to native salmon from antibiotic use in the Puget Sound. In other countries, however, considerable concern remains about the levels of antibiotics used in marine aquaculture (Cardia and Lovatelli 2007, Fortt and Buschmann 2007).

Recent interest in the use of probiotics to promote fish health and decrease the need for antibiotics has opened a new avenue for immunological and husbandry research. Probiotics are nutritional supplements generally comprising yeast, algae and bacteria thought to be beneficial for health, growth, immunocompetence and survival (Das et al. 2008). Early studies have resulted in promising results for cultured species (Aguilar-Macías et al.

2010, Dharmaraj and Kandasamy 2010). Probiotics have been in use in China since the 1980's (Qi et al. 2009) and are being investigated for use in U.S. aquaculture as well.

While some research to understand the effects of antibiotics used in marine finfish culture has been conducted, there are many unanswered questions. For example, additional research to investigate the role of the sediment beneath farms as a reservoir for resistant bacterial or the development of resistant strains of infectious diseases is warranted. Because antibiotics may persist in the marine environment, questions remain about the long-term impacts to biodiversity, ecosystem function and human health. Although their use in marine fish farming is limited in the U.S. (e.g., no antibiotics have been applied at Maine salmon farms in the last 6+ years, Jon Lewis, personal communication), and the environmental impacts of antibiotics may be minimized at coastal and offshore sites through dilution (Goldburg et al. 2001, Holmer 2010), it will continue to be important to consider the ecological effects that antibiotics can have in the marine environment. An Integrated Pest Management approach, which decreases stress to the fish, employs stocking densities to keep fish healthy and uses preventative vaccination, is used to maintain fish health while minimizing or eliminating the use of antibiotic drugs.

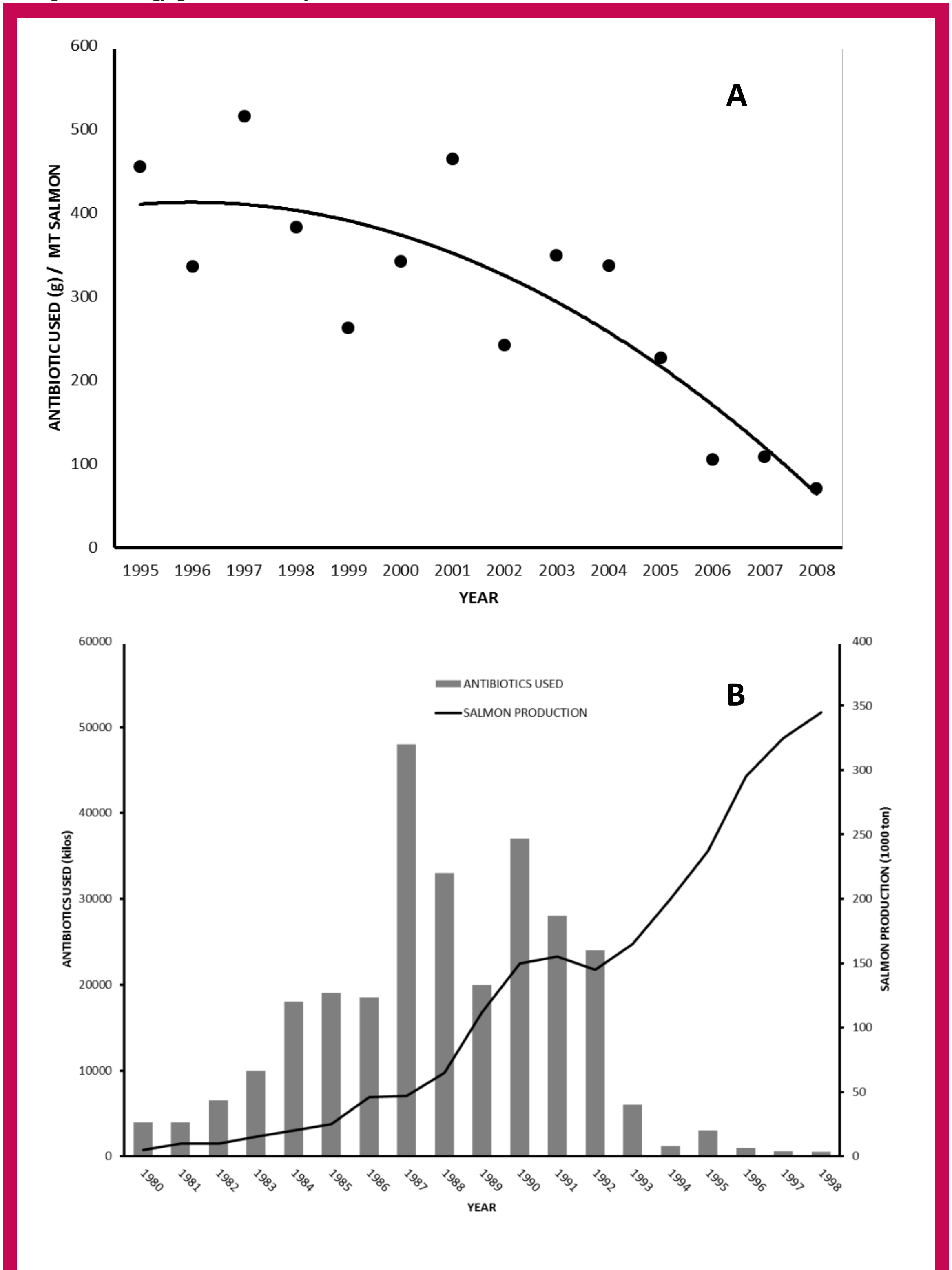
Photo courtesy of NOAA.

Therapeutants

The environmental effects of therapeutic chemicals used in marine finfish aquaculture are consistently identified worldwide as a concern (Cardia and Lovatelli 2007, Pittenger et al. 2007). Therapeutants are used to treat parasitic, viral, fungal and bacterial infections and to treat aquaculture facilities for disease causing agents. These drugs may be administered in medicated feed or by immersing the fish. Therapeutants are released into the environment from uneaten food, the feces if not absorbed in the gut, or direct release into the water. Therapeutants may be present in the water column or may accumulate in the sediment below cages. Assessments of the therapeutants being used in aquaculture have been conducted in the U.S. (Nash 2001, Phillips 2005), Scotland (Black et al. 2002), Canada (Burridge 2003, Scott 2004, Burridge et al. 2008), Europe (International Council for the Exploration of the Seas 2002, Huntington et al. 2006, Burridge et al. 2010), Asia (Graslund and Bengtsson 2001), the Mediterranean (The Mediterranean Science Commission 2007) and by the United Nations (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection 1997, Cardia and Lovatelli 2007). These reports review known and potential environmental impacts of therapeutants to the environment in order to promote their safe and effective use. In the U.S., the FDA maintains the list of therapeutants approved for use in aquaculture, which is currently limited to hydrogen peroxide (applied as an extra label use with veterinarian approval) and formalin (which is not currently used in marine fish farming operations) (www.fda.gov/AnimalVeterinary/DevelopmentApprovalProcess/Aquaculture/default.htm; visited 14 February 2011).

Therapeutants pose several environmental risks including the evolution of resistant strains of pathogenic organisms, nonlethal toxicity, direct

Figure 5. *Antibiotic use in salmon aquaculture.*
(A) Adapted from graph on the British Columbia Ministry of Agriculture webpage (http://www.agf.gov.bc.ca/ahc/fish_health/antibiotics.htm; visited



mortality, and bioaccumulation in the food chain. Summary reports by Hallig-Sorensen et al. (1998) and GESAMP (1997) provide earlier compilations of research done on the environmental effects of therapeutants, documenting acute and sublethal impacts of drugs to non-target organisms in the marine environment. Hallig-Sorensen et al. addresses a very wide range of pharmaceuticals that are present in terrestrial and aquatic environments, but with no focus upon aquaculture. However, many of the compounds covered are used in fish farming. The GESAMP report is specifically geared toward chemicals used in coastal aquaculture. While much has been added to the body of knowledge since its publication, this report remains a valuable source of information.


Photo courtesy of NOAA.

More recently, summaries have been prepared by Gräslund and Bengtsson (2001) for shrimp aquaculture in Asia, by Burridge (2003) for Canadian marine finfish aquaculture, by Scott (2004) for Canadian freshwater aquaculture, by Haya et al. (2005) for sea lice therapeutants, and by Burridge et al. (2008) for chemicals used in salmon aquaculture. Collectively, these reports review a wide range of chemicals used topically or in feed at aquaculture operations around the world. They address the applications of therapeutants, the dosages used, and known or potential effects these chemicals have on plants and animals in the aquatic environment. Most of the effects that are documented in these reports are LC_{50} values from laboratory toxicity trials. Less information is available about sublethal impacts or cumulative impacts resulting from accumulation of therapeutants in marine sediments.

Persistence of therapeutants in the environment is highly variable. Half-lives in the water column may be only a few hours. In sediments, however, therapeutants may accumulate and remain high for months after application (Telfer et al. 2006) and it is the effects of residual therapeutants in sediments that are generally believed to pose the greatest environmental risk (Black et al. 2002, Huntington et al. 2006, Burridge et al. 2008).

Some of the most common therapeutants in use in North America and Europe are insecticides including pyrethroids, emamectin benzoate, teflubenzuron, ivermectin. In the U.S. only emamectin benzoate is approved for limited use under an INAD and is typically administered using a well boat to avoid dumping the treatment bath at sea. Therapeutants are administered either by immersion or in medicated feed, and are often used to treat sea lice and other external parasites. The insecticides can have toxic effects on molting marine organisms like crustaceans, amphipods and zooplankton (Grant and Briggs 1998, Beveridge 2004, Tett 2008), including commercially important species such as crabs, lobsters and shrimp which may reside or forage in sediments near fish farms (Haya et al. 2001).

In addition to direct mortality in crustaceans, insecticides are found to inhibit chitin production, induce behavioral changes, affect swimming ability, decrease spawning, cause premature molting (Burridge 2003, Haya et al. 2005) and changes in enzyme activity (Gowland et al. 2002). Field and laboratory studies reporting little or no effects of insecticide treatment on non-target organisms are also reported (Graslund and Bengtsson 2001, Burridge 2003, Haya et al. 2005). For example, a study in Scotland determined that the sea lice medicines cypermethrin, hydrogen peroxide, azamethiphos and emamectin benzoate had no measurable impact to phytoplankton, zooplankton, benthic macrofauna or barnacle settling rates near four active salmon farm sites (Black et al. 2005). Copepod and nematode communities were negatively impacted by sea lice treatments at one site, though these changes were also related to an organic enrichment gradient. The cypermethrin and emamectin benzoate concentrations were elevated around the cages when treatments occurred, yet these levels were generally lower than what laboratory studies found to be toxic to copepods (Willis et al. 2005).

Currently, hydrogen peroxide can be used as a parasite treatment in aquaculture in the U.S. Hydrogen peroxide is commonly used as an immersion treatment for sea lice and other external parasites, bacteria and fungi. Because it dissolves quickly in water, this chemical is perceived to pose very little environmental risk (Haya et al. 2005, Schmidt et al. 2006, Yanong 2008). Hydrogen peroxide was found to have no significant side effects on walleye blood chemistry (Tort et al. 2003) suggesting that it may pose low risk to non-target fishes that may be exposed in treated water released into the ocean. Mansell et al. (2005) measured acute secondary hematological effects of hydrogen peroxide to infected cultured fish (kingfish), but concluded they were outweighed by overall health benefits to the fish. The use of cleaner fish like wrasse is suggested as an ecological alternative to hydrogen peroxide for the treatment of external parasites (Costello et al. 2001).

The use of cleaner fish like wrasse is suggested as an ecological alternative to hydrogen peroxide f or the treatment of external parasites.

Formalin, the other therapeutant approved for use in the U.S., is used as a fungicide and to control ectoparasites (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection 1997) and as a disinfectant (Burridge et al. 2008). Acute toxicity trials of formalin have been conducted for fish (Graslund and Bengtsson 2001, Scott 2004), but sublethal effects in marine organisms are not well studied. In the U.S., formalin is not specifically approved for use in the marine environment and is not applied in open ocean fish farms.

Many types of chemicals are used in aquaculture facilities as disinfectants for pens, facilities and gear including iodophores, chlorine derivatives, benzalkonium chloride, malachite green (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection 1997, Burridge 2003, Burridge et al. 2008). Most of these are not approved for use in U.S. marine fish farms by the EPA. Acute toxicity trials have been conducted for some of these chemicals, and they are recognized as environmental toxins, but little is known about their potential impacts in the marine environment (Burridge 2003). These chemicals are used effectively to control a wide range of unwanted or harmful organisms in aquaculture facilities, and it is their non-specific toxicity which poses a threat to non-target marine organisms. Persistence in marine sediments needs to be evaluated as degradation of these compounds is highly variable and dependent upon environmental factors like temperature, pH, the level of dissolved oxygen, light intensity and the presence of micro-organisms (Graslund and Bengtsson 2001).

Because improvements in fish husbandry have decreased the use of therapeutants and the few therapeutants approved for use in the U.S. are considered to be relatively non-toxic in the marine environment, some believe that these chemicals pose low risk to the environment (Nash 2001, Fairgrieve and Rust 2003, Nash 2003). More research is needed to understand cumulative, long-term and sublethal effects that therapeutants may have in the marine environment. Environmental risk should be evaluated for each chemical and take into consideration site characteristics like flushing rate and sediment type. Costello et al. (2001) provide a list of best practice recommendations to guide the use of chemicals in the environment. The illegal application of non-approved therapeutants, the misuse of approved drugs or the use of INADs are avenues by which additional drugs may be introduced to the environment (Love et al. 2011, Ocean Conservancy 2011).

Antifoulants

Antifoulants are used to control or eliminate the growth of marine organisms which attach to aquaculture cages, ropes, and structures. Heavy and persistent biofouling impedes water flow through cages, increases biological oxygen demand in cages, causes net drag and can shorten the useful life of nets and ropes (Swift et al. 2006, Braithwaite et al. 2007, Belle and Nash 2008, Burridge et al. 2010). Chemical antifouling treatments on nets and other farm structures are effective at reducing biofouling because their toxicity to many marine attaching organisms prevents settlement of larvae on nets and equipment. For this same reason, their toxic effects on other organisms in the water and sediments around fish farms are a concern (Wu 1995, Burridge 2003, International Union for Conservation of Nature 2007, Tett 2008, Burridge et al. 2010).

Photo courtesy of Snapper Farm, Inc.

In the past, tin compounds (e.g., tributyltin) were used in antifouling treatments, but were banned in many countries for use in aquaculture because of their harmful environmental effects (Davies et al. 1988, Minchin et al. 1996, Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection 1997, Kan-atireklap et al. 1997, Minchin et al. 1997, Nash 2001). Tin compounds are currently not in use on fish farms in the U.S., Canada, much of Europe and other countries. However, tin is still used for other marine applications — in antifouling paint for boats, for example. The accumulation of anthropogenic tin in coastal waters (Sudaryanto et al. 2002, Ščančar et al. 2006) and its toxic effects continue to be documented for marine life including mollusks (Meng et al. 2005) and fish (Dimitriou et al. 2003). Elevated tin levels were found in some marine aquaculture products in Japan six years after the use of tin was banned (Ueno et al. 1999) and in pearl culture areas following reported illegal use of tin compounds (Ramaswamy et al. 2004).

Currently, copper-based antifoulants are the most common and effective chemical net treatments in use worldwide (Burridge 2003, Braithwaite et al. 2007, Guenther et al. 2009). Burridge et al. (2010) provide a thorough overview of the effectiveness and biological impacts of copper used in aquaculture. They report copper has been found to leach out of nets and accumulate to levels above regulatory water quality guidelines in sediments below fish farms in Canada and Scotland. Copper tends to bind strongly with sediments, so its bioavailability and long-term toxicity warrant further investigation. Two reviewed studies found that tissue from fish inside copper-treated net pens did not show copper accumulation. Likewise, Solberg et al. (2002) detected no differences in copper levels in muscle and liver tissue in both farmed salmon or wild fish collected at farm sites using copper net treatments versus a reference farm that did not use copper.

Burridge et al. (2010) provides a general summary of copper's toxicity to marine organisms and documents lethal and sublethal effects to phytoplankton, bacteria, crustaceans, crabs, mollusks and fish. With respect to research conducted specifically at fish farming sites, Chou et al. (2002a) found that lobsters collected near aquaculture sites had elevated copper levels in their digestive glands. Similarly, Chou et al. (2003) found elevated copper levels in sea urchins collected within 75 m of salmon aquaculture sites. Additional reviews summarizing the use and toxic effects of copper in aquaculture are available (Graslund and Bengtsson 2001, Burridge 2003, Burridge et al. 2008).

Little research has assessed the persistence of copper in sediments near marine fish cages and its accumulation in benthic marine organisms. In a study to predict benthic recovery at farm sites in New Zealand, Morrisey et al. (2000) suggest that accumulation of copper and other metals in the sediments may impair recolonization of benthic organisms. Nash et al. (2005) conclude that best management practices to reduce copper contamination has greatly reduced risk to the marine environment around fish cages, and that copper is limited to non-toxic levels when combined with sulfides in organic sediments. Rensel and Forster (2007) report no measurable copper increase has been found in sediments monitored at net pen sites in Puget Sound. The IUCN (2007) reports that current environmental effects of antifoulants are less than in the past.

Work is underway to develop and implement alternative chemicals and methods to reduce biofouling at marine fish farms. For example, the pan-European Collective Research on Aquaculture Biofouling project (CRAB, www.crabproject.com) is working to develop and implement effective strategies to manage biofouling. CRAB estimates that more effective control of fouling will result in saving of 5-10% of the market value in European aquaculture (Willemsen 2005). Nets may be air dried to kill biofouling organisms by lifting the top area above the water line, or manually cleaned (preferably on land to eliminate bioloading to the sediment) using high pressure spray or scraping to remove encrusted organisms (Belle and Nash 2008). Air drying of nets is phasing out the use of copper in antifouling agents (Braaten 2007, Holmer et al. 2008). Other, less toxic chemicals like acetic acid (Forrest et al. 2007) are being investigated as

Air drying of nets is phasing out the use of copper in antifouling agents.

immersion treatments. The use of non-toxic biofilms as alternative net coatings is also being researched (Bazes et al. 2006, Sarà 2007). Biofilms can be derived from marine organisms including plants, bacteria and sponges that naturally repel the larvae of sessile marine organisms (Qian et al. 2007). This technology is still in its early stages, but may yield promising results in the development of less or non-toxic antifoulants. Using grazing animals or mechanical robots inside fish cages to remove attaching organisms have also been proposed as alternatives to copper treatment (Willemsen 2005, International Union for Conservation of Nature 2007). Sala and Luchetti (2008) describe a low cost, effective Wave Brush ® prototype that prevented biofouling in oyster farms and which may be adapted to other aquaculture operations. One study (Lander et al. 2009) has reported positive results of recycling the mussel encrusted nets from fish farming for spat collection in integrated multi-trophic aquaculture (IMTA).

Heavy Metals

Heavy metals are present in trace amounts as nutrients in feed used at marine fish farms and over time may accumulate in benthic sediments beneath cages. Both direct toxicity of heavy metals and accumulation in the benthic food chain have been identified as potential environmental impacts of marine aquaculture in the U.S. (Goldburg and Triplett 1997, Pittenger et al. 2007), Canada (Johannessen et al. 2007), Chile (Buschmann et al. 2009), the European Union (Black et al. 2002, Huntington et al. 2006), the Mediterranean (International Union for Conservation of Nature 2007, The Mediterranean Science Commission 2007), Australia (Cole 2002) and globally (Cardia and Lovatelli 2007, Burridge et al. 2010). Much research has been done in the last ten years to measure the release, accumulation and persistence of heavy metals at marine fish farms.

In the U.S., the accumulation of heavy metals such as zinc and copper (also see antifoulants section) was identified as an issue of concern in salmon net pen farming (Nash 2001). However, reduction in the bioavailability of metals due to soil geochemistry and improvements in feed formulation were identified as factors which could decrease environmental risk. Zinc does not tend to accumulate readily in muscle tissue and therefore the risk to humans is thought to be low (Nash et al. 2005). Nash (2003) states that in long-term studies background levels of metals are achieved after fallowing, but no specific work was cited. Phillips (2005) compiled a summary of recent contaminant research on farmed salmon and other fish. The potential effects of these contaminants – including metals, PCBs, organochlorine and dioxin – range from negligible to very serious.

Many heavy metal studies have been conducted in the last ten years at Canadian farm sites providing valuable insight for potential U.S. farm operations (Scott 2004). Copper (up to 55 µg/g compared to 13 µg/g) and zinc (253 µg/g compared to 49 µg/g) levels were elevated beneath salmon cages at 14 sites in New Brunswick compared to reference stations, but iron and manganese were not (Chou et al. 2002b). There was a decreasing trend of copper and zinc enrichment 50 m from the cages, with anoxic sediments showing the highest levels of accumulation. In this same study, wild lobsters *Homarus americanus* were captured around farm sites. Although copper levels were higher at one heavily farmed site, all tissue concentrations were comparable to other North American lobsters. These same results were used in a later paper (Chou et al. 2004) to develop regression models for understanding sediment dynamics for environmental monitoring. In their study of sea urchin tissue collected under and up to 100 m from salmon aquaculture cage sites, Chou et al. (2003) found that at normoxic sampling sites the tissue levels of copper, zinc, iron, manganese and cadmium levels were comparable to reference locations. At hypoxic and anoxic sites, varying elevations of heavy

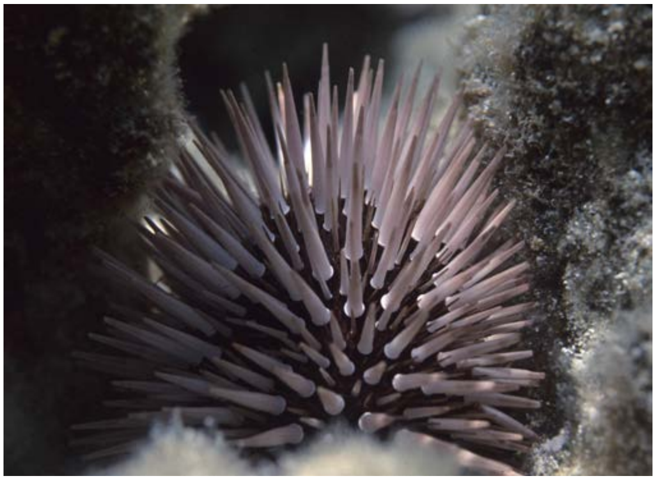


Photo courtesy of NOAA.

metals in the urchins were correlated with body size and distance from the cage site. Sampling at a salmon farm in British Columbia over a fallowing cycle found that elevated zinc sediment levels (up to 200 µg/g) returned to background concentrations within six months (Brooks et al. 2003), but never exceeded the apparent effects threshold of 260 µg/g. In British Columbia, sampling along a single transect (0-300 m from a salmon farm) found some zinc and copper levels above the sediment quality guidelines, but this was not the case for iron, aluminum and manganese (Schendel et al. 2004). A sediment geochronology study in the Bay of Fundy showed elevated levels of copper and zinc in cores taken in an area with 20 years of salmon farming (Smith et al. 2005). Enrichment was highest in the immediate vicinity of cage sites, with decreasing levels out to 200 m. Even five years after cage removal, copper and zinc levels remained high indicating that bioremediation of these metals may be slow. Zinc concentrations were higher at 16 out of 22 sampling stations near fish farms in British Columbia compared to reference sites (Sutherland et al. 2007). Copper was also increased at near field (0-30 m) sites, especially in fine-grained sediments. This study's objective was to determine if metals like copper and zinc could be used as waste tracer elements to differentiate between natural and anthropogenic sources of contamination at larger scales. Yeats et al. (2005) similarly found that zinc and copper could be used in sediment analysis to identify waste directly linked to aquaculture cage sites.

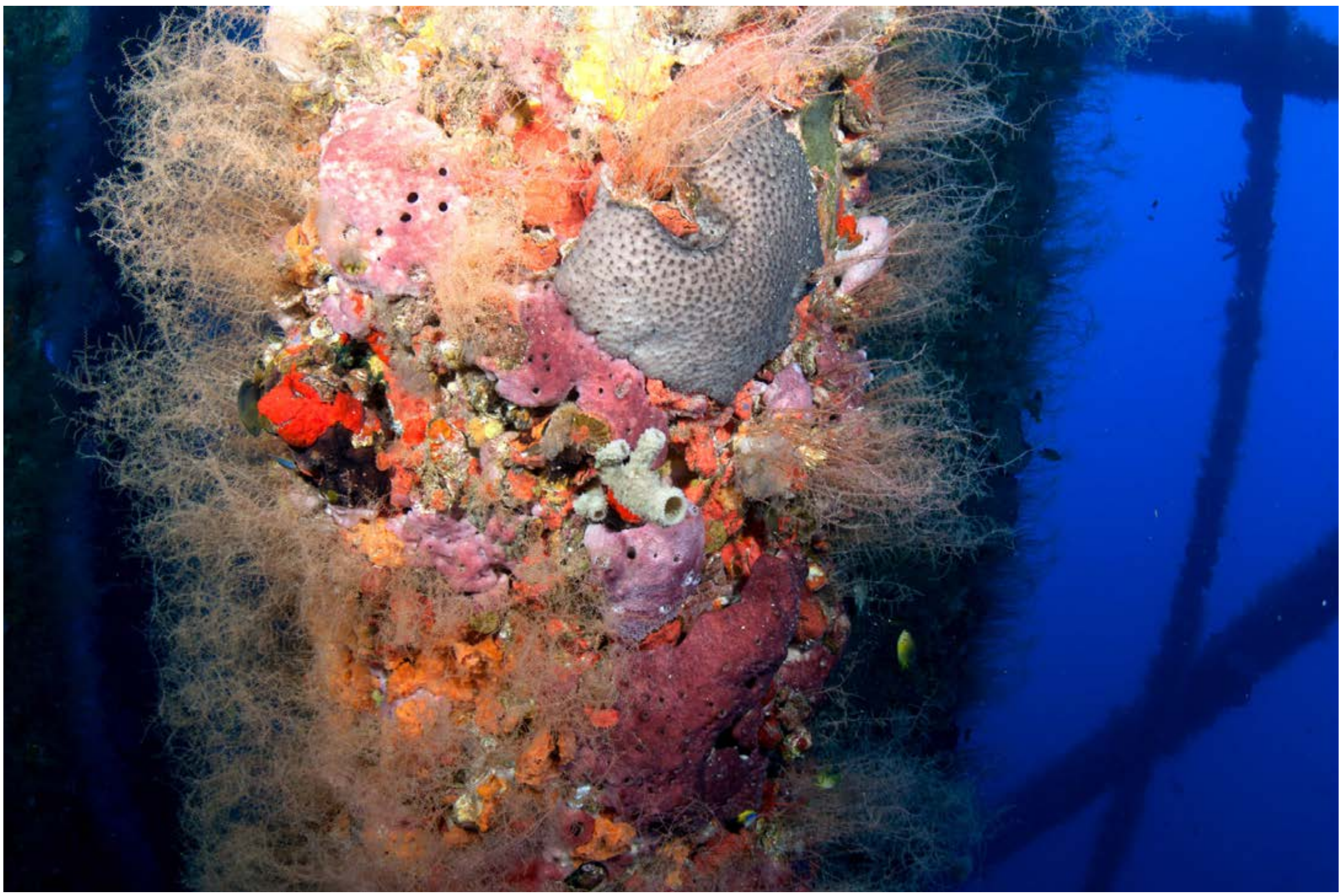


Photo courtesy of Randy Cates.

Burridge et al. (2010 and references therein) provide a comprehensive review of heavy metal release and accumulation at fish farms in Chile, Norway, Canada and the U.K. Research in all of these countries has detected metal accumulation in sediments and fish tissue. In Chile, as in other countries, sampling generally found elevated copper in farm sediments, but Burridge concludes that copper likely is not readily bioavailable in carbon-rich, oxygen-poor sediments which tend to bind metals. Similarly, they conclude that zinc, also found in elevated levels beneath Chilean cages, is also bound in the sediments minimizing its availability. This conclusion is supported by non-specific ecotoxicological bioassays in which mesocosms were stocked with test organisms and sediments collected from aquaculture sites (Rudolph et al. 2009). No toxic effects were observed, but the authors recommended monitoring to detect changes and effects at larger spatial and temporal scales. A Chilean study investigating the use of fish farm sediments as agricultural manure measured nutrient and heavy metal concentrations in sediment samples from below salmon farms (Salazar and Saldana 2007). Generally, manure from marine salmon farms contained lower heavy metal concentrations than freshwater lake or trout farm manure. Only copper concentrations were consistently higher at 89 mg/kg dry weight compared with 45 and 33.4 mg/kg, respectively. All concentrations were well below environmental limit values.

A Scottish review of the environmental impacts of aquaculture reports that elevated levels of zinc and copper from fish feeds and antifoulants have been found at farm sites (Black et al. 2002). One study found that sediments beneath and within 30 m of farms were contaminated with zinc and copper and adverse effects to the benthic community were predicted. While immediate bioavailability may be minimal, remobilization of the metals by strong currents or trawling was identified as a potential concern. Heavy metal contamination may be a barrier to recolonization during fallowing. Further research addressing the toxicology, biological impacts and management was recommended. Dean et al. (2007) sampled 70 stations near a Scottish fish farm and found maximum sediment concentrations of 921, 805 and 3.5 µg/g of zinc, copper and cadmium, respectively. The calculated losses from the farm (feed input minus fish output) were 87.0%, 4.3% and 14.0% of the background-corrected inventories for Zn, Cu and Cd, respectively, indicating that for Cu and Cd at least, the feed is not the only source. Metal concentrations decreased away from the farm and reached background levels about 300 m from the farm. Background heavy metal concentrations must be accounted for by using standard methods such as lithium normalization appropriate for the region being sampled (Yeats et al. 2005). Huntington et al. (2006) determined that the release and persistence of metals into the water and sediments is an important environmental effect to consider, but note that information about bioavailability and long-term ecological implications is lacking.

The accumulation of heavy metals in marine sediments due to fish farming has been reported in Spain. Compared to upstream control sites, Mendiguchia et al. (2006) found increased levels of zinc (140% above levels), copper (362%) and lead (97%) in several marine aquaculture facilities. Macroalgae cultivated in an intensive Spanish sea bream growout facility did not accumulate heavy metals during a normal growth period and were considered safe for the human food industry (Hernandez et al. 2005). An analysis of a variety of commercial fish feeds used in Italian aquaculture found no mercury present in any samples and only low levels of arsenic, cadmium, chromium and lead (Abete et al. 2004). The researchers concluded that although the feeds used complied with governmental standards, but raised the potential for cumulative impacts to the cultured fish and the food chain after long term application of feeds.

In the eastern Mediterranean, heavy metal enrichment of the water column and sediments around three fish farms was measured and attributed directly to the feeds used (Belias et al. 2003). The greatest increases in sediment metal concentrations relative to control sites were for iron (up to 80 ppb compared to 28 ppb), zinc (up to 9 ppb, compared to 4 ppb) and copper (up to 1.3 ppb compared to 0.5 ppb). The three farms sampled had been in operation for 7-9 years. Similarly, Aksu et al. (2010) sampled sediments off Turkey at eight sea bream and sea bass farms. Although the farm sites generally had elevated levels of zinc, iron and copper, the concentrations detected were below guideline limits or probable effect levels. The authors concluded that the sediments had not reached metal concentrations that were ecologically harmful.

Sediment samples from three marine aquaculture sites in Hong Kong found elevated levels of zinc and copper (Wong et al. 2001). The farm sited in an isolated area with low human population generally had lower heavy metal levels indicating that anthropogenic sources of metal other than aquaculture also contributed to sediment pollution.

Sampling at a farm site in New Zealand found sediment zinc levels of 665 µg/g dry weight (Morrisey et al. 2000). This was about 38 times the level measured at nearby (100 m away) control sites, suggesting that metal accumulation was localized. No differences in copper concentrations were detected.

Recent research indicates that heavy metals do tend to accumulate in the sediments below fish farms. However, most studies have found that concentrations are within acceptable environmental guidelines even at farms that have been in production for many years. Because the metals are often bound in the sediments, they are generally perceived to be of low risk in terms of environmental effects. Improvement in feed formulation is expected to decrease zinc loading to the marine environment, as many manufacturers are adding lower amounts of a more available form, zinc methionine (Burridge et al. 2010). Long term monitoring is usually recommended, particularly if fish farm manure is going to be used for agricultural fertilization.

In addition to heavy metals, other contaminants have been measured around Canadian fish farms. For example, Hellou et al. (2005) analyzed feed pellets and sediment samples for polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and chlorinated pesticides including DDT. PAHs and pesticides were found in three of the five feeds tested and in fish oil. PCBs were found in two of the feeds and the oil. In sediment samples, PAHs concentrations ranged from 90-10,234 ng/g compared to 4ng/g at reference sites. PCBs were generally highest under cage sites, decreasing with distance. Of the 12 pesticides analyzed, only DDE (a DDT breakdown product) was consistently detected with the same trend as PCBs.

A recent study reported increased mercury bioaccumulation in rockfish *Sebastes spp***.** around aquaculture facilities in British Columbia as the rockfish switched to feeding at higher trophic levels by including overall more fish prey in their diet (Debruyn et al. 2006). Mercury in the prey fish was thought to originate from foraging on waste feed and fish feces and the mobilization of native and added mercury in sediment due to farm-induced anoxia, resulting in increased bioaccumulation in the rockfish predators.

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MANAGEMENT TOOLS

Perhaps the most effective marine fish farm management tool is good decision making when selecting sites. This approach is emphasized in the preceeding chapters, with recurring recommendations to locate farms in well-flushed waters, including deep offshore areas over erosional sediments. Additionally, computer simulation models (Cromey et al. 2002, Nordvarg and Hakanson 2002, Doglioli et al. 2004, Rensel et al. 2007, Jusup et al. 2009, Tett et al. 2011, Cromey et al. 2012) that track nutrient discharge and predict environmental impacts are tools for farm managers and government regulatory agencies to understand interactions of fish farms and the marine environment and to guide decision making about siting, monitoring and management. However, this topic is not covered here as it was beyond the scope of this report to provide a comprehensive analysis and comparison of such models.

The next sections cover two areas of marine fish farm management that have received attention due to their potential to reduce environmental impacts. Fallowing is recommended and implemented to allow the benthic sediments and communities below fish cages to recover from negative effects of nutrient loading. We reviewed research that aims to establish how long it takes for the benthic habitat to recover and whether fallowing is effective at re-establishing a normal faunal assemblage. Integrated multi-trophic aquaculture, or IMTA, is a tool that can both broaden the economic base of the mariculture industry while at the same time adding species to the farm facilities that can decrease nutrient loading, improve water quality and decrease sedimentation.

Fallowing

Fallowing refers to the practice of relocating marine fish cages or delaying restocking of cages to allow the sediment below to undergo natural recovery, both geochemically and ecologically, from the impacts of nutrient loading. This management tool is implemented around the world for preventing long-lasting damage to the benthic environment and for decreasing risks to farms of pathogens and parasites. This section provides an overview of the duration, extent and degree of recovery associated with the practice of fallowing.

Nash (2001, 2003) summarizes information collected in Pacific Northwest salmon farms showing that geochemical recovery may take as little as a few weeks or months at some sites, but up to two or three years at others. Biological remediation typically lags behind chemical recovery depending upon recruitment of new fauna. Typically, as organic

Photo courtesy of NOAA.

material is dispersed or degraded and sediment redox potential increases recovery of the benthic fauna progresses with generalists and bottom feeders recolonizing rapidly, and rare taxa reappearing more slowly. A study at a Hawaiian Pacific threadfin farm reported on the effectiveness of a six month fallowing period, as reflected by faunal community recovery, following five years of commercial farm activity (Lee et al. 2006). Changes in the community had been evident up to 80 m from the cage site compared to controls almost 400 m away. Although improvement was evident during the study period, comparisons of community structure indicated that complete recovery was not yet achieved. As part of an extensive completion report on a mutton snapper and cobia farming operation, fallowing was recommended by Alston et al. (2005) as a management practice for aquaculture operations in Puerto Rico.

A comprehensive analysis of fallowing practices at salmon farms was prepared for Fisheries and Oceans Canada in the late 1990s (Stewart 1998), but was driven primarily by fish health rather than environmental impact concerns. It concluded that fallowing of at least three months, in combination with good farm practices such as adequate distance between cages, was beneficial in reducing the spread of infectious pathogens. Brooks et al. (2003) conducted an 18 month study to determine the extents of benthic chemical and biological impacts at high production salmon farms in British Columbia. Impacts increased progressively from stocking through the production cycle and were evident to at least 50 m from the cages. Chemical remediation of the sediments was evident immediately following the onset of harvest in August and was considered complete nine months later when harvest ended in April. However, it took another six months of fallowing before biological indices suggested that the benthic community was also recovered. In contrast, a seven year study of remediation conducted at a nearby (5 nm away) set of salmon farms reported much longer recovery times (Brooks et al. 2004). After eight years in production, there was extensive waste accumulation and sediment degradation up to 200 m away from the cages. Twelve surveys over five years indicated steady, but very slow and incomplete remediation at this site. Chemical improvements were evident after the first year and continued to progress over time. The biological indices reflected an even slower pattern of improvement and after five years there was minimal recovery within the first 80 m impact zone. Biodiversity indices from samples within 100 m of the farm also remained below reference values and the taxa were primarily common or generalist species. The highest impact area shifted 50 m down current of the cage site after four years. The researchers believe that siting the farm in a net depositional hydrodynamic regime was responsible for this abnormally extended recovery time. A review by Wildish and Pohle (2005) supports the idea that shorter fallowing cycles of 6-24 months are generally adequate for restoring benthic macrofauna, depending upon site specific conditions. Tlusty et al. (2005) reports that Canadian salmon farm sites without fallowing protocols displayed higher organic loading and impacts to nematode diversity compared to fallowed farms.

Studies in Europe also support the effectiveness of fallowing and point to the influence of local conditions on the extent of the recovery period. Kraufvelin et al. (2001) compared recovery at two farming sites in Finland 4-7 years after decreased nutrient loading and cessation of farming. The two sites varied greatly in topography, water circulation and hydrodynamic conditions. At the shallow sheltered site, there was no recovery of the infaunal community and even after seven years there were sampling stations with no organisms present. In contrast, the well flushed site showed faunal colonization and recovery even with ongoing fish farming in the area. Sediment sampling at Norwegian salmon farms found severe chemical and biological benthic impacts within 50 m of cages, but detectable effects up to several hundred meters away (Carroll et al. 2003). Fallowed farms exhibited significantly less environmental impacts, so fallowing was recommended as a management tool for sustainable fish farming. When Schaaning and Hansen (2005) sampled sediment beneath abandoned farm locations they found evidence of chemical remediation approaching reference site levels. Sediments became normalized within 0.5-3 years after farming stopped, thus demonstrating the positive results that might be expected from fallowing.

A similar study was conducted at 10 salmon cages in Scotland (Pereira et al. 2004) after the cessation of farming. Chemical and biological samples were collected over 15 months. Within this time the sites 30 and 55 m from the farm indicated a recovered benthic assemblage, but at the station adjacent to the cage significantly reduced and hypoxic conditions persisted. Species abundance and diversity also remained in degraded conditions at the cage site compared to the other two sites where biological recovery steadily increased over the study period. This farm had been under constant production for several years prior to fallowing, and the results of the study suggest that additional time was required to fully recover benthic conditions at this farm.

As the marine finfish aquaculture industry expands, there may be increased demand for farm management protocols emphasizing nutrient uptake or other potential advantages of IMTA.

A research project conducted in the Canary Islands quantified the use by wild fish assemblages of the area below sea bream and sea bass cages before and after the cessation of farming (Tuya et al. 2006). Over the course of fallowing the abundance of large mugilids, rays and *Pagellus* species decreased drastically, while the numbers of herbivores and benthic carnivores remained relatively stable. Large carnivorous fishes increased in numbers. The authors concluded that the lack of farm feed input was the driving factor in shifting the fish assemblage.

Investigations in the Mediterranean support fallowing as a management option to reduce environmental impacts. La Rosa et al. (2001)

sampled microbes and meiofauna at a sea bass farm off western Italy just prior to harvest and following the removal of the cage. Within four months significant chemical and biological recovery was evident, but not complete. Microbial response was quite rapid — in only 15 days, microbial components returned to control values. In a eutrophic lagoon heavily impacted by fish farming effluents, Lardicci et al. (2001) found an impoverished benthic community even six years after the implementation of environmental restoration measures. While not a fallowing study *per se*, these results are useful in understanding the interplay between nutrification from aquaculture waste, geochemical processes and benthic community response in enclosed, poorly flushed marine habitats. Porrello et al. (2005) recommended fallowing as a management tool at sea cages to minimize environmental impacts. Their study concluded that the negative impacts to the benthic chemistry were confined to within 50 m of the open ocean sea bass farm they evaluated. Because the bottom currents were slow and the cages were placed in shallow water, fallowing was suggested to allow recovery of the sediments. A comparison of benthic impacts at seven Greek fish farms in the eastern Mediterranean found low organic carbon concentrations, high redox and high diversity index at the single operational farm which implemented fallowing (Lampadariou et al. 2008). In fact, the fallowed farm was the only one at which there were no differences between samples taken beneath the farm and at distances out to 50 m. Additional comparative studies would be useful in developing fallowing guidelines for the Mediterranean.

Vezzulli et al. (2004) compared the effectiveness of two bioremediation products for mobilizing carbon in organic rich sediments below fish cages. Biovase, a proprietary blend of indigenous microorganisms, stimulated carbon mobilization (up to 23% increase) and enhanced extra-cellular enzymatic activity in the sediment. A commercial product containing oxygen releasing compounds was less effective, but did result in a slight increase in carbon mobilization. The widespread use of such remediation products is likely cost prohibitive, but continued development of technology to aid in farm waste management is warranted (Chavez-Crooker and Obreque-Contreras 2010).

Morrisey et al. (2000) conducted a study at New Zealand marine salmon farms, including a site fallowed after more than a decade of commercial mariculture, to validate a modeling approach to predict benthic impacts. The observed levels of carbon sedimentation were in agreement with values generated by the model, and the model accurately estimated one-year recovery rates for the fallowed sediments. Additional findings suggested that zinc and copper in farm sediments may impair the process of chemical and biological remediation. In Tasmania, sediments below a salmon farm recovered very quickly after removal of the cage (Macleod et al. 2004). After only two months geochemical parameters indicated marked improvement. However, the macrobenthos remained unrecovered for 36 months. This study stresses the importance of defining recovery benchmarks to make certain the correct environmental indicators are used to establishing fallowing guidelines. Fallowing was strongly recommended based upon an investigation of nutrient fluxes in the sediments below bluefin tuna farms in Australia (Lauer et al. 2009). High sedimentation rates and up to ten-fold increases in nitrogen and phosphorus were reversed following a four month fallowing period. The high potential for organic sediment enrichment in this industry makes the implementation of fallowing an important aspect of ensuring long term environmental sustainability.

Lin and Bailey-Brock (2008) constructed a summary table of ten recent (since 1999) fallowing studies from seven countries with five cultured species. Fallow time ranged broadly from 3-48 months. Current flow, depth, substrate and biological response information are included. Additional work to investigate the correlations between farm site characteristics and the required duration and effectiveness of recovery would aid development of fallowing guidance for the mariculture industry. Fallowing is being implemented or suggested as a valuable component of modern marine fish farm management in the U.S. (Nash 2001, Nash et al. 2005, Tucker and Hargreaves 2008), Canada (Environment Canada 2001, Sutherland 2004), the Mediterranean (International Union for Conservation of Nature 2007, Borg et al. 2011), Europe (Black et al. 2002, International Council for the Exploration of the Seas 2002, Huntington et al. 2006), Australia (Crawford 2003), globally (Stewart 1998, Halwart et al. 2007) and by the Global Aquaculture Alliance (Global Aquaculture Alliance 2011).

IMTA

Integrated multi-trophic aquaculture, or IMTA, is the practice of culturing finfish in combination with other species that utilize waste particulates and dissolved nutrients, thereby reducing nutrient discharge and expanding the economic base of a farming operation (Chopin 2006). The Food and Agriculture Organization of the United Nations (FAO) produced a comprehensive report on the current state and the requirements for expansion of IMTA in fish and shellfish aquaculture in temperate and tropical waters, and the Mediterranean (Soto 2009). In addition to nutrient uptake benefits and production enhancement, there may be mitigation of pathogens (Pang et al. 2006) and improved social acceptance (Barrington et al. 2010). The organisms most commonly integrated with finfish culture are seaweeds and shellfish. Polyculture has been an integral part of aquaculture for hundreds of years, but IMTA differs in two important ways. First, IMTA always employs organisms from different trophic levels as biofilters, while polyculture may refer more broadly to the growing of different fish species together without a biofiltering benefit. The IMTA approach strives to emulate natural nutrient cycling processes. Also, polyculture systems generally grow animals in the same enclosure, while IMTA systems may strategically position the different trophic components nearby the fish cages to take advantage of current-driven nutrient plumes.

Photo courtesy of NOAA.

The commercial feasibility of IMTA is under investigation around the world and has gained momentum in the past decade (Troell et al. 2009). In their summaries of the environmental impacts of marine cage culture, Wu (1995) and Pearson and Black (2001) review studies of nutrient uptake by algae, seaweeds and shellfish, and promote expanded research on the use of other organisms like polychaetes for filtering and bioremediation. As the marine finfish aquaculture industry expands, there may be increased demand for farm management protocols emphasizing nutrient uptake or other potential advantages of IMTA. IMTA is a remediation and filtering system with the potential to recoup its implementation costs (in the form of revenue from additional seafood products), as all other approaches incur costs without the potential for generating revenue (Troell et al. 2009).

Research at marine fish farms has demonstrated the potential benefits of IMTA with shellfish. For example, early work by Stirling and Okumus (1995) found that mussels cultured on rafts and lines at

Scottish salmon farms showed augmented growth compared to those grown at a nearby shellfish farm. Local primary productivity and seasonal mussel growth cycles were noted as significant factors to be taken into account when considering mussel culture. Changes in cage design to increase buoyancy and the potential for shellfish to harbor organisms, chemicals or therapeutants which affect humans or fish were also identified as important factors.

A demonstration farm in the Gulf of Maine grew mussels on long lines deployed 200 m from submersible fish cages (Langan 2004). The amount of nitrogen discharged from the cages over a three year growout cycle of halibut and haddock was calculated as was the amount removed by bivalve harvest. The total discharge exceeded assimilation by mussels, and installation of another six lines was estimated to be needed to compensate for all the nitrogen waste. Ultimately, the scale of the mussel culture would need to be greater than that of the fish farm to achieve no net nitrogen increase to the environment. However, the study found that improved feed formulation or addition of seaweed culture could also be incorporated to increase nutrient removal. Another study in Maine found that sea scallops *Placopecten magellanicus* cultured in suspension at salmon farms grew to sizes comparable to those grown at a nearby scallop aquaculture site (Parsons et al. 2002).

Photo courtesy of NOAA.

A lab and field study in Canada measured the absorption efficiency of blue mussels cultured adjacent to open water salmon cages (Reid et al. 2010). In the lab study, mussels consuming salmon feed and fecal particulates showed the same organic matter absorption efficiency as those on commercial algal bivalve feeds. The mussels grown at the cage sites appeared to rely on both farm waste and natural seston. Hydrodynamics of particulate waste is important for deciding the placement of mussel growing structures within a constant nutrient plume. A successful IMTA pilot project at salmon farms in the Bay of Fundy is growing seaweed and mussels with the fish (Ridler et al. 2007). The profitability of this approach was economically evaluated. The additional profits from the mussel and seaweeds compensated for the added investment needs and there was a 24% increase in net present value. When different risk scenarios were run, IMTA was more economically resistant than salmon monoculture to catastrophic events or decrease in market value of salmon. Social acceptability surveys found an increased approval rating for IMTA compared to monoculture, reflecting an additional public perception benefit when IMTA practices are implemented.

The profitability of a seaweed market must be proven, but there is interest in developing the technological capacity for coastal IMTA.

The economic potential for salmon and mussel IMTA in the United Kingdom was assessed by Whitmarsh et al. (2006). They found that under current economic conditions appropriately sited mussel lines could assist in removing a proportion of the organic waste produced by fish farms while also offering financial benefits to the farm owner. However, the future market price for both cultured species and integration benefit are important when considering long-term economic opportunities. A study in Italy (Sarà et al. 2009) tested the potential of integrating mussel culture at a sea bass and sea bream farm. Mussels grown downstream of fish cages showed greater growth after one year compared to those at control sites. Results suggested that bivalve culture could be helpful in recycling organic waste from marine fish farms. However, implementing IMTA in the Mediterranean may be a challenge because the predominantly oligotrophic conditions mean the baseline productivity may be insufficient to support cultivation of other organisms, even when farms are discharging nutrients (Angel and Freeman 2009).

In contrast to the above studies Navarrete-Mier et al. (2010) concluded that oysters and mussels grown for three months along an 1800 m transect downstream of a sea bream and sea bass farm in Spain did not show enhanced growth from exposure to farm waste. Stable isotope and heavy metal bioaccumulation analysis indicated that farm waste was not a significant part of the bivalve diet. Other studies have found no growth enhancement of mussels grown in proximity to fish cages (Cheshuk et al. 2003), yet recent work on feeding behavior of mussels near salmon farms (MacDonald et al. 2011) and the use of stable isotopes to trace assimilation of fish feed in mussels (Redmond et al. 2010) indicate that these shellfish can be successfully used to capture and absorb farm nutrients.

In addition to shellfish, other invertebrates are being considered for IMTA. Voluntary recruitment of spiny lobster post-larvae was observed at sea cages in Puerto Rico (Davis et al. 2006). This pilot study confirmed the feasibility of collecting larval and juvenile lobsters for commercial grow out at the sea cage. Ahlgren (1998) showed that sea cucumbers stocked into salmon net pens in Alaska effectively cleared organic debris from the pens while also displaying increased growth compared to sea cucumbers feeding naturally. While not a common food species in the U.S., sea cucumbers are a commercially harvested detritivore with the potential for use in IMTA. Sea urchins *Paracentrotus lividus* cultivated in nets suspended in Scottish salmon cages grew faster than urchins grown 2.5 km away. Though tests diameter was similar, gonad maturation – which determine marketability – was higher for urchins cultured with the fish. Urchin survivorship in the fish pens was 98% compared to 57% at the reference station, resulting in much higher final total biomass.

The culture of primary producers for human consumption at fish farms is common in land-based and nearshore aquaculture (Neori et al. 2004), but the technology to make it possible at high energy off shore sites is still being developed. Buck and Buchholz (2004) describe an offshore ring structure successfully used to cultivate *Laminaria saccharaina*, a kelp used for food and biofiltration, in the North Sea. Such IMTA initiatives are being integrated with offshore wind farm installations (also see Michler-Cieluch et al. 2009) in this part of the world, but require structures rigid enough to withstand the intense wave energy while being easily handled during harvest. The ring system performed better compared to long-line, ladder and grid structures that were simultaneously tested. Technical problems were associated with all structures due to rough sea conditions, but the ring structure allowed for easier sampling and could be towed to shore intact. This study was not conducted near a fish farm, so it remains to be seen how this technology might be integrated with sea cage operations.
Efforts in Chile to incorporate IMTA approaches are reviewed by (Buschmann et al. 2009), but primarily in land-based, freshwater systems. The profitability of a seaweed market must be proven, but there is interest in developing the technological capacity for coastal IMTA. It is estimated that culturing 50-60 hectares of algae downstream of a salmon farm producing 1500 tons yearly would result in an 80% reduction of nitrogen entering the environment. This could also be integrated with existing mussel production.

Photo courtesy of NOAA.

The growth of *Porphyra* (nori) at salmon farms in the North Atlantic Ocean was compared to seaweed growing away from farm influence (Chopin et al. 1999). Seaweed nitrogen and phosphorus levels varied with location and seawater nutrient concentrations, and growth varied by species and seasonally. The use of local cultivars and a solid understanding of seaweed biology are needed to make its cultivation commercially attractive and useful as a bioremediation tool. There is still only limited knowledge about a few species that may be useful for marine finfish IMTA endeavors and include *Ulva*, *Porphyra, Gracilaria* and *Laminaria* (Neori et al. 2004). Challenges facing this industry are epiphyte growth on seaweed monocultures or biofilters, grazing by herbivores, managing plant tendrils in oscillating and strong currents, the physiological dynamics of nutrient uptake. While much can be learned from land-based operations, the turbulence and remoteness of the open ocean will require innovative solutions.

The application of IMTA primarily as a filtration or remediation technique, rather than for food production, is also being investigated (Chavez-Crooker and Obreque-Contreras 2010) and improvements in culture technology are being made for the open ocean environment. Chung et al. (2002) evaluated several species of seaweed in

Korea to determine which would be most effective at nutrient uptake to reduce the eutrophication in coastal fish farming areas. *Porphyra* and *Ulva* had up to six times higher rates of short term ammonia uptake than the other algal species analyzed. A simple model was developed to predict the overall nitrogen scrubbing that could be expected from integrating algal culture into farming areas.

As part of a study in Japan, three species of seaweeds were cultured year round at fish farms to improve the water quality (Kitadai and Kadowaki 2007). The nitrogen and phosphorus uptake, oxygen production and growth rates of the seaweeds were calculated. Growth rates of up to 4.2 cm/day were reported and oxygen production was 8-11 times higher than consumption. Nitrogen and phosphorus uptake were 2.9-3.6 mg/m^2/day and 0.19-0.54 mg/m^2/day, respectively. These results were used to determine the seaweed biomass needed to clear the nitrogen output from the fish farms. A similar effort was made at sea bass and croaker farms and macroalgae culture areas in Nansha Bay, China (Jiang et al. 2010). Water nutrient levels, eutrophication status and the fish nitrogen excretion rates were determined in order to estimate the optimal co-culture proportions of fish to macroalgae needed to maintain environmental quality. The authors calculated that for each fish cage 450 m^2 of *Laminaria* and 690 m^2 of *Gracilaria* were required to maintain water quality and prevent eutrophication. At an intensive sea bream growout farm, *Ulva* and *Gracilaria* tanks were added to treat the farm effluent and remove nitrogen and phosphorus (Hernandez et al. 2005). After less than three months the algal growth exceeded the capacity of the tanks. The *Ulva* removed 8.9% of the phosphorus input and 24% of nitrogen. The *Gracilaria* removed 3.2% of the phosphorus and 19% of the nitrogen input. Heavy metal analysis of the seaweeds determined there was no contamination making the tissues eligible for use in the food industry. Asian and U.S. species of *Porphyra* have also been tested in the laboratory by Kraemer et al. (2004) and appear to be an excellent choice for commercial and bioremediation applications based upon nutrient uptake rates. Lab experiments in Korea with *Codium*, a seaweed with food and medicinal applications, suggest this species may be useful for IMTA in fish farming areas with high water temperatures (Kang et al. 2008).

Photo courtesy of NOAA.

Mathematical models designed to predict waste dispersion and carrying capacity relative to multi-species invertebrate mariculture are being developed (Duarte et al. 2003, Reid et al. 2009, Reid et al. 2011), and may be useful in designing IMTA systems that balance the nutrient inputs of the finfish with optimized culture of filtering organisms. Recently (Sarà et al. 2012) applied Dynamic Energy Budget modeling to examine growth of blue mussels *Mytilus galloprovincialis* and oysters *Crassostrea gigas* grown around fish cages in the Mediterranean. The model predicted that both species would exhibit greater growth (nearly doubled for oysters) in water enriched by farm effluent, compared to sites away from cages. The modeling results correlated well with results from field experiments with mussels. Development of advanced models to integrate IMTA into nutrient discharge models will be especially relevant in areas with high fish production demands and moderate flushing capacity to help manage nutrient inputs by harnessing the assimilative capacity of IMTA biofiltering components.

Troell et al. (2009) provide a useful summary of the current status of IMTA knowledge, research and engineering for offshore marine systems. Generally, there is great interest in pursuing the expansion of IMTA to marine cage culture, and successful pilot projects indicate that it is feasible (Blouin et al. 2007, Robinson et al. 2011) and profitable. The high energy environment of the open ocean poses great challenges to all aspects of mariculture in that environment, but significant advances are being made. For seaweed culture, open ocean harvesting techniques and estimating the capacity to remove nutrients in an open water system are two areas requiring further work. The integration of bivalves and other filter feeding organisms into sea cages also needs further research and technological innovation. For both seaweeds and filter feeders, economic cost and benefits analyses are still needed.

IMTA has been attempted for many years, but due to significant knowledge gaps, technological challenges and economic viability, it is not yet a widely-implemented management tool. The incorporation of IMTA into marine aquaculture is of interest for both commercial and environmental reasons, and it is identified as a best management practice (Stickney 2002, Belle and Nash 2008, Johnson et al. 2008). IMTA systems are thought to be near commercial scales in the U.S. (Barrington et al. 2009). As this industry expands domestically, continued research and development efforts to identify the right species and technologies for co-culture will advance IMTA from an experimental to a profitable aspect of marine fish aquaculture. The integration of IMTA into marine monoculture may also increase societal acceptance of marine aquaculture if it reduces potential negative impacts such as nutrient discharge (Barrington et al. 2010).

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CONCLUSION

This report provides a comprehensive review and summary of some predominant environmental effects of marine finfish aquaculture. We compiled over 420 research papers, studies and reports to gather current information as a tool for industry, coastal managers, scientists and the public. Our work intends to provide stakeholders a scientific basis for decision making about siting, monitoring, regulating and managing a marine aquaculture industry in the U.S.

There is opportunity to proactively apply environmental lessons learned in the U.S. and other countries to existing and new locations in U.S. waters. As the scope of human activities in the coastal and marine environment expands, there is a need to understand the individual and collective, short and long-term impacts that may result, and how to prevent, minimize or mitigate these effects. Marine cage aquaculture is only one such activity. The NOAA Aquaculture Policy presents national guidance for marine aquaculture which provides food security and economic opportunity for the U.S., while also conserving our ocean resources. This policy supports the joint goals of environmental and economic sustainability, and implementation of the policy will be aided by having the best available science to guide decision-making.

The scope of our report does not allow for a quantitative or comprehensive analysis of the environmental effects of marine finfish aquaculture. Yet, we are able to discern certain trends in the research and draw some general conclusions about the risks of the industry to marine ecosystems. We also highlight aspects of the industry that would benefit from further investigation or further technical advancement.

Water quality is the first issue covered in this report. The trend over the last 20 years reflects great improvements in feed formulation and management, which are largely credited for the reduction in water quality impacts. Proper siting in areas with sufficient flushing is important for eliminating nutrient enhancement, turbidity, and decreased dissolved oxygen. In the open ocean, water quality impacts are not likely to pose a great environmental threat when farms are properly sited and appropriately managed. Protection of water quality will be best achieved by siting farms in deep, well-flushed waters. Impaired water quality is typically observed around farms in nearshore or intertidal habitats where flushing is minimal and at farms using feeds that include unprocessed raw fish rather than formulated feeds.

Elevated levels of nitrogen and phosphorus are the most common impacts to water quality, but are typically not measurable 30 m beyond farm perimeters. Generally, both nutrients follow the same trend in terms of measurable changes in concentration, although sometimes nitrogen increase is found without a concomitant rise in phosphorus. Nutrient elevations will be most evident following feeding and just prior to harvest when the farm stock biomass is at its greatest. Farm management and monitoring protocols should take this into account.

The trophic status and background nutrient flux of the receiving waters, as well as other sources of nutrient loading, should be considered when assessing the relative contribution of marine fish farm discharge to the environment. Because nutrients tend to get flushed away from the farm area faster than they can be assimilated into the local food web, it is difficult to measure direct impacts to local phytoplankton production. It is uncommon for phytoplankton productivity and blooms, including harmful algae blooms, resulting from eutrophication to be attributed to fish farms. Continued research to understand and model the complex array of forces driving nutrient dispersion in and around fish farms will provide additional tools to effectively manage fish farming practices. Few comparative analyses have investigated correlations between farm site characteristics (e.g., depth, latitude, current profile), farm management factors (e.g., species cultured, volume of cages, biomass, feeding rate), and observed water quality impacts so additional research in this area would be valuable.

Operating farms in well-flushed areas over erosional sediments and improved feeding practices are factors which also reduce geochemical impacts to the sediments below farms. Organic carbon, nitrogen and phosphorus discharge from fish farms continues to be an environmental concern because benthic enrichment will occur if nutrient discharge and sedimentation exceed the environment's assimilative capacity. Because much of the nutrient input to farms is lost through excretion and excess feed, it is important to continue optimizing feed formulation and closely monitor feeding to reduce waste. The accumulation of some organic matter below farms is to be expected, especially toward the end of a grow-out period when farm biomass is at its peak. Benthic environments typically recover to baseline condition in less than one to three years after a farm is removed from a site. Visual observations of benthic conditions below farms are a valuable

Domestic production of seafood can aid in decreasing U.S. reliance on imported products, provide jobs and food security, and meet the rising demand for seafood.

tool throughout a crop cycle for assessing whether operations are within the capacity of the ecosystem. Farms located in deep water with continuous or episodic benthic scouring of organic waste will be less likely to exhibit sediment degradation. As with water quality, benthic geochemical impacts are most pronounced at enclosed, nearshore or coastal farm sites with insufficient depth and flow to disperse organic wastes.

Further research is needed to determine the best indicators of biogeochemical perturbation which also incorporate seasonal or regional variability. Total organic carbon, sulfides and redox potential are consistently the most reliable parameters that reflect the geochemical condition of sediments below farms. Of course, these must be assessed relative to background levels of the surrounding sea floor. Local pre-farming conditions should be determined for comparative analyses and sediment management should contribute to regulatory decision-making, developing monitoring protocols and informing site management. Where changes in the sediment are documented, they are generally confined to within 500 m of the cages and often recovery progresses quickly after harvest. At well-managed farms this footprint may be reduced to 100 m.

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Effective monitoring protocols should be implemented that ensure early detection of geochemical perturbations that signal potential ecological consequences with adaptive management response options to minimize impacts. Ongoing work continues to identify new benthic monitoring methods resulting in reliable, accurate and cost-effective data which provide early indications of biogeochemical alterations. Such methods will also prove useful for surveying benthic conditions in very deep open ocean sites inaccessible for diver surveys or at farms over hard bottom habitats. There is a need for long-term data to evaluate cumulative impacts of organic matter accumulation from multiple farms over many production cycles to the benthic processes at large, regional scales. Analytical methods to quantify the relative contribution of fish farm discharge are critical for understanding and modeling the full scope of impacts within marine ecosystems under nutrient loading from many anthropogenic and natural sources.

Early detection and intervention will be important to minimizing ecological benthic impacts. Once sediment chemistry is deleteriously affected by farm operations, the benthic community responds by shifting toward generalist species tolerant of perturbed conditions. Often these effects are of short duration and the benthic community recovers within months following harvest and fallowing. At farms with high fish biomass production and nutrient enrichment, fallowing for several years may be required before recovery is evident. Effort should be made to prevent the need for extended fallowing periods due to severe enrichment. Proactive, careful site selection and modeling to predict likely impacts based on production parameters and site characteristics can optimize farm locations to minimize or eliminate most effects. Once a farm is operational, best management practices should be followed, environmental monitoring should be conducted for early detection of environmental impacts, and adaptive farm management strategies should be implemented if warranted. Cost effective, quick sampling methods to assess the condition of the benthic community and site-specific indicator species that reflect impaired sediment conditions are tools that will enhance on-site evaluation and management.

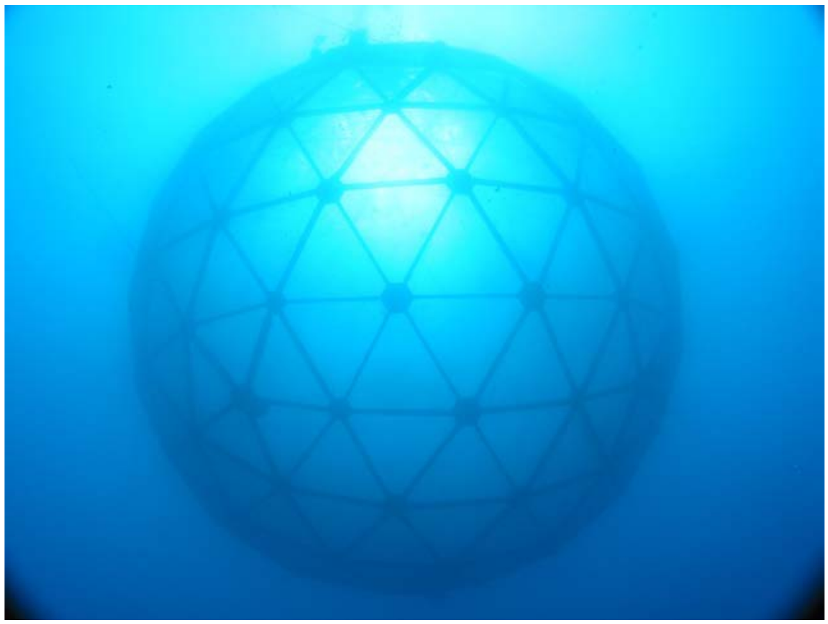
As with water quality and sediment condition, improvements in farm siting and management have tended to decrease impacts to benthic communities. Effects to the infaunal communities are usually confined to within 100 m of a farm. Most studies of marine fish farm impacts to benthic communities highlight site-specific factors that affect the response and stress that the availability of good historical records of local biodiversity is a key factor in being able to assess the changes due to enrichment. Opportunistic polychaetes are the most common indicator species of degraded benthic conditions. However, other local benthic species or assemblages that best reflect sediment condition and quality should be identified for optimal monitoring. Biodiversity indices should be coupled with geochemical assessment to fully ascertain the degree of sediment and community perturbation. An interesting finding at fish farms is that moderate organic enrichment may stimulate benthic community productivity and even enhance biodiversity. As the relationships between sediment geochemistry and the benthic community response are better understood, computer models are beginning to incorporate benthic community response to farm nutrient loading. This approach will enhance our ability to make decisions about fish farming within an ecological context.

The broader ecological role of aquaculture operations within the marine environment should also be considered. Nitrogen and phosphorus inputs to the water column may increase primary productivity, especially in oligotrophic waters. However, rapid uptake by phytoplankton and zooplankton, coupled with dispersive water currents make it difficult to track or measure such impacts over large spatial scales. Dissolved nutrients may contribute to increasing biomass of the fouling community on farm structures. Hydrology of farms located near shore or in semi-enclosed water bodies must be carefully examined to prevent eutrophication and increased primary productivity in coastal areas and habitats. One knowledge gap continues to be how dissolved nutrients are dispersed and assimilated over large marine areas, and how productivity may be affected under increasing production from more farms. The cumulative effects of long-term nutrient loading to marine waters should remain a research priority. It is especially important that as marine fish farming expands to larger scales in a variety of geographic regions and marine habitats, monitoring protocols incorporate a framework for discerning cumulative, far-field and long-term nutrient responses in phyto- and zooplankton productivity and the mobilization of energy from fish farms into marine food webs.

Scavenging fish also serve as a route for mobilizing farm nutrients into the marine food webs, thus providing a natural approach for decreasing nutrient accumulation and organic waste impacts on the sea floor. Wild fish often aggregate and forage around fish cages and this is often considered a beneficial impact to marine life. As fish are attracted to farms, the potential for interactions with human fishers may increase and farm management or regulatory steps should be considered to minimize such conflicts. Likewise, marine fish and mammalian predators may also be attracted to farms. Little research has documented the extent to which marine predators target wild fish around farms, but this would be useful for understanding ecological interactions between farming and marine life. In contrast, impacts to predatory sharks and marine mammals are being minimized with improved net technologies that prevent predation on cultured fish. Proactive siting away from areas known to harbor dense populations of protected marine organisms is an effective strategy for minimizing negative interactions. Impacts to cetaceans, sea turtles and sea birds are typically minimal. Acoustic deterrent devices should be avoided as they have not proven to be an effective long-term solution and may have negative secondary consequences to non-target species.

Concerns about siting marine cage farms near corals, seagrass meadows and mangrove forests support the need for monitoring to detect impacts to these habitats. Because of the ecological roles these habitats play, caution should be used when siting farms near them. If farms are sited upstream of sensitive habitats, careful monitoring should be in place for early detection of any nutrient or sedimentation impacts directly to corals, seagrasses or mangroves, or the ecological functions and biodiversity associated with them. Although the potential for impacts to deep-water coral habitats is unknown, potential effects should be considered in siting farms in deep water locations with known corals.

The use of antibiotics, therapeutants and antifoulants at marine farms has greatly decreased in the last 20 years, resulting in decreased potential harmful effects on the marine environment. The misuse of approved chemicals or the application of unauthorized chemicals has the potential to cause environmental damage. In the U.S and other nations implementing modern fish farming, vaccination has largely replaced the use of antibiotics and less toxic, soluble therapeutants are more commonly approved for use. Better husbandry techniques to improve fish health are also being implemented. Best management practices such as onshore net de-fouling and mechanical alternatives for net cleaning reduce the release of antifoulant chemicals into the ocean. Ideally, few chemicals will be used on a regular basis at farms by implementing best management practices. Continued efforts should be made to determine the persistence and accumulation of antibiotics, therapeutants and other farm chemicals in the marine environment, and the extent to which they affect wild organisms. However, the most effective way to avoid negative impacts to marine life is to continue use and refinement of non-toxic therapeutic measures along with effective farm management and husbandry practices to safeguard health of cultured fish. Mechanical methods for de-fouling cages contribute greatly to the decline in heavy metal use at farms and should be continued. Though heavy metals are a small component of fish feed, they can build up in sediments after many years of operation and should be monitored to detect long-term accumulation.



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Fallowing and IMTA are two management tools which may mitigate or reduce environmental effects of some marine aquaculture operations. Siting and operating farms appropriately may eliminate the need for fallowing altogether. However, where benthic impacts are observed, fallowing should be implemented to avoid long-term damage to benthic ecosystems and reduce risks to farm animals from pathogens. Farm lease sites should be large enough and cage spacing appropriate to allow for such rotation of production cages. Benthic sediment and faunal community recovery generally occur within months of initiating fallowing. Because biological recovery may lag behind chemical recovery care should be taken to select appropriate, site-specific indicators of ecosystem health to evaluate the remediation process. Ideally, farms managed in equilibrium with the ecosystem's capacity to assimilate nutrient waste will not require fallowing to offset organic enrichment. Fallowing for the purposes of reducing the presence of pathogens, and thus the risk of disease outbreaks, may be appropriate even if no benthic impacts are measured.

IMTA technology and methods are improving. This approach integrates the culture of additional marketable marine organisms and provides benefits in terms of a reduction in nutrient enrichment and economic profitability. Though still largely experimental, IMTA is becoming more viable and offers economic as well as social acceptance benefits, sometimes at little extra cost. There is a long tradition of integrated culture in freshwater aquaculture, particularly at smaller community or family farms. Making use of farm effluent as the energy input for additional crops at other trophic levels provides efficiency and reduces harmful impacts. Globally there is an increased focus on fish production that reduces waste discharge. IMTA in the turbulent open ocean faces technological challenges, yet there is considerable interest in making it a viable component of ocean aquaculture.

Research to shed light on far-field and regional processes, especially in intensively farmed areas and over longer time scales, should continue to examine the ecological role of fish farms in marine environments. The research in this report was conducted at farms in temperate, subtropical and tropical waters. Geographical determinants of the type and extent of environmental impacts from marine fish farms include latitude, temperature and current regimes, sediment type and trophic status of the water. Generally, the extent to which such geographical aspects of farms interact with local hydrography and bathymetry is a driving factor behind the risk associated with farming in marine environments remains unclear. The combination of these is likely important in trying to understand and predict how fish farms will affect and interact with ocean ecosystems. The correlation of latitude, geographic area and trophic status of the receiving waters with the degree of biological and geochemical response to farm discharge is an area for further investigation. Comparative meta-analyses of environmental impacts would provide additional information, but are challenging to conduct because of the different monitoring protocols used, inconsistency in reporting of farm site (latitude, depth, current regime, sediment type, background nutrient levels, biodiversity) and management characteristics (farm size, loading density, stock biomass, feed type, feeding rate), and language barriers.

One pattern that does emerge is that decreasing environmental risk from aquaculture appears to be driven by prudent siting of operations outside of shallow, enclosed, coastal and nearshore waters lacking dispersive current regimes, coupled with modern feed and farm management. This observation is important as it suggests that fish farming with minimal environmental effects is possible in many ecosystems as long as proper safeguards are in place to minimize nutrient and chemical discharge and to manage its immediate and cumulative impacts. These safeguards may be in the form of regulatory oversight or industry-developed best management practices. Ideally, a combination of the two approaches is most beneficial.

This report provides a broad perspective on a range of potential environmental impacts and their relative intensity, which should be coupled with detailed, site-specific information to make good management decisions about a proposed or operational farm site during its lifetime. If marine fish farming expands, cumulative impacts may or may not become more apparent, but robust monitoring protocols are necessary and should be proactively designed to be able to discern both near and far-field environmental impacts. A standard guide and protocols for environmental monitoring at marine fish farms may be useful in the U.S. for

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monitoring and comparing results at local, regional, and national levels.

The scientific information reviewed in this report provides current information to NOAA and other stakeholders about the environmental effects of marine finfish cage culture. Development, regulation and operations of marine finfish cage farming should continue to be supported by a strong underpinning of scientific knowledge and expertise. Additional national, regional and local decision-making tools, including computer simulation modeling, to aid in siting and refining monitoring protocols would be useful to government agencies and fish farm operators. Continued assessments of the effects of marine fish farming in the ocean has on marine environments should be undertaken. Our understanding of nutrient flux and accumulation in the water and sediments around farms, and resulting impacts to local biodiversity has greatly improved in the last decades. However, questions remain about far-field effects over large time scales.

The rising world population is becoming more reliant on aquaculture for food production. In the U.S., the regulatory process for permitting offshore aquaculture facilities is moving forward and industry growth is expected to follow. Domestic production of seafood can aid in decreasing U.S. reliance on imported products, provide jobs and food security, and meet the rising demand for seafood. Every effort should be made to ensure that industry growth occurs within a framework of environmental responsibility and ocean stewardship.

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