PACIFIC COAST SHELLFISH GROWERS ASSOCIATION

ENVIRONMENTAL CODES OF PRACTICE

FOR

PACIFIC COAST SHELLFISH AQUACULTURE

SECTION I: INTRODUCTION

Executive Summary

These Environmental Codes of Practice (ECOP) have been developed by the Pacific Coast Shellfish Growers Association, representing shellfish farmers in Alaska, Washington, Oregon, California and Hawaii. This document is intended to serve as a road map for implementation of PCSGA's Environmental Policy, developed by growers and first published in 2001. The document undergoes periodic updates as policies and science advance.

The original Environmental Policy set forth general principles for shellfish farming operations, which encompassed these primary areas:

- Environmental Stewardship and Responsible Management
- Environmental Excellence
- Regulatory Compliance
- Waste Management
- Sharing Resources

Given the vast differences in farming operations from region to region, and even from farm to farm, these codes are designed to allow for flexibility in individual farm management plans and farming practices. They are intended to serve as a guideline for developing, complying with and monitoring best management practices for shellfish aquaculture operations that complement the ecosystem in which farmers work. This document forms the basis for establishment of Best Management Practices (BMPs) for all stages of shellfish aquaculture operations.

Background

Shellfish farming began on the West Coast over 150 years ago. Because farmers' livelihoods depend upon the health of the marine environment, farming families have long played a unique role in keeping watch over the estuaries and watersheds in which they operate. The Environmental Management System being developed by the industry, as detailed in these Codes, is in keeping with this traditional stewardship role.

This document attempts to identify interactions between farming practices and the ecosystem – with a goal of promoting sustainable farming practices. To do this, we have made every effort to use the best available science to evaluate interactions that may occur in the course of farming shellfish, from the initial preparation of shellfish beds through cultivation, harvest, processing and transport to market.

Innovations developed over the years by shellfish growers have made it possible for them to stay in business despite significant challenges. Increasing development of the shoreline, loss of approved growing areas due to pollution, limited and diminishing natural resources, and an increasingly complex regulatory environment all contribute to a climate that makes conducting a shellfish aquaculture business challenging. These Codes are intended to encourage growers to continue seizing opportunities for innovations that favor environmental outcomes over prescriptive guidelines.

In 2011, the U.S. Department of Commerce (DOC) and the National Oceanographic and Atmospheric Administration (NOAA) updated their national aquaculture policies in an effort to increase the value of domestic production of aquaculture. NOAA launched a National Shellfish Initiative to implement the updated policy and Washington launched a state shellfish initiative to implement the national initiative. Since then other west and east coast states have followed suit resulting in a steady growth in shellfish aquaculture on both coasts. With this growth, implementation of these guidelines becomes all the more crucial to ensure responsible practices.The Code of Conduct for Responsible Fisheries, developed by the Food and Agriculture Organization (FAO) of the United Nations, has also set forth a policy to create sustainable economic opportunities in aquaculture that are "environmentally sound and consistent with applicable laws and policies."

It is the intent of these guidelines to provide a framework and tools for applying best management practices. It is assumed that growers will abide by or exceed all legal requirements already imposed upon their operations. Compliance with existing regulations is mandatory and defines the terms under which shellfish farmers are licensed and permitted to operate. Farmers are encouraged to stay abreast of regulatory issues and changes to assure they obtain and operate according to required permits.

Standards required under the National Shellfish Sanitation Program (NSSP) for assuring the safety of shellfish as a food product are not incorporated here. These federal laws, and the state laws which in some cases are even more stringent than their federal counterparts, are extremely comprehensive and subject to regular review and revision, but they are outside the scope of these codes, which focus primarily on issues of avoiding potential environmental impacts.

These Environmental Codes are intended to provide a framework for developing individual farm plans that implement best management practices, while also continuing in the tradition of innovation that has been a hallmark of the shellfish aquaculture industry. Much is already known about the marine environment and the interaction of shellfish aquaculture in that environment, but more knowledge is being gained all the time. As our understanding of the ecosystem, environment and habitat conservation issues evolve, so too will farming practices.

Purpose of Environmental Codes of Practice

The Environmental Codes of Practice is designed to be a living document— to be updated periodically as the industry develops new innovations in operations, and as we develop better scientific understanding of environmental and habitat interactions of shellfish culture operations. The goal of the PCSGA is to continue to promote sound and sustainable environmental practices that enhance the marine environment, and to provide high quality protein to consumers looking for healthful, sustainable foods.

The strategies recommended in this document are also aimed at improving public understanding of shellfish aquaculture activities as a legitimate and beneficial use of marine resources. To aid growers in developing their own individual farm plans, this document is divided into sections, beginning with a general overview of operations common to most growers on the Pacific Coast, then broken into specific species and culture methods, allowing growers to utilize only those sections that pertain to their particular activities. Each section ends with a list of example strategies that could be included in a farm plan compliance checklist.

Acknowledgements
The original ECOP was prepared through the joint efforts of Pacific Shellfish Institute staff and the Environmental Management Committee and the PCSGA Board of Directors that was in place at the time. It was funded in part by U.S. Department of Commerce/National Oceanographic and Atmospheric Administration/National Sea Grant College program, as part of its National Marine Aquaculture Initiative. (NOAA Award No. 0FA621:RAW). Subsequent updates have been prepared through funding of PCSGA member dues. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA, any of its sub-agencies, or contractor affiliations.

Industry Overview

The roots of the Pacific Coast shellfish industry can be traced back centuries. Native coastal cultures depended on shellfish as an important mainstay of their diet. Even tribes east of the Cascade mountain range were known to travel hundreds of miles to feast upon West Coast shellfish.

By the mid 1800's, pioneers to the West Coast began actively cultivating and harvesting native oysters (*Ostrea lurida*) from San Francisco Bay. To keep up with the demand of hungry gold miners during the California Gold Rush, commercial oyster harvesting expanded north from San Francisco into Oregon's Yaquina, Netarts and Tillamook Bays and Washington's Willapa Bay and Puget Sound.

Oregon was the first West Coast state to actively encourage the cultivation of oysters. In 1862, Oregon lawmakers officially designated certain tidelands in Yaquina, Netarts and Tillamook Bays specifically for propagation of oysters.

Intensive cultivation began in Washington State as a result of the Bush and Callow Acts passed by the Washington State Legislature in 1895, which provided for the sale of tidelands into private ownership specifically for the purpose of culturing shellfish. The intention of the Bush and Callow Acts was to stimulate an oyster culture industry to supplement dwindling native oyster stocks. As a result, oyster farmers were able to acquire and manage their tidelands, to create ideal environments for the propagation, growth and survival of the native oyster.

The production of native oysters rose steadily in Washington as a result of these cultivation techniques, but success was short-lived due to pollution, overharvesting, increased siltation due to upland logging practices, etc. For example in 1927, a sulfite pulp mill was constructed in Shelton, upland from a prolific oyster growing area in the far southern portion of Washington's Puget Sound. The pulp mill effluent was toxic to the sensitive Olympias, and by 1933, Olympia oyster production had declined by 57 percent. To sustain the crippled industry, the hardier Pacific oyster (*Crassostrea gigas*), was introduced from Japan on an experimental basis in the early 1900s. It took hold and became the dominant oyster cultivated in Washington.

The single greatest environmental factor affecting the shellfish industry has been, and continues to be, pollution of marine waters. Statistics over the past 25 years illustrate this ongoing problem. In 2009, approximately 24% of Puget Sound's commercial growing areas were restricted (at least for short periods) from harvest due to pathogen and bacterial pollution (WDOH 2010). Oregon and California have also suffered from pollution, with few shellfish growing areas classified as fully approved. The greatest social factor affecting the shellfish industry is the intensive residential development of shorelines where new residents may object to farming operations in their viewshed. The added residential development further contributes to the environmental impacts of the shoreline waters.

Despite such significant setbacks, shellfish farming as a whole continues to be a significant food producer and employer in rural shoreline communities. Originally, all Pacific oyster seed was imported from Japan. In about 1935 Pacific oysters began to become naturalized and spawn naturally in Willapa Bay and Hood Canal. This natural setting and the advent of shellfish hatcheries allowed importation of seed from Japan to end in the 1970s. To provide for improved predictability of oyster seed supply in years when little or no natural oyster setting occurred, modern private hatcheries have developed on the West Coast, revolutionizing the industry. Domestic hatcheries are the main source of shellfish larvae and seed for farmers up and down the West Coast today, and most shellfish cultivated on the West Coast are from seed produced in West Coast hatcheries and/or nurseries, with some wild seed caught in a few locations.

Like the majority of land-based agricultural groups, Pacific Coast shellfish farms are largely based on the culture of species that were deliberately or accidentally introduced in the last century. These species, including Pacific oysters and Manila clams (*Venerupis philippinarum*), have naturally thrived and make a significant contribution to rural economies in the farming, fishing and recreational harvesting sectors.

Advances in technology and other innovations have provided shellfish farmers the means to "do more with less," which creates the potential for significant growth. Unfortunately, significant challenges have arisen since the original publication of these guidelines that have the potential to thwart the realization of potential opportunities. In particular, increasing CO_2 levels in the atmosphere and oceans have caused issues associated with ocean acidification, which affects seed survival, and in turn necessitates significant alterations in hatchery practices.

Similarly, an increasingly complicated regulatory regime threatens the economic viability of both existing farms and proposed new farms. Because multiple regulatory agencies address similar issues in their permitting reviews, there is a significant need for coordination among agencies to avoid redundancy and duplication. Regulatory agencies have at times focused on data gaps and speculative environmental impacts, without fully considering existing scientific literature or the beneficial impacts of shellfish culture. Finally, because the regulatory regime for shellfish is fairly new, permit processes have often taken an extended period of time to complete. At times, state agencies have been inconsistent in their interpretation of regulatory requirements in different regions. These issues have increased the costs entailed in permitting shellfish farms, particularly expanded or new farms.

Finally, while the benefits of shellfish are broadly recognized in the scientific community, and form the foundation of bivalve restoration policies being aggressively implemented on the East Coast, the net environmental benefits provided by West Coast shellfish growers (water filtration, habitat benefits, species diversity) often go unrecognized.

Selective Breeding

For as long as plants and animals have been domesticated, farmers have engaged in selective techniques for enhancing growth, disease resistance and other characteristics leading to better yield. While the shellfish industry lags behind other agricultural groups with respect to domestication of cultured stocks, there is increasing effort put forth in hatchery practices and husbandry efforts that select for characteristics linked to productivity, survival, and consumer preference.

Three traditional methods have been employed along the Pacific Coast to improve performance of shellfish species: (1) selective breeding, (2) cross breeding, and (3) polyploidy. Traditional selective breeding involves identifying shellfish broodstock that present desired characteristics such as fast growth rate, attractive shape, good meat-to-shell ratio and resistance to disease. These animals are selected as desired broodstock, and bred to create the next generation. This is the method being used in the Molluscan Broodstock Program (MBP) housed at the Hatfield Marine Science Center in Newport, Oregon. It has also been a long established practice to use broodstock resulting from wild set oysters. It is felt that through the natural selection process, broodstock from the wild may provide for a more naturally disease resistant strain of larva.

The cross-breeding technique is based on the principle of "hybrid vigor" which has been clearly demonstrated in the corn industry, where crosses between two highly inbred families may lead to a hybrid progeny presenting exceptional growth characteristics. The Western Regional Aquaculture Center is currently supporting research involving the cross breeding of Pacific oysters to improve performance.

Polyploidy is a technique applied to early embryos, which prevents the loss of chromosomes that would normally be lost during meiosis, resulting in multiple sets (X) of chromosomes (n). These polyploid (Xn) individuals contain the same chromosomes that were present in the eggs and sperm. To be clear, this is not a method of genetic modification as no genomic alteration is done and no foreign genes from other species are introduced in this process. This approach has been widely used in agricultural industries. For example, bananas are triploids (3n), wheat is hexaploid (6n), blueberries are naturally tetraploid (4n) and sugar beets are triploid (3n). PCSGA grown shellfish are all non-GMO shellfish.

Polyploidy allows shellfish farmers to produce triploid animals that are sterile. This has many advantages in the culture of bivalves and their commercial value during a natural spawning period. Normally, commercially cultivated shellfish species expend considerable energy on gametogenesis (reproduction). In a sterile animal this energy is partially redirected to growth. Spawning oysters become soft or milky in the summer months, making them less desirable for the market, whereas sterile oysters stay firm and full of glycogen year-round. When oysters spawn, they release up to 50% of their body mass and dramatically reduce crop yield for extended periods of time. This problem is averted with a sterile crop.

PCSGA's GMO Policy

These selective breeding activities are entirely separate from and should not be confused with genetic engineering or "genetically modified organism" (GMO) technology that involves the transfer of genes from one organism into another, a technology known as "gene splicing."

In response to growing concerns regarding GMO technology, the PCSGA Board of Directors has adopted the following policy:

> Shellfish growers who are members of PCSGA do not introduce genes from other species into their shellfish. PCSGA is not aware of this technology being utilized by any shellfish growers on the West Coast of the United States.

Definition of "Genetically Modified Organism": by Dr. Emerson D. Nafziger, Professor of Crop Production at the University of Illinois (October 28, 1999):

> "The acronym GMO stands for 'genetically modified organism,' a term first used years ago to designate microorganisms that had genes from other species transferred into their genetic material by the then-new techniques of "gene-splicing." Applied to crops, the term refers to any genetic plant type that has had a gene or genes from a different species transferred into its genetic material using accepted techniques of genetic engineering, and where such introduced genes have been shown to produce a gene product (a protein)."

Benefits of Shellfish Aquaculture

The cultivation of shellfish provides multiple benefits to the marine ecosystem, due to both the biological functions performed and the habitat provided by the shellfish themselves, as well as the stewardship role of shellfish farmers who constantly monitor their growing areas for environmental threats.

<u>Habitat</u>. Cultivated shellfish create three dimensional structures through a portion of the water column that can simulate "artificial" reefs, providing habitat for an array of marine plants and animals. While much of the positive impact occurs at the lower end of the food chain, the increased abundance of fish and shore birds often found around shellfish beds is a direct response to this improved habitat and available food source. Farmers report significant increases in the natural abundance of marine plants, animals and wildlife around their farms when new beds of shellfish are cultivated. Current studies have provided quantifiable data that supports these observations by shellfish farms (Žydelis et al. 2006; Žydelis et al. 2009).

Shellfish beds provide habitat for a variety of benthic and epibenthic invertebrates that can exceed the abundance, biomass and diversity found in open mud or eelgrass-dominated habitat. Oysters and other cultured shellfish also provide attachment surfaces for algae, mussels, barnacles and small invertebrate prey used as protection or food by juvenile Dungeness crabs, juvenile salmon and other marine species (Bigford 1998; Dumbauld 1997; Dumbauld et al. 2000a; Meyer and Townsend 2000; O'Beirn et al. 2004; DeAlteris et al. 2004; Pinnix et al. 2005; Powers et al. 2007; Tallman and Forrester 2007).

Biofiltration. Shellfish provide a critical function in the ecosystem through the biofiltration that occurs as part of their feeding activities. The ability of shellfish to clarify the water column can be used as a means for effectively mitigating the impacts of anthropogenic activities and shoreline development that promote nutrient enrichment into the nearshore. Biofiltration and a clearer water column allows for sunlight to reach deeper and promote growth of sea grasses, which provide further environmental benefits. Shellfish aquaculture may provide the most economical and environmentally suitable means for offsetting shoreline development impacts on eutrophication that contributes to degradation of our coastal environments (Asmus and Asmus 1991; Newell et al. 1999; Newell et al. 2000). A full discussion of biofiltration effects from shellfish aquaculture is provided in Section II (Shellfish Aquaculture–Interactions in the Marine Environment).

Stewardship. In addition to these important ecosystem functions, growers themselves play an important role in protecting the environment. Because shellfish farmers' livelihoods have always depended upon clean water and maintaining the delicate balance of the marine environment, shellfish farmers have a long-standing history of marine stewardship and are incentivized to remain environmentally vigilant. Their bottom line depends upon the protection of water quality and habitat. The advocacy role played by oystermen in the mid 1900's, when they launched an exhaustive campaign to force pulp mills to clean up toxic effluent, continues today, and the results of their efforts can be seen in the restoration of growing areas, and increasing populations of native oysters once considered all but extinct in many West Coast bays and inlets.

Portrait of the Pacific Coast States

Washington dominates the West Coast shellfish industry with extensive culture of Pacific oysters in the coastal bays of Willapa and Grays Harbor. These are sold both as fresh-shucked meat and live in the shell. Willapa Bay also has a growing Manila clam industry, which is currently being impacted by the invasive Japanese eelgrass Zostera japonica. Southern Puget Sound and Hood Canal follow close behind the coastal region, with crops of Pacific oysters, and Manila clams cultivated in highly productive nutrient rich waters.

Two species of mussels (Mytilus trossulus and Mytilus galloprovincialis) are grown in both Northern and Southern Puget Sound. Northern Puget Sound (including Hood Canal) is also home to a small segment of family-owned clam and oyster farms and shellfish nursery operations. The Washington shellfish industry supports numerous families, tribes, and employees, in addition to subsistence, ceremonial and recreational harvests that contribute significantly to coastal economies and cultures.

Some Washington shellfish growers have developed niche markets by cultivating a variety of specialty oysters targeted at the half-shell market, including Kumamotos (*Crassostrea sikamea*), the Eastern oyster (*Crassostrea virginica*), European flats (*Ostrea edulis*), and the native oyster. Washington is also home to a burgeoning geoduck clam (*Panopea generosa*) culture industry, which started with enhancement of wild stocks in 1991 and moved toward commercial scale enhancement in 1996 (Straus et al. 2009).

California follows Washington in shellfish production output. Tomales Bay supports a growing native Littleneck clam (*Leukoma staminea*) and bay mussel industry, and a thriving oyster industry targeting a voracious San Francisco half-shell market. Humboldt Bay in Northern California supports extensive bottom, rack-and-bag, hanging basket, and intertidal longline culture of Pacific and Kumamoto oysters, as well as a nursery system that serves as one of the industry's key shellfish seed suppliers.

Oregon's shellfish culture efforts are focused primarily on the Pacific and Kumamoto oysters. Growers in the Umpqua estuary and in Coos, Winchester, and Yaquina bays on the South and Central coasts of the state use a variety of bottom and suspended culturing methods. Tillamook Bay in the North, once a leader in bottom-cultured Pacific and Kumamoto oysters, struggles today to survive the effects of ghost shrimp (*Neotrypaea californiensis*) and mud shrimp (*Upogebia pugettensis*) by using bottom, intertidal longline, and raft culture methods. Also in the North, Netarts Bay supports a small but growing half-shell producing industry, and is home to one of the West Coast's four shellfish hatcheries.

Alaska supports a hardy lot of family farms pioneering shellfish culture in the last frontier. Against great odds, Alaskan growers produce mussels and half-shell Pacific oysters grown on suspended culture systems in their cold, pristine waters.

Hawaii has seen occasional start-ups of experimental shellfish farming operations over the years, and the potential for farms in the subtidal or offshore zone could be significant. However, Hawaii is currently most notably a crucial link for the entire West Coast due to the shellfish nurseries and hatcheries sited there. Washington-based companies have hatcheries and nurseries on the Big Island where the tropical climate provides the perfect environment for algae production required for boosting seed production, particularly beneficial during the cool, slow growing winter months in the Pacific Northwest.

Annotated Bibliography—Section I

Aerni, P. 2004. Risk, regulation and innovation: The case of aquaculture and transgenic fish. Aquat. Sci. 66 pp. 327–341.

The public and scientific debates over the risks and benefits of aquaculture and aquatic biotechnology is reviewed. Growth enhanced transgenic salmon may become the first bioengineered animal product approved for use as food in the United States. The fish may boost future salmon harvests, contribute to productivity increases in aquaculture and lower consumer prices for salmon. But it also faces public opposition, reluctant investors and scientific skepticism due to mainly environmental concerns. The paper argues that even though the regulatory framework in the United States is well-elaborated, it may not be able to reassure public opposition once transgenic salmon should be approved. Analogous to genetically modified food crops, the consumer market rather than regulation will determine the ultimate fate of transgenic fish.

Agar, N., Lodge, D. M., McKenny, G.P., Wolfenbarger, L. 2006 Altering Nature Volume Two: Religion, Biotechnology, and Public Policy.

This book chapter discusses the relationship between biotechnology and biodiversity, particularly transgenic organisms. Opponents of genetically modified organisms regularly point to the potential effects of these organisms on biodiversity as a reason for prohibiting or strictly regulating research on and application of transgenics. This chapter attempts to evaluate these claims by a careful consideration of the issues they raise in the context of current scientific research. In order to evaluate the claims regarding transgenic research and biodiversity we must ask two preliminary questions: 1) What are the potential impacts of genetically engineered organisms on biodiversity? 2) What do we know about the likelihood of such effects?

Bert, T.M., Crawford, C.R., Tringali, S.S., Galvin, J.L., Higham, M., Lund, C. 2007. Genetic Management of Hatchery-Based Stock Enhancement. Methods and Technologies in Fish Biology and Fisheries. Volume 6: Ecological and Genetic Implications of Aquaculture Activities.

Including genetic considerations in stock enhancement can reduce the probability that enhanced (admixed) populations will undergo damaging genetic alteration through the stock enhancement effort. Avoiding alterations in genetic diversity, decreases in fitness, and reductions in effective population size (Ne) of admixed populations and their wild-population components is important for the long-term sustainability of those populations. Maintaining the genetic diversity of admixed populations and their wild-population components first requires managing both the genetic variability (e.g., numbers of alleles) and the genetic composition (frequencies of alleles) in the broodstock and the broods. Genetic monitoring programs for specific stock enhancement efforts should contain sufficient procedures to address all potential genetic concerns. A principal objective of stock enhancement is to improve the probability that wild populations will sustain and be viable over ecological or evolutionary time frames.

Dolmer, P., Frandsen, R.P. 2002. Evaluation of the Danish mussel fishery: suggestions for an ecosystem management approach. Helgol Mar. Res. 56. pp. 13–20.

Ten year study conducted in Limfjorden, Denmark, concerning the impact of wild stocks of *Mytilus edulis* dredging on the ecosystem. To evaluate the impact on clearance capacity of a reduction in mussel densities due to mussel dredging, mussel filtration activity measured in situ has been related to the mixing of the water column and the amount of near-bed phytoplankton. Fishery practice for mussel dredging in Limfjorden is discussed in relation to its known impact on the ecosystem and the ecological role of the mussels, and modifications towards an ecosystem management approach and a more sustainable fishery are suggested including: a fishery practice where the mussel beds are thinned out when the mussels have attained good quality, and a transplantation practice of mussels from areas with a high mortality to areas with a high growth rate. This will intensify the production in a certain area, leaving other areas open for alternative production or for permanent closure for the benefit of the benthic flora and fauna. In addition, other shellfish species represent interesting new resources for fishing or aquaculture. Habitat restoration, such as the relaying of mussel shells from the mussel industry, is another important management tool.

Erbland, P., Ozbay, G. 2006. Community shift associated with shellfish aquaculture in two mid-atlantic estuaries. Journal of Shellfish Research. Vol. 25, no. 2, p. 726.

In response to the interest in the culture of *C. virginica* enclosed in "grow out gear" (GOG) to increase yields, impacts on the host ecosystems should be evaluated. This is a two part study investigating shifts in the benthic and infaunal communities by comparing the diversity and abundance of species inhabiting subtidal "Rack and Bag" type GOG, containing *C. virginica*, with an adjacent, created *C. virginica* reef in Indian River Bay, DE. Then by comparing the diversity and abundance of infaunal species present below intertidal oyster gear with an adjacent control area of open sand flat on the eastern shore of Delaware Bay. This study will provide insight into the ecological impact of shellfish aquaculture and be useful in incorporation of *C. virginica* aquaculture into the management schemes.

Knibb, W. 1997. Risk from genetically engineered and modified marine fish. Transgenic Research 6, pp. 59–67.

In support of the emerging industries of warm water marine fish mariculture, genetic engineering and classical genetic improvement programs have been initiated for a variety of exclusively marine fish. These programs have the potential to perturb allele and genotype frequencies, or introduce novel alleles and genes into conspecific wild populations. Despite concerns to the contrary, the following hypothesis remains to be falsified: 'laboratory induced allele frequency/genotype changes and novel alleles or genes have a negligible probability of being selectively favored in wild populations under natural selection, and accordingly, without sustained large scale releases, have little potential for ecological impact'.

Rheault, R.B. 2008. Carrying Capacity. Report on Biological Impacts of Aquaculture. Coastal Resources Management Council. pp. 49-59.

The term "carrying capacity" has been used with varying definitions to describe the quantity of something that can be added to an ecosystem before some undesirable impact occurs. Small-scale shellfish aquaculture has been shown to have ecological benefits, but at some point too much of a good thing invariably has negative consequences. Where to draw that line can be a subjective question that depends on which specific consequences are of concern.

Wetherall, J.D., Groth, D.M. 1998. DNA variation: Nature and possible applications in aquaculture. Australian Shellfish Aquaculture Conference.

This paper provides an overview of two instances of variability in DNA sequences and discusses the possible applications to aquaculture of analyzing this variation using the techniques of molecular biology. The first instance reflects the number of related tandemly repeating core segments comprising nuclear minisatellite DNA dispersed throughout the genomes of many metazoans. Such variable number tandem repeat polymorphism, characteristic of minisatellite DNA, can be exploited to generate DNA fingerprints which are unique for individuals within a species and can be used to predict degrees of relatedness within breeding groups and can be used for marker assisted improvement of breeding stock. Also relatively simple analysis of mitochondrial DNA sequence variability can be used to assess the extent of genetic similarity between species and relationships between subgroups within a species.

Wisehart, L., Hacker, S.D., Dumbauld, B.R., Ruesink, J.L. 2006. Oyster aquaculture may positively affect eelgrass (*Zostera marina L.*) through enhanced seed production and germination. Journal of Shellfish Research. Vol. 25, no. 2, p. 792.

The interactions between oyster aquaculture and eelgrass are explored, particularly how such aquaculture may affect eelgrass recruitment. Surveys in Willapa Bay, WA showed higher seedling densities in dredged beds than in longlines or eelgrass beds. The authors hypothesized that this pattern was due to variations in seed density and/or differences in germination. Estimated seed densities were found to be highest in dredged beds and lowest in longlines. We also tested the hypothesis that dredging positively influences germination. Germination was highest in the eelgrass beds, where, interestingly, eelgrass removal had a positive effect. Higher germination in removal plots suggests that reduced competition for light and other resources may positively influence recruitment. Greater recruitment in dredged beds may thus be due to both enhanced seed densities as well as removal of neighboring adults. Together these studies suggest ground culture practices may positively affect eelgrass recruitment while longlines may have a negative effect.

SECTION II: SHELLFISH AQUACULTURE – INTERACTIONS IN THE MARINE ENVIRONMENT

The Effects of Shellfish Aquaculture

These Environmental Codes of Practice and the strategies listed in this section are based upon the best available science. As more is learned about the interactions of shellfish aquaculture with the marine environment, the codes and recommended farming practices will be amended to reflect the latest body of knowledge.

This document is intended to identify impacts of shellfish aquaculture on the natural environment and provide guidance to growers in utilizing Best Management Practices (BMPs). Growers should strive to understand the particular impacts their activities have on the environment, and conduct activities so as to minimize negative impacts and maximize positive effects.

Shellfish aquaculture is unique among agricultural activities in that, when properly done, it does not exploit or dissipate natural resources. Rather, shellfish are intrinsic to the overall healthy functioning of the marine environment, and when cultivated at a level appropriate to the carrying capacity of the growing area, offer more benefits than drawbacks.

The following sections identify specific components where there is interaction in the environment with shellfish farming activities. The Conclusions section and Objectives and Strategies tables are intended to assist growers in identifying those areas where their activities have a potential for impact and possible mitigation efforts.

Note: The Objectives and Strategies tables that follow after each section are intended as suggestions or examples only. Growers should use these in combination with a Farm Plan Compliance Checklist to develop their own individual Farm Plans.

The Benthic Community

The benthic (bottom) environments in shellfish growing areas range from intertidal and shallow subtidal to deepwater habitats. [1]. Benthic plant and animal life consists largely of communities of drift algae, infaunal organisms such as annelid worms and small bivalves, and a wide range of epifaunal animals such as amphipods, crabs, starfish and groundfish, including predator and prey species.

Sediments found in the benthos usually consist of fine-grained materials, such as sand, silt, clays and organic materials. Gravel and shell debris are also commonly found at many locations.

[1] The intertidal benthic area contains the important base of the food web important to nearly all the estuary biota. It is recognized that this lower fluvial energy environment of the nearshore results in a sedimentary environment usually consisting of fine clastics (sand and silt) and depending upon location additional clay and organics. The critical sedimentary surface with heterogenous clastics creates surface stability and that along with atmospheric exposure of the mudflat or shallow intertidal puddles during low tides for solar exposure the diatom-biofilm habitat is possible. The epipelic or benthic diatoms form the rich organic biofilm from excess organic material, which is then utilized by other biota including bacteria. The diatoms under optimal conditions and with high fecundity produce the necessary lipids and carbohydrates to supply initiate the rich near shore food web. When the intertidal diatom-biofilm habitat is used for sessile or subsurface shellfish the habitat becomes various even more available to various dozens of additional species and abundance increases in others. Notable beside the basal phytosythesizing benthic diatom flora would be important macroalgae (e.g. Ulva), crustaceans (e.g. ostracods, amphipods, decapods), mollusca (bivalves, gastropods), different phyla of worms and a series of higher trophic level predators such as crabs, shorebirds, fish, and yes, humans. Shellfish provide this boost to the habitat by providing additional surface attachment areas while maintain protection from physical impacts, such as tidal currents and wind waves. In general, the ground crop of shellfish are a stabilizing factor to the sediment surface allowing certain small amphipods to maintain burrows (e.g.

Corophium, a key prey amphipod for shorebirds). Oysters provide protection of invertebrates whether prey or predator creating forage areas for fish, shorebirds and crabs. Diatoms have the capability to derive essential nutrients from the mineral breakdown of igneous silicate mineral in the sediments, as well as, from the water and atmosphere which gives them the ability to supply the lipids and carbohydrates needed to fuel the near shore biota. However, sedimentary pollutants, change in pH by organic decomposition such as under thick eelgrass areas all can act to inhibit the diatom-biofilm formation and extent and thus limit abundance and diversity of the intertidal biota. The rich diatom/biofilm layer dependent upon a stable sediment surface attracts the primary consumer invertebrates, which either arrive with the tide (zooplankton) or have burrowed or found refuge at low tide on the mud flat.

Beneficial Effects

Structurally, epibenthic shellfish create three-dimensional habitat, utilized by numerous species of benthic invertebrates and vertebrates (Dumbauld et al. 2000b; Meyer and Townsend 2000). This surface area offers a foundation for the attachment of algae, mussels and other epibionts, resulting in enhanced biodiversity and greater density of prey species. For many species of shorebirds, seabirds and fish, species richness and abundance has been shown to increase as a result of the presence of shellfish aquaculture (Roycroft et al. 2004; Žydelis et al. 2006) and related gear.

Dealteris et al. (2004) found that shellfish aquaculture gear supported more organisms, had higher species richness and higher species diversity than non-vegetated seabed, and was similar or superior to eelgrass (*Zostera marina*) or submerged aquatic vegetation habitat. Likewise, Meyer and Townsend (2000) showed that created oyster reefs had a higher number of fish, molluscan, and crustacean invertebrate species than adjacent natural reefs.

O'Beirn et al. (2004) reported a wide variety and large number of marine organisms associated with the mesh bags of cultured oysters in Virginia, including worms, mollusks, crustaceans, and fish. Powers et al. (2007) documented that the macroalgal growth on protective netting placed over hard clam (*Mercenaria mercenaria*) aquaculture sites supported elevated densities of mobile invertebrates and juvenile fishes similar to natural seagrass (*Z. marina* and *Halodule wrightii*) habitats. In a three year USFWS study in North Humboldt Bay (Pinnix et al. 2005), oyster culture habitat either exceeded or was equivalent to eelgrass habitat in terms of fish species diversity and abundance. In addition, the most common species collected within the aquaculture locations included common prey species for salmonids and numerous avian predators (e.g., Pacific herring, northern anchovy, and shiner surfperch). Other studies have focused on the association between small fish (i.e., sculpin, surf perch, etc.) or groundfish species and various aquaculture operations (O'Beirn et al. 2004; Laffargue et al. 2006; Tallman and Forrester 2007). Overall, it is evident that fish and invertebrates are attracted to the structure and food resources available from shellfish culture, which can provide a surrogate for ecological processes found in eelgrass beds.

Areas of Potential Concern

Benthic communities can be negatively altered by intense farming activities that exceed the carrying capacity of a growing area. Studies have shown that large, intensively cultivated floating or off-the ground systems can result in the alteration of sediment chemistry as a result of increased organic solids and nutrient levels. For example, studies of very intensive raft-based cultivation in Spain indicated the diversity of the benthic community beneath the most intensively cultivated systems was lowered because of organic enrichment from mussel feces and pseudofeces (Blanco et al. 1996; Brooks 2000; Stenton et al. 1996). Reduced or limited affects were seen at locations with lower density, less intense suspended bivalve culture. However, there are no reports that the comparatively low densities at which shellfish are cultured on the West Coast have any significant potential to impact estuarine carrying capacity.

There are also indications that shellfish farming activities can alter the community structure of an aquaculture plot at culture densities below ecological carrying capacity. Spencer et al. (1997) reported that the netting used to reduce Manila clam predation led to an increase in surface deposit-feeding worms compared to a community dominated by subsurface deposit-feeding worms in non-netted plots. The authors suggested that competition from surface-deposit feeding worms on the netted plots may have excluded the subsurface deposit-feeding worms. Mechanical disturbance of the benthic habitat may also create a shift in the benthic community structure. Kaiser et al. (2006) commented that recovery may take longer in cases where recolonization through larval recruitment is the dominant mechanism, but in general evidence suggests that the short-term recovery by benthic invertebrates is relatively rapid (Kaiser et al. 1998; Ferns et al. 2000; Dernie et al. 2003; Kaiser et al. 2006).

Structures such as bags, racks, and longlines can also interrupt the action of waves and currents, resulting in deposition of fine sediments in the immediate vicinity of the structure. Small structures located in shallower productive nearshore/littoral waters that limit the amount of vegetation that gets into a system may reduce the amount of organic material available for detritus-feeding organisms, such as many polychaetes, amphipods, and isopods.

While these effects may be observed, Ferraro and Cole (2007) reported that oyster habitat was equivalent to eelgrass in terms of diversity and productivity of benthic macrofauna in Willapa Bay. The authors identified increased habitat complexity, food availability, shelter, substrate stability, sediment total organic carbon, and decreased predation, competition, and water flow velocity as primary factors in predicting species utilization of both oyster and eelgrass habitat. The body of literature on benthic community changes examined with shellfish aquaculture is substantial (*see* Dumbauld et al. 2009 for recent review). The high degree of variability in benthic community changes reported largely reflects variations in the geography, habitat type, culture method and culture density of the sites studied and emphasizes the value of site specific farm planning. While habitat is created for numerous species through the gear and structure provided from shellfish beds, some species can be displaced or otherwise unattracted to the habitat created.

Finally, invasive species impacts on and from aquaculture remain an area of concern that will continue to require vigilance and focus by growers. Invasive species such as Japanese oyster drill and Japanese eelgrass *Zostera japonica* create significant economic and ecological damages on tidelands used for shellfish farming in several regions along the West Coast. When such species invade shellfish beds after they are planted the beds can become less suitable growing environments (Tsai et al. 2010). In turn, the industry recognizes how practices from decades ago have been attributed to the introduction of some of the very invasive species that cause problems for the industry. From these experiences and the recognition of the ecological impacts of invasive species in the aquatic environment generally, the PCSGA firmly supports federal invasive species policy as outlined in the National Invasive Species Management Plan directed under Executive Order 13112. This policy essentially states, in order of priority, that federal agencies and stakeholders should work in concert to: (1) prevent the introduction of invasive species, (2) pursue early detection and rapid response (eradication) actions for species whose introduction was not prevented, and (3) prevent the further spread of established invasive species through the implementation of coordinated control and management actions.

Conclusions
In siting and determining the size of shellfish aquaculture activities, farmers must seek balance so that optimum filtration and three-dimensional habitat functions are achieved without exceeding densities that lead to excessive organic enrichment and eutrophication. Culture techniques should incorporate timing considerations to the benthic resources available and the amount of mechanical disturbance being exerted on the environment.

Water and Sediment Quality

Shellfish growers are wholly dependent on a healthy marine environment in which to grow their crops, as all shellfish feed on food filtered directly from the natural marine waters. Phytoplankton is the most important food source, but dissolved organic matter, bacteria and small detrital particles are also consumed.

Mussels and oysters can filter and ingest organic particles ranging in size from a few microns up to several hundred microns (Bayne 1998). They are also able to select between algae and silt particles by concentrating the algae between five and thirty times and rejecting the silt as pseudofeces (Winter 1978; Newell 2004). Their ability to filter and concentrate bacteria and viral debris from human sources has well-known public health implications. Therefore, maintaining an extremely high level of water quality in growing areas is imperative to growers.

Shellfish remove carbon and nutrients from the water during their growth (and eventual harvest), with some of the carbon and nutrients deposited back into underlying sediments, where they are slowly released back into the water (Dame 1993; Newell 2004). These animals also release soluble nitrogen waste in the form of ammonium and consume oxygen from the surrounding waters.

Generally, shellfish tend to stabilize phytoplankton concentrations – reducing the intensity of blooms and extending the period during which moderate levels of phytoplankton are produced (Newell et al. 2000).

Beneficial Effects
Bivalve molluscan shellfish derive most of their nutritional needs from filtering particles from the water, including suspended silt and clay, phytoplankton and detritus. This biofiltering function increases water clarity and light penetration (Peterson and Black 1991; Rice et al. 2000) and decreases the effects of eutrophication. Eutrophication can increase the duration and intensity of phytoplankton blooms, which then result in shading, leading to loss of seagrasses and other submerged aquatic vegetation (Short and Burdick 1996).

Through filtration, shellfish exert "top-down" control on phytoplankton stocks and reduce turbidity, thereby increasing light available to benthic plants for photosynthesis (Newell and Koh 2004; Grant et al. 2007; Rice 2008). Newell et al. (2000) documented that rehabilitation of eastern oysters in Chesapeake Bay would have the beneficial effect of removing phytoplankton from the water column without stimulating further phytoplankton production because no dissolved inorganic nitrogen was recycled to the water column under the oxic conditions tested in the laboratory.

Shellfish provide an efficient and effective means for mitigating the effects of nutrient loading as well. There is growing evidence that increased nutrient inputs caused by anthropogenic activities (fertilization, agricultural practices, sewage, stormwater runoff) can result in increases in the length and duration of low oxygen (hypoxic) events in estuarine waters that in turn can result in deleterious effects on the estuarine ecosystem as a whole (Rice et al. 2000). Although the amount of nitrogen in shellfish meats is only about 1% by weight (Dumbauld et al. 2009), about 16.8 grams of nitrogen is removed from estuaries for every kilogram of shellfish meat harvested (Rice et al. 2000). When put into farm production terms, this means a modest farm producing 5,600 oysters per year would mitigate the nitrogen produced by a single person). Estimates for total nitrogen in oysters, including shell, range from around 0.2 to 0.5 g N/oyster, with variation depending on species, condition, size, and geographical location.

Incorporation of nutrients in shellfish soft tissue through filter feeding and removal of these nutrients at harvest is not the only means by which shellfish culture directly mitigates nutrient pollution and coastal eutrophication. Cultured bivalves may assert a greater cumulative effect on water quality through "bottom-up" nutrient dynamics within the sediment than they do through the accumulation and removal of nitrogen through tissue growth (Newell 2004). When shellfish feed they accelerate the flux of organic material to the benthos where it is made available to benthic deposit feeders. Specifically, N and P that are not digested and incorporated into tissue are processed through the bivalves and excreted as soluble ammonia and biodeposits of mucous-bound feces and pseudofeces. When these biodeposits become incorporated into aerobic surficial sediments, microbial-mediated processes facilitate nitrification-denitrification coupling to permanently remove sediment-associated nitrogen as nitrogen gas (N2) (Newell 2004). To this end, Doering et al. (1987) showed that the presence of infaunal northern quahogs, Mercenaria mercenaria, increased the rates of inorganic nitrogen turnover in sediments, suggesting that biogeochemical processes in the sediments are stimulated. Assessing nitrogen removal potential of oysters in the Chesapeake Bay Newell et al. (2002) found the associated bacteria in sediments of an oyster bed can remove 20% or more of the N in oyster wastes, using the same nitrification/denitrification process that is used in modern wastewater treatment plants.

When appropriately balanced, biogeochemical coupling provided by filter feeding bivalves provides a fundamental role in nutrient cycling by facilitating the exchange of water column nutrients with the sediments through biodeposition. In comparing the feeding rates of two different shellfish species grown on the West Coast, Fisher et al. (2008, unpublished) reported that biodeposition of individual harvest size geoduck exceeds that of individual oysters—owing to their size differences. However, the biodeposition of oysters planted at commercial densities would exceed that of commercial densities of geoduck by more than 2-fold (Table 2.1).

Table 2.1 – Feeding rates for Pacific oysters and geoduck clams

Species	Feeding Rate (L filtered/individual/day)[1]	Biodeposition (mg-produced/individual/day)[2]	Feeding Rate (L-filtered/acre/day)[3]	Biodeposition (kg deposited/acre/day)[4]
Medium Pacific Oyster	70	187	100 mill. (cluster) 20 million (single)	215 (cluster) 43 (single)
Geoduck Clam	100	500	4.6 million	17.5

[1]Liters of water filtered/individual shellfish/day; [2] The amount of feces and pseudofeces produced per individual, per day; [3]The rate of filtration on a per acre basis, considering whether cluster (cultch) or singles are produced; [4] The amount of feces and pseudofeces projected from the biomass produced per day on a per acre bases.

Source: J. Davis, *as cited in* Fisher et al. 2008a, unpublished

The nutrient cycling aspects of shellfish populations may be a significant element in the maintenance and growth of eelgrass communities in estuarine ecosystems as well. Eelgrass growth may increase in areas where the plants are co-mingled with bottom-growing shellfish (Newell 2006). Mussels (*Modiolus americanus*) enhanced seagrass (*Thallasia testudinum*) productivity in a Florida study by increasing porewater nutrient concentrations, which correlated with increased nitrogen and phosphorus content in seagrass blades and faster growth (Peterson and Heck, 2001). A similar study in southern California examined interactions between eelgrass (*Zostera marina*) and an introduced mussel (*Musculista senhousia*) (Reusch and Williams, 1998). Mussels were placed in eelgrass beds and near eelgrass transplants at several densities. At high densities, mussels inhibited rhizome extension of eelgrass, but across a range of densities, eelgrass blade growth rates increased. This finding of enhanced growth was consistent with those of Tallis et al. (2009) in their evaluation of bottom cultured oysters in Willapa Bay, and their documentation that disturbance/displacement of eelgrass varies by oyster culture method.

Areas of Concern

The chief concern regarding the effect of shellfish aquaculture on water and sediment quality is that of the potential to exceed ecological carrying capacity; specifically, at what point does the quantity of shellfish being cultivated in a given area become too great to sustain an optimally viable ecosystem? The principal water quality pathway with a nexus to carrying capacity is related to the biogeochemical coupling of shellfish, their resultant deposition of feces and pseudofeces, and the cycling of nitrogenous-based compounds back into the water column, sediment, and atmosphere (denitrification). If the intensity/density of culture operations causes biodeposition to exceed the rates of nitrification/denitrification and nutrient removal through harvest and other N/P recycling processes, clearly microbial respiration in the sediments may exceed oxygen supply. Such imbalances can result in localized oxygen deficits (anoxia), releases of P to the water column, and increased hydrogen sulfide concentrations within the benthos. Concern has thus been raised where impacts have been proposed both from nutrient reduction as a result of shellfish competition, as well as nutrient excess--if culture densities result in excessive ammonia release or sediment biological oxygen demand (i.e., from excessive biodeposition). For example, Gibbs (2004) proposed that shellfish limit nutrient availability for marine vegetation and non-cultured species in areas of intensive long term culture. In contrast, Pacific oysters in Totten Inlet, which has a large amount of anthropogenic nutrient input and the largest densities of shellfish culture of any of the water bodies in Puget Sound, had faster growth rates compared to anywhere else in the Puget Sound area (Ruesink 2009), and only local phytoplankton depletion around raft structures was documented (Dumbauld et al. 2009). Ruesink (2009) went on to conclude that the shellfish biomass in Totten Inlet is well below carrying capacity, based on the available nutrients to support filter feeders. These data would suggest that other embayments where shellfish are cultured along the West Coast are unlikely to be exceeding ecological carrying capacity under current production regimes.

In contrast, a general feature observed where shellfish have been intensively cultivated in Europe is a tendency for depression of growth rates of the shellfish themselves. Shellfish grown in high densities can result in depletion of suspended organic matter in the vicinity. In the case of a large, intensively cultivated raft system observed in Spain, thermal stratification caused reduced availability of nutrients above the thermocline in the vicinity of the mussel rafts (Blanco et al. 1996). It should be noted that there are orders of magnitude difference in the intensity of culture in Europe compared to the United States, and this is not an effect that has not been experienced on the U.S. West Coast.

Conclusions

Shellfish aquaculture can significantly benefit water quality at the waterbody scale. The degree to which this benefit accrues is dependent in part on the environmental baseline of water quality in the water body, and the density of the cultured organisms. Though culture densities in U.S. waters have not been reported to exceed ecological carrying capacity, continued efforts to model shellfish populations under a variety of conditions are needed to accurately predict carrying capacity criteria for shellfish aquaculture as the industry expands. To best assess the appropriate and most sustainable scale of activities for any given growing area, we must continue to enhance our understanding of the effects of shellfish cultivation methods on water column flow dynamics, depletion of nutrients, and re-suspension of ingested materials, biodeposition of feces and pseudofeces and conversion of materials into shellfish tissue. It has been suggested by Ferreira et al. (2007) and Lindaul and Kollberg (2009) that models estimating annual phytoplankton production and comparing that production with the nutritional needs for all "natural organisms" within a bay might lead to economic credits for shellfish growers for their role in maintaining water quality. Several projects are now underway in collaboration with researchers and shellfish farmers in Washington, Oregon and Alaska to further verify these relationships.

The Upland Environment

The upland environment is extremely important for shellfish farmers. There are well-documented and clear links between activities in upland areas and the health and safety of cultured shellfish (Mallin et al. 2000; May et al. 1997; Tonkin et al. 2007). For example, Tonkin et al. (2007) reported that bulkheads impound sediment and prevent erosion of "feeder bluffs" above a beach, which can (but does not always) affect beach composition and structure. Further, the result of increased turbulence and erosional energy at the base of a bulkhead can result in substrate coarsening and lowering of the beach profile (McDonald et al. 1994). In some areas, such as Willapa Bay, large areas of salt marsh have been diked, which eliminated these areas contributing food to the estuary. Recent projects have returned some of these areas to the food web, which may increase carrying capacity.

The sanitary quality of shellfish growing waters is strongly linked to the scale and intensity of upland development, including the presence of sewage and stormwater outfalls, agriculture, domestic animals, wildlife and other upland sources of contamination. The classification of growing waters is largely a reflection of those sources (WDOH 2010).

Beneficial Effects

As a matter of survival, shellfish growers become involved in watershed protection activities in most growing areas of the West Coast. Because they stand to lose the most if upland activities result in degradation of water quality, growers often become involved in local environmental, regulatory, political and community activities related to the watersheds that affect their growing areas. By the same token, it is in the growers' best interests to operate responsibly in upland areas to assure that their activities support, or do not negatively impact, the marine waters below. Growers are in a good position to model appropriate behavior in upland habitat, and are often the first eyes and responders to incidents of environmental upset because they are 'on the ground' regularly to monitor conditions.

Areas of Concern

Shellfish growers' activities generally take place in upland areas as well, for example in the process of transport to and from the growing area, the siting of hygienic facilities for workers, and management of waste generated from cultivation activities. Farmers have a responsibility for assuring that those activities do not negatively impact either the upland or marine environment. They have a critical role to play in displaying appropriate upland use.

Conclusions

Because most farming operations involve some activities in the upland area, it is critical that growers carefully assess their potential for negative impacts and take precautions to assure that their activities do not result in damage to marine waters.

Critical Habitat Issues

These environmental codes are a first step toward helping growers comply with a multitude of fish, wildlife and habitat protection statutes, including the Endangered Species Act (ESA), the Marine Mammal Protection Act (MMPA), the Magnuson-Stevens Fishery Conservation and Management Act (MSA), and other critical habitat protection measures implemented at the federal, state and local level. Our goal is to assure shellfish cultivation practices minimize negative impacts and maximum positive effects so that our vital marine resources are protected while also assuring the viability of shellfish farming businesses and the jobs and food production they represent.

The Endangered Species Act

Under the ESA, several species that share habitat with shellfish have been listed as threatened or endangered. Because cultivated shellfish not only share a common marine environment, but actually provide this habitat service for many species, shellfish farmers have the potential for interaction and impact during the course of normal operations.

Beneficial Effects

Shellfish beds create a three dimensional structure that can provide habitat and forage for a variety of important prey species for ESA-listed animals. Shellfish beds also create structure for threatened and endangered species that may use the beds directly for both cover and forage, especially juvenile salmonids during their out-migration and juvenile rockfish during their passive migration (Doty et al. 1989; Dumbauld 1997; Dumbauld et al. 2000a; BRT 2009). Although quantification of use relative to other habitat types remains to be fully resolved, mechanistic relationships and behavior of juvenile salmonids and rockfish in the nearshore do not support a conclusion of adverse effects from the shellfish and associated culture structures.

Adverse water quality impacts have been identified as one impediment to the successful recovery of threatened and endangered species. Shellfish farmers' promotion of water quality protection initiatives at local watershed, state, and federal levels; the filtration and nutrient mitigation provided by the shellfish cultured; and the implementation of other common goals and combined efforts should continue to benefit listed and priority aquatic species as well as human uses of marine waters.

Areas of Concern

In the process of farming, such as turning oyster bags and harvest activities, there is a potential for species of concern to be impacted by physical disturbance, increased suspended sediments or turbidity, or human presence (behavioral disturbance, compaction). Exposure of salmonids to high levels of suspended sediment has been found to cause stress, as indicated by gill flaring, or other potential sublethal effects including physiological changes, gill damage, and increased susceptibility to disease (Servizi and Martens 1992; Newcomb and Jensen 1996). Juvenile salmonids exhibit both attraction to waters of moderate turbidity and suspended sediment concentration and avoidance of higher concentrations. For example, in an estuarine environment, juvenile Chinook salmon have been observed to increase their rates of foraging in relation to increased turbidity (18-150 NTUs), which was attributed to the increase in cover provided by turbid waters (Gregory and Northcote 1993; Gregory 1994).

It is unlikely that aquaculture results in direct mortality of adult life stages for ESA-listed species. Some prey species may use habitat associated with aquaculture sites for forage or refuge or spawn in shallow areas near or on aquaculture sites or gear (e.g., Pacific herring[1]) and have the potential to experience direct effects from aquaculture operations (e.g., trampling of substrate-deposited eggs by foot traffic, dislodgement during harvest). However, adverse interactions

[1] Note that even though forage fish are not ESA-listed species, their importance is emphasized in permit applications because they are an important prey species.

between such forage fish species and shellfish aquaculture operations are largely avoided by physical separation from areas where forage fish spawn and/or by ceasing harvests when spawn is identified on gear or product. Specifically, spawning for Pacific sand lance and surf smelt typically occur higher on the beach (+5 feet MLLW to mean high water and +7 feet MLLW to extreme high water, respectively) than where most culture activities occur (+5 and below, with majority below +3 MLLW). Further, when spawn for Pacific herring (which spawn lower in the intertidal; Stick and Lindquist 2009) is noted on aquaculture gear, both best management practices and U.S. Army Corps of Engineers conditions for permitting existing farms require avoiding disturbance of herring spawn on gear, shell and/or associated macroalgae, until spawn is no longer visible. Aquatic prey species that utilize shallow areas for spawning or rearing may be present near aquaculture sites, but adverse interactions are largely avoidable because of the spatial separation of the majority of activities and the harvest avoidance BMP for preventing injury to herring spawn.

The design of overwater structures can also influence the occurrence of protected species. For example, placing flat caps on pilings that support raft structures can increase potential resting areas for foraging birds such as cormorant, which are known to consume juvenile salmonids. Overwater structures used to support shellfish farming activities that attract avian and piscine predators of listed species thus may be considered to increase the potential for negative interactions. In other studies unrelated necessarily to shellfish farming, overwater structures have been found to increase shading of macroalgae and eelgrass, and alter fish migration behavior (*see* Nightingale and Simenstad 2001 for review). These impacts, in turn, have potential to indirectly affect protected species through habitat and bioenergetic effects. The magnitude of potential effect from overwater structures largely depends on their design, their geospatial overlap with habitat resources of concern (e.g., eelgrass; salmonid critical habitat, forage fish spawning substrate, etc.), their position in the drift cell, and the cumulative number of such overwater structures in the waterbody. Where these structures are required for operations, growers should pursue all necessary permits and environmental review required for authorization and minimize potential effects on protected resources through appropriate conservation measures.

Conclusions

If endangered species or forage fish have been identified in a growing area, growers should exercise extreme caution during the periods those species may utilize the shellfish beds and adjacent tidelands under their management to avoid impact and minimize disturbance. Harvesting or mechanical disruption of beds at these times should be avoided, as practicable. Farmers should contact the Services (NMFS and USFWS) to obtain up-to-date lists of ESA species and forage fish and the time frame in which they may occupy their farm sites.

The Marine Mammal Protection Act (MMPA)

Marine mammals protected under the MMPA may at times utilize shellfish cultivation sites for haul-out, or as migration corridors. In Alaska, when sea otter populations become very dense, and their normal food supply runs short, there have been cases of predation on oysters and clams. In some cases marine mammal populations occur seasonally in high concentrations, and they also constitute permanent populations in a number of Pacific Coast locations.

This co-habitation can cause problems for shellfish farmers. High concentrations of mammals in shellfish growing areas can lead to harvest closures due to increased levels of fecal coliforms directly attributable to these animals (Nash et al. 2000). Measures to restrict or limit protected marine mammal access to culture areas are strictly regulated (Morris 1996). Various predator control devices, such as netting systems to keep animals away from crops and underwater acoustic devises designed to scare the animals away, have been used with very limited success.

Beneficial Effects

Shellfish culture gear (e.g., mussel rafts, log booms, oyster long lines) often provide habitat for marine mammals, both as a handy structure for haul-out and as a food source. Additionally, the improved water quality that results from the presence of bivalves provides for a healthier overall marine environment for these animals.

Areas of Concern

Improperly placed or maintained exclusionary devices, such as predator netting, can pose a health risk to marine mammals that may become entangled and injured. Although injury is rare, avoidance of aquaculture farms can prevent species from utilizing higher quality foraging habitat. On the other hand, poorly designed or placed structures can increase the occurrence of haul out opportunities and create more potential interactions between the aquaculture operation and the marine mammal.

Conclusions

Timing culture activities to coincide with those periods when marine mammals are unlikely to be present on culture sites is a benign and effective means for protecting crops from marine mammals, and potentially adverse interactions with marine mammals from farming activities. Designing structures that discourage haul out activities can also reduce interactions with marine mammals. Growers must avoid any harmful interactions with mammals protected under the MMPA and should continue researching other benign exclusionary devices that will protect their crops while not harming protected animals.

The Magnuson-Stevens Fishery Conservation and Management Act

The MSA, as amended by the Sustainable Fisheries Act of 1996 (Public Law 104-267), requires Federal agencies to consult with NMFS on activities that may *adversely affect* Essential Fish Habitat (EFH) for any fish that are covered under a Fishery Management Plan (FMP). Essential Fish Habitat is any habitat (including both water and substrate) that is required by fish for spawning, breeding, feeding, or growth to maturity. The Pacific West Coast (excluding Alaska) has three FMPs, including Pacific salmon, coastal pelagic species, and groundfish.

Beneficial Effects

Similar to ESA-listed fish species, shellfish beds create three-dimensional structures for rearing and foraging activities exhibited by EFH species. Both Atlantic and Pacific researchers have observed an increase in both taxa abundance and density for certain epibenthic and fish species in areas with shellfish aquaculture gear compared to surrounding areas (Dumbauld et al. 2000b; Meyer and Townsend 2000; Pinnix et al. 2005; Powers et al. 2007), and many growers would contend this is an obvious occurrence from their personal observation. For example, in the three year Pinnix et al. (2005) study in Humboldt Bay, oyster culture habitat either exceeded or was equivalent to eelgrass habitat in terms of its support of species diversity and abundance. In addition, the most common species collected within the aquaculture locations included common prey species for ESA-listed salmonids (e.g., Pacific herring, northern anchovy, and shiner surfperch), some of which are EFH species for which a federal fishery management plan has been developed (e.g., anchovy).

Furthermore, many studies have focused on the association between small fish (i.e., sculpin, surfperch, etc.) or groundfish species and various aquaculture operations (O'Beirn et al. 2004, Pinnix et al. 2005, Laffargue et al. 2006, Tallman and Forrester 2007). In the results of these studies, it was concluded that aquaculture did not negatively affect these species assemblages, and may improve feeding and cover opportunities.

Areas of Concern
Harvesting practices can cause increased sediment concentrations in the water column for the length of the harvest cycle. As discussed above, increased levels of turbidity can affect fish health. However, the turbidity and suspended sediment levels generated from harvest and other shellfish farm activities are well within the range experienced under the range of natural conditions experienced at farm sites.

Conclusions
If EFH species have been identified in a growing area, growers must then exercise due care during the periods those species utilize shellfish beds. Harvesting or disruption of beds at these times should be avoided as practicable.

Submerged Aquatic Vegetation
Submerged aquatic vegetation (SAV) is common in West Coast estuaries and considered to be a critical component of the marine ecosystem in the intertidal and shallow subtidal zones and is considered to include seagrasses and kelp species for the purposes of this ECOP. Native seagrasses, particularly *Zostera marina*, the native eelgrass of the West Coast, should be recognized by growers as important habitat, providing foraging and refuge areas for a variety of fish, including salmonids and their prey. Another species of eelgrass, Japanese eelgrass, *Z. japonica*, an invasive to the Pacific Coast, is increasingly found in Pacific Coast estuaries and growers have observed that it is altering habitat, displacing native species and converting tidelands into meadow-like areas (WDFW 2011).

Many shellfish farms along the West Coast operate in tidelands that support seagrasses, and growers frequently report the establishment of new seagrass colonies occurring after the planting of shellfish beds. For example, in a review of aerial photographs of Drakes Estero, documents that eelgrass habitat has increased from 368 acres to 736 acres within 17 years (1991 to 2007) in the eastern portion of the estuary, which California Department of Fish and Game (CDFG) attributed primarily to the oyster operation that is located within the densest portion of the eelgrass bed (Bartley et al. 2009). In Bahía San Quintín, Mexico, one of the foremost seagrass areas in western North America, satellite (SPOT, and Landsat 5 and 7) imagery was used to track long term changes in eelgrass distribution in a portion of the bay with recently expanded oyster operations (Ward et al. 2003). The authors noted that oyster rack farming was not associated with any detectable loss in eelgrass spatial extent, despite the increase in number of oyster racks from 57 to 484 over the study period. On the contrary, there was an apparent gain in eelgrass coverage in oyster culture areas, and a small loss outside these areas, with the data showing no significant impact on eelgrass distribution from oyster racks. Numerous studies are currently being conducted to further the understanding of the interactions between shellfish and submerged aquatic vegetation, as despite the positive interactions as exemplified above and others further described below, impacts from competition and displacement can occur to eelgrass with some culture methods (Tallis et al. 2009).

Beneficial Effects

Shellfish beds parallel many of the important habitat functions of submerged aquatic vegetation. Epibenthic shell creates habitat that is utilized by several species of benthic invertebrates and vertebrates, providing surface areas for the attachment of algae, mussels and other epibionts, resulting in enhanced density of several prey species (Doty et al. 1989; Dumbauld et al. 2000b; Pinnix et al. 2005). Additionally, filter feeders can benefit eelgrass photosynthesis by clearing the water of particles and allowing for further penetration of sunlight.

Like many habitat effects, the main drivers in eelgrass recruitment to a culture area depend on the type and frequency of shellfish aquaculture. For example, Wisehart et al. (2007) reported that oyster beds dredged every three years resulted in higher seedling abundance and higher seed production compared to adjacent control or longline culture areas. The authors suggested that this was because mechanical harvest removes neighboring adult plants and reduces competition for light and other nutrient resources. Such post-harvest findings may reflect a manifestation of an 'edge' effect, as is observed in terrestrial agriculture and siviculture.

As previously discussed, one of the benefits that may accrue to eelgrass from bivalves is through the enrichment of sediments with nutrients. Shellfish feces and pseudofeces increase sediment nutrient content and these increased nutrients are then biologically available to the plants. The biofiltering capacity of bivalves also helps reduce nutrient loading in the water column, allowing greater light penetration, further supporting the growth of seagrasses (Peterson 1999).

The degree to which these benefits are manifest where eelgrass and bivalve shellfish co-occur *within the farm footprint* does appear to be dependent, to some degree, on the overall coverage of the shellfish cultured within an eelgrass bed. Rumrill and Poulton (2003) studied effects of longline culture on eelgrass in Arcata Bay, California over a two-year period. The study focused on how eelgrass cover and density varied as a function of the distance between longlines. In general, eelgrass became more abundant with increased spacing between lines, but found no difference from control plots when spacing equaled or exceeded 5 feet. In Willapa Bay, limits on eelgrass growth appear to be because of light and not nutrients (Tallis et al. 2009). Thus, eelgrass grew faster in ground cultured oyster beds in Willapa Bay than on control plots. While growth was faster, likely as a result of improved water clarity, reduced eelgrass competition, and perhaps sediment nutrients, overall eelgrass density was lower in oyster beds at bottom coverages of about 20% and higher. Thus, basin-wide benefits may accrue to eelgrass from the filter feeding biomass of shellfish in an embayment where culture is practiced, though direct displacement can occur at higher culture densities within the footprint of a farm.

Areas of Concern

Although shellfish aquaculture can improve eelgrass growth at the basin scale, direct impacts to eelgrass can occur from disturbance through specific aquaculture activities. Introduction of shellfish into a culture area can create space competition between shellfish and eelgrass (Griffin 1997; Carvalho et al. 2006; Hosack et al. 2006), and harvest can directly result in the removal of entire plants and rhizomes via mechanical actions (Tallis et al. 2009). While this can occur, the duration of work on a bed is limited and thus it is unlikely that any significant number of plants are ever removed.

Longline culture may entwine plants and increase desiccation, thus reducing the density of vegetative and flowering plants (Wisehart et al. 2007). Surveys document that the magnitude of negative impact varies, but follows an expected gradient from mechanical harvest > narrow spaced longlines > widely spaced long-lines > handpicked beds for oyster aquaculture. Results from a study supported by the Western Regional Aquaculture Center (Rumrill and Poulton 2003) revealed that long lines spaced at 1.5 and 2.5 ft. resulted in a reduction in eelgrass density (turions/m^2) and percent cover, but spacing at 5 and 10 ft. intervals increased eelgrass coverage relative to control plots over the same period. As discussed previously, however, areas void of SAV may quickly become populated with dense SAV, after farm installation and thus this gear can provide a valuable habitat service. Further, while localized displacement of eelgrass can occur from shellfish farming, it is important to note that it has not led to the exclusion of eelgrass in any embayment on the West Coast where eelgrass and shellfish culture co-occur, and in many locations such as Willapa and Coos Bay, a mutualistic relationship appears to play out.

Some culture methods utilize overwater structures, such as raft culture, can shade benthic habitats and may eliminate or reduce submerged aquatic vegetation from beneath the structure as discussed (Nightingale and Simenstad 2001). However, floating structures used for shellfish culture are typically located at depths or in highly productive turbid waters where light is attenuated and there is not significant submerged aquatic vegetation under them to be impacted.

Conclusions

Shellfish growing areas and the cultivation of shellfish provides habitat suitable for several species of flora and fauna. Cultivation and harvest operations planning should be outcome-based to assure the greatest protection of habitat and biodiversity in shellfish farming areas. Given the propensity for submerged aquatic vegetation and shellfish to cohabitate, growers should take into account whether seagrass existed prior to planting. Where this is the case, and threatened or endangered species are present, growers should include impact minimization efforts in their farm management plans, as appropriate.

Protection of native eelgrass beds is of particular concern in several regions along the West Coast, where stringent regulations are in place to assure no disruption or net loss. Growers must be familiar with the laws that govern operations in eelgrass beds in their particular region and assure that their farm practices comply with applicable regulations and permit requirements.

An evaluation of impacts of shellfish aquaculture, both positive and negative, is a continuing focus of several studies and must be part of any farm management plan where native submerged aquatic vegetation exists in areas utilized by threatened or endangered species. It is critical that growers continue promoting scientific research and work with representatives from academia, industry, and resource agencies to determine the best available science for identifying specific areas of potential impact.

Annotated Bibliography—Section II

Andrew, M.L., Frank, L. 2004. Integrated aquaculture system for nutrient reduction in agricultural wastewater: potential and challenges. Bulletin of Fisheries Research Agency (Japan). No. Sup. 1, pp. 143-152.

The integration of aquaculture with agriculture takes advantage of the nutrient output of one crop to increase pond primary productivity, subsequently, enhancing herbivorous fish production. Applying this integration concept for the purpose of reducing the environmental impact of agriculture via the nutrient extraction ability of various shellfish, plant and fish species is a relatively new concept and is increasingly justified by nutrient discharge regulations and associated increasing effluent treatment costs. This paper will review current strategies to apply this concept in the field, present an overview of specific efforts in Florida and summarize the challenges of implementation of integrating production of various aquaculture species to reduce nutrients in agricultural wastewater.

Banas, N.S., Hickey, B.M., Newton, J.A., Ruesink, J.L. 2007. Tidal exchange, bivalve grazing, and patterns of primary production in Willapa Bay, Washington. Marine Ecology Progress Series 341. pp. 123-139.

Modeling study to explore causes of declining phytoplankton abundance into Willapa Bay. The model shows that, during the summer, phytoplankton declines from bay Center to Sunshine Pt (junction of Naselle R and Lon Island Slough) more than would be expected from simple mixing of rich ocean and poor river water. The extra loss is consistent with the capacity of cultured oysters to filter it out. [Funding: NOAA Sea Grant. NSB at UW Oceanography].

Bartoli, M., Nizzoli, D., Viaroli, P., Turolla, P., Castaldelli, G., Fano, E.A., Rossi, R. 2001. Impact of *Tapes philippinarum* farming on nutrient dynamics and benthic respiration in the Sacca di Goro. Hydrobiologia. pp. 203-212.

In recent years, short-neck clam cultivation in Sacca di Goro has been seriously impacted due to the appearance in the lagoon of large macroalgal beds and the occurrence of dystrophic events causing anoxia and massive deaths of mollusks in the cultivated areas. Two areas, a farmed and a control one, were compared for benthic fluxes and results were correlated with clam (*Tapes philippinarum*) biomass. Our results indicate that clam farmers should carefully consider sustainable densities of *Tapes* in order to prevent the risk of sediment and water anoxia. Rapid nutrient recycling (up to 4000 mu mol NH sub (4) super (+) m super (-2) h super (-1) and 150 mu mol PO sub (4) super (3) m super (-2) h super (-1)) stimulated by the high biodegradability of clam feces and pseudofeces could in turn favor macroalgal growth.

Baudrimont, M., Schäfer, J., Marie, V., Maury-Brachet, R., Bossy, C., Boudou, A., Blanc, G. 2005. Geochemical survey and metal bioaccumulation of three bivalve species (Crassostrea *gigas*, *Cerastoderma edule* and *Ruditapes philippinarum*) in the Nord Medoc salt marshes (Gironde estuary, France). Sci.Total Environ. pp. 265-280.

A 15-month experiment combining a geochemical survey of Cd, Cu, Zn and Hg with a bioaccumulation study for three filter-feeding bivalve species (oysters, *Crassostrea gigas*; cockles, *Cerastoderma edule*; and clams, *Ruditapes philippinarum*) was conducted in a breeding basin of the Nord Medoc salt marshes connected to the Gironde estuary, which is affected by historic polymetallic pollution. The geochemical behavior of metals in water, suspended particulate matter and sediment and their ecotoxicological impact on the three bivalve species were evaluated by in situ exposure of juvenile oysters (water column) and adult cockles and clams (sediment surface). A distinct daily periodicity (except salinity) indicated intense photosynthesis and respiration. Results suggest trace metal recycling due to reductive dissolution under subtoxic conditions at the sediment surface resulting in trace metal release to the water column and adsorption onto suspended particles. Growth, bioaccumulation rates and kinetics in the whole soft body of the bivalves were analyzed every 40 days. These results suggest physiological differences between the species and/or differences in the exposure of the organisms due to physico-chemical conditions and metal distribution between dissolved and particulate phases.

Berg, C. J. Jr., Alatalo, P. 1984. Potential of chemosynthesis in molluscan mariculture. Aquaculture 39. pp.165-179.

The large edible clam *Codakia orbicularis* lives in sulfide-rich environments in subtropical regions. It possesses simplified gills, palps, and digestive systems. Gill tissues contain intracellular prokaryotic cells and yield enzyme activities associated with sulfide oxidation, carbon fixation, and nitrogen reduction. Together with carbon-13 depletion values, these findings suggest chemoautotrophic capabilities similar to those of deep-sea hydrothermal vent animals. Reproduction, growth rates, and chemical composition of *C. orbicularis* are similar to other commercially exploited clams.

Berry, A. W. 1996. Aquaculture and sea loch nutrient ratios: a hypothesis. Aquaculture and sea lochs. pp. 7-15.

This hypothesis suggests that discharges from cage fish farming enhance bacterial biomass production and perturb ambient nutrient ratios, promoting seasonal physiological nutrient stress in, and the production of biotoxins by, organisms in the receiving waters. Systematic nutrient limitation may also develop on a wider scale.

Burford, M.A., Costanzo, S.D., Dennison, W.C., Jackson, C.J., Jones, A.B., McKinnon, A.D., Preston, N.P., Trott, L.A. 2003. A synthesis of dominant ecological processes in intensive shrimp ponds and adjacent coastal environments in NE Australia. Marine Pollution Bulletin. Vol. 46, no. 11, pp. 1456-1469.

In this paper we synthesize the results of our multidisciplinary research linking ecological processes in intensive shrimp ponds with their downstream impacts in tidal, mangrove-lined creeks. The incorporation of process measurements and bioindicators, in addition to water quality measurements, improved our understanding of the effect of shrimp farm discharges on the ecological health of the receiving water bodies. Ultimately, reduction in nutrient discharges is most likely to ensure the future sustainability of the industry.

Chapelle, A., Menesguen, A., Deslous-Paoli, J.M., Souchu, P., Mazouni, N., Vaquer, A., Millet, B. 2000. Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oysters farming and inputs from the watershed. Ecological Modelling. Vol. 127, no. 2-3, pp. 161-181.

An ecosystem model based on nitrogen cycling and oxygen has been developed for the Thau lagoon. This model is compared with a year survey data and used to estimate nitrogen and oxygen fluxes between the different ecosystem compartments. The yearly simulation shows that the ecosystem behavior is driven by meteorological forces, especially rain which causes watershed inputs. Shellfish farming also plays an important role in the whole lagoon through biodeposition. Driven by biodeposition, sediment release is the major source of nitrogen in the water column and causes oxygen reduction. The oysters contribute to the recycling activity by excretion, which supports the regenerated primary production. They are also involved in oxygen consumption by respiration which can cause local hypoxia.

Further improvements are proposed before this model may become a functional environmental model for a lagoon ecosystem.

Chopin, T., Yarish, C., Neefus, C., Kraemer, G., Zertuche-Gonzalez, J., Belyea, E., Carmona, R. 2001. Aquaculture from a different angle: the seaweed perspective, and the rationale for promoting integrated aquaculture. Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. pp. 69-72.

To develop innovative, effective and responsible practices - maintaining the health of coastal waters, and, consequently, of the cultured organisms - fed aquaculture types (e.g. finfish, shrimp) and organic or inorganic extractive aquaculture types (e.g. shellfish or seaweed) need to be integrated to avoid pronounced shifts in coastal processes. Most impact studies on aquaculture operations typically have focused on organic matter/sludge deposition. However, the inorganic output of aquaculture is presently emerging as a pressing issue as nutrification of coastal waters is a worldwide phenomenon, which has not spared the Bay of Fundy (Chopin et al. in press). Conversion, not dilution, is the solution so that the "wastes" of one resource user become a resource (fertilizers) for the others.

Crawford, C. 2003. Environmental management of marine aquaculture in Tasmania, Australia. Aquaculture. Vol. 226, no. 1-4, pp. 129-138.

The two main species cultured are the introduced Pacific oyster, *Crassostrea gigas*, and Atlantic salmon, *Salmo salar*. Local impacts on the seabed around salmon farms are monitored using video footage, analysis of benthic invertebrate infauna, and chemical measures (redox and organic matter).Monitoring of shellfish farms is minimal because our research has shown that shellfish culture is having little impact on the environment. Studies include investigating appropriate inexpensive measures for an industry-wide long-term monitoring program. A new project is investigating system-wide effects of salmon farming on the environment, in particular, increased release of nutrients into waterways. This includes monitoring dissolved oxygen, nutrients and phytoplankton, modeling the system, and investigating ecological indicators of eutrophication.

Crawford, C., Mitchell, I., Macleod, C. 2001. Effects of shellfish farming on the environment. Aquaculture 2001: Book of Abstracts. p.143.

The production of shellfish, mainly *Crassostrea gigas*, in Tasmania, Australia is approximately 2,500 metric tons per annum, which is small by world standards. Nevertheless, there is considerable community opposition to the expansion of the industry, partly because of concerns about possible detrimental effects on the environment. The effects of shellfish farming on the benthic environment were investigated in detail at three deep water shellfish farms in Tasmania which have had a relatively high level of production. Overall, the shellfish farms showed a minor effect on the benthic environment within the lease area, and the impact was much less than that from salmon farms. The risk of ecological impact from shellfish farming in Tasmania was also assessed qualitatively through an international scientific literature search. Beneficial effects of shellfish farming were identified as increased monitoring of the health of estuarine and coastal waters, the potential for scallop aquaculture to enhance wild stocks, and the likelihood of improved water clarity and reduced nutrients and phytoplankton concentrations in some areas. Detrimental effects include the risk of spread of pests and pathogens as a result of shellfish farming activities, noting that this risk also exists through other anthropogenic activities. Changes to the habitat may occur on lease areas, whereas the risks of ecological impact due to organic enrichment and reduced food resources for filter feeders were rated as low.

Crawford, C.M., Macleod, C.K., Mitchell, I.M. 2003. Effects of shellfish farming on the benthic environment. Aquaculture. Vol. 224, no. 1-4, pp. 117-140.

The benthic environment under and near three shellfish farms in Tasmania, Australia, which had had a relatively high level of production over many years was investigated. Benthic samples were collected along transects which ran across the farms, generally from 100 m upstream to 100 m downstream. It was concluded from these results that shellfish farming is having little impact, and much less than salmon farming, on the benthic environment in Tasmania. Thus extensive monitoring of shellfish farms would appear to be not necessary.

De Casabianca, M.L., Laugier, T., Collart, D. 1997. Impact of shellfish farming eutrophication on benthic macrophyte communities in the Thau lagoon, France. Aquaculture International. Vol. 5, no. 4, pp. 301-314.

In a large marine lagoon (Thau lagoon, southern France) with a shellfish farming dominant eutrophication, the macrophyte communities were sampled by six transects of three depths (1.5, 2.5 and 5 m) and their characteristics (species composition, diversity and biomass) were described in relation to environmental and sediment parameters. With increasing eutrophication, silt fraction and shell fragments in sediments increased. Different types of macrophytic communities could be defined in the shallow zone (1.5-2.5 m) corresponding to four main and successive stages of degradation. A pure eelgrass stand (*Zostera marina* and *Z. noltii*) and an eelgrass community colonized by macroalgae were observed in SW sites and could be distinguished by their sedimentary features. In sites (NE) more affected by eutrophication (fine-textured sediment), available incident light determined two main seaweed communities: an *Ulva rigida* community, outside the shellfish tables, and a *Gracilaria bursa-pastoris* community in the shellfish tables (lower incident light).

Dewey, W. F. 2000. The various relationships between shellfish and water quality. Journal of Shellfish Research. Vol. 19, no. 1, p. 656.

This paper discusses the dichotomy between the views of shellfish as polluters versus the view of shellfish as capable of improving water quality and habitat.

Doering, P. H., Kelly, J. R., Oviatt, C. A., Sowers, T. 1987. Effect of the hard clam *Mercenaria mercenaria* on benthic fluxes of inorganic nutrients and gases. Mar.Biol. pp. 377-383.

The effect of the hard clam *Mercenaria mercenaria* on the exchange of dissolved nutrients (silicate, phosphate, ammonium, nitrate+nitrite) and gases (oxygen, carbon dioxide) across the sediment-water interface was examined in 1983 and 1984 using experimental mesocosms (13 m super (3)), designed to simulate shallow coastal ecosystem, that allow for reciprocal biogeochemical interactions between water column (5 m) and bottom sediments (similar to 30 cm deep). Benthic, fluxes, measured during a spring-summer warming period, were compared for mesocosms maintained either with added *M. mercenaria*) (16 per m super (2) treatment) or without *M. mercenaria*) (control) as a component of the benthic community.

Dolmer, P., Frandsen, R. P. 2002. Evaluation of the Danish mussel fishery: suggestions for an ecosystem management approach. Helgoland Marine Research. Vol. 56, no. 1, pp. 13-20.

See Section 1 references for abstract.

Dumbauld, B., Armstrong, D., Roegner, C., Feldman, K., Loggerwell, L., Rumrill, S. 2001. Implementing a study to determine the value of molluscan shellfish culture areas as fish habitat in West Coast estuaries. Journal of Shellfish Research. Vol. 20, no. 3, p. 1196.

We are initiating a study designed to quantify both adverse, but also beneficial impacts of shellfish farming on selected estuarine fauna and flora. We will focus our initial efforts on oyster ground culture and on eelgrass as benthic habitats given the extent and previously documented value of these habitats respectively. Field and laboratory objectives include: 1) utilizing remote sensing and ground-truthing to document annual variability in eelgrass cover in oyster culture and eelgrass meadows in Willapa and Coos Bay estuaries; 2) compare species diversity, density and biomass in culture areas as well as eelgrass meadows; 3) conduct field experiments to examine the impacts of various culture activities on eelgrass and associated infaunal and epifaunal communities; and 4) conduct surveys of fish utilization in oyster beds and eelgrass meadows. Finally, we hope to prepare guidelines to assist both shellfish farmers and estuarine managers in avoiding and/or reducing adverse impacts on estuarine habitat while maximizing the potential beneficial impacts of aquaculture activities.

Dumbauld, B.R., Booth, S. Cheney, D., Suhrbier, A., Beltran, H. 2006 An integrated pest management program for burrowing shrimp control in oyster aquaculture. Aquaculture 26. pp. 976-992.

Burrowing thalassinid shrimp clearly cause oysters to sink under the surface of the sediment and die. A burrowing shrimp program which examines recruitment is proposed.

Dumbauld, B.R., Ruesink, J.L., Rumrill, S.S. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. Aquaculture 290. pp. 196–223.

Bivalve shellfish aquaculture can be viewed as a disturbance which modifies the estuarine system in three ways: 1) changes in material processes — bivalves process food and produce wastes; 2) addition of physical structure — aquaculture introduces the cultured organisms and in some cases a physical anchoring structure; and 3) pulse disturbances like harvest and bed maintenance disturb sediments, remove species in addition to the cultured organisms themselves, and change resource or habitat availability. This article reviews these effects in U.S. West Coast estuaries. Scale seems a very important management consideration .Though local and short term effects from aquaculture are clearly evident in U.S. West Coast estuaries, bivalve aquaculture does not remove area from the estuary or degrade water quality.

Dumbauld, B.R., Wyllie-Echeverria, S. 2003. The influence of burrowing thalassinid shrimps on the distribution of intertidal seagrasses in Willapa Bay, Washington, USA. Aquatic Botany 77. pp. 27-42.

Experiments to investigate the effect of oyster shell and the pesticide carbaryl used to control burrowing shrimp on tideflats in Willapa Bay showed that removal of shrimp with the pesticide causes eelgrass (particularly *Zostera japonica* but also *Z. marina* where present) to survive and expand its distribution. The shrimp cause seeds to be distributed to depth, but the effect appears to be due to seedling survival which is greatly reduced when shrimp bioturbation is present.

Erbland, P., Ozbay, G. 2006. Community shift associated with shellfish aquaculture in two mid-atlantic estuaries. Journal of Shellfish Research. Vol. 25, no. 2, p. 726.

See Section 1 references for abstract.

Filgueira, R., Grant, J. 2009. A Box Model for Ecosystem-Level Management of Mussel Culture Carrying Capacity in a Coastal Bay. Ecosystems 12. pp. 1222–1233.

A multiple box dynamic ecosystem model was constructed to examine the carrying capacity for mussel (*Mytilus edulis*) aquaculture in Tracadie Bay, Prince of Edward Island, Canada. The model validation process indicated that the differential equations and parameters used in the simulation provided robust prediction of the ecological dynamics within the bay. Results verified that mussel biomass exerts top-down control of phytoplankton populations. The model indicates that conditions observed during 1999 are more sensitive to grazing pressure from aquaculture than was observed during 1998, highlighting the importance of inter-annual variability in carrying capacity of the bay. This result is important from a management perspective because it emphasizes application of a precautionary policy and prediction in regulation of aquaculture activity in the bay. Retrospective scenarios showed that although the bay could yield greater mussel biomass production, stress on the environment would lead the ecosystem outside of its natural range of variation.

Gangnery, A., Bacher, C., Buestel, D. 2001. Assessing the production and the impact of cultivated oysters in the Thau Lagoon (Mediterranean, France) with a population dynamics model. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 58, no. 5, pp. 1012-1020.

The Thau Lagoon (France) standing stock of cultivated filter feeders is around 20 000 t and consists of two main species, the Japanese oyster *Crassostrea gigas* and the Mediterranean mussel *Mytilus galloprovincialis*. To predict changes in the standing stock and the annual production, a mathematical model of the population dynamics was defined.

Gibbs, M. T. 2004. Interactions between bivalve shellfish farms and fishery resources. Aquaculture. Vol. 240, no. 1-4, pp. 267-296.

The expansion of large-scale aquaculture has costs in terms of loss of water space that could be used for other activities, and carbon flows directed through the bivalves that could have been used to support other marine plants and animals (predation and production foregone). Resource managers are faced with making resource allocation decisions between alternate sectors, and these decisions should be based on robust knowledge of the costs and benefits of each alternative use. In the case of allocation decisions between bivalve aquaculture and wild stock fisheries, there is presently a paucity of knowledge surrounding the interactions between these two activities. The aim of the work presented here was to develop a framework for understanding these interactions and applying the framework in a case study in New Zealand.

Gifford, S., Dunstan, R.H., O'Connor, W., Roberts, T., Toia, R. 2004 Pearl aquaculture--profitable environmental remediation? Science of the Total Environment. Vol. 319, no. 1-3, pp. 27-37.

Bivalve molluscs are filter feeders, with pearl oysters able to filter water at rates up to 25 l h super(-1) g super(-1) of dry wt. tissue. Since this process leads to rapid bioaccumulation of recalcitrant pollutants such as heavy metals, organochlorine pesticides and hydrocarbons from impacted sites, it has prompted the widespread use of molluscs as biomonitors to quantify levels of marine pollution. This paper proposes pearl oyster deployment as a novel bioremediation technology for impacted sites to remove toxic contaminants, reduce nutrient loads and lower concentrations of microbial pathogens. Method of cultivation and site selection are the key to minimizing negative environmental impacts of bivalve cultivation. Deployment of oysters at sites with high nutrient and contaminant loadings would be advantageous, as these compounds would be removed from the ecosystem whilst generating a value-added product.

Giles, H., Pilditch, C.A., Bell, D.G. 2006. Sedimentation from mussel (*Perna canaliculus*) culture in the Firth of Thames, New Zealand: Impacts on sediment oxygen and nutrient fluxes. Aquaculture 261. pp. 125–140.

To determine the impact of a mussel farm (45 ha) in the Firth of Thames we measured sedimentation rates by deploying sediment traps, sediment characteristics by collecting sediment cores and sediment oxygen and nutrient fluxes by deploying benthic chambers in four seasons. Sedimentation under the farm was increased by 106 g m−2 d−1 compared to the reference site. Sediments under the farm had elevated organic carbon, nitrogen, and chlorophyll a and phaeopigment concentrations indicative of the additional organic input due to bivalve biodeposition. Oxygen consumption was higher under the farm compared to a reference site but this increase was only significant in summer. Ammonia release rates were higher under the farm compared to the reference site in spring (1.8×, non-significant p=0.588) and autumn (3×, significant p=0.006) but in summer release rates at the reference site were 1.4× higher than those under the farm. Nitrate fluxes were significantly higher at the farm site. Oxygen and nutrient fluxes generally demonstrated the typical response to increased organic input due to sedimentation from mussel culture. Benthic regeneration at the reference site could supply 74% of nitrogen required by pelagic primary producers whereas under the farm it could account for 94%. This demonstrates the importance of benthic nutrient regeneration in this region and that mussel culture can lead to a redistribution of nutrients. We suggest that site-specific hydrodynamic and biogeochemical conditions have to be taken into account when planning new mussel farms to prevent excessive modifications of nutrient dynamics.

Glasoe, S. D., Fagergren, D. 2000. Shellfish water quality trends and threats in Puget Sound. Journal of Shellfish Research. Vol. 19, no. 1, p. 656.

In the 1980s a number of the Sound's commercial shellfish areas were downgraded primarily because of nonpoint source pollution and additional monitoring information. This decline stabilized in the 1990s as a result of targeted efforts to restore water quality. A broader review presents a mixed picture and forecasts an uncertain future for the Sound's shellfish tidelands, especially given the region's fast-growing population. Some successful restorations have been reversed by recurring problems. Other sites have never recovered. And the harvesting classifications in most restored areas are tenuous, requiring constant monitoring and follow-up work. Case studies from Drayton Harbor, Burley Lagoon and Lower Hood Canal are used to gain some insight into these problems.

Goldberg, R. 1978. Some effects of gas-supersaturated seawater in *Spisula solidissima* and *Argopecten irradians*. Aquaculture. 1978; pp. 281-287.

Two size classes of the surf clam, *S.solidissima*, and the bay scallop, *A.irradians*, were exposed to different concentrations of gas-supersaturated seawater in a flowing seawater system. Mortality, gill tissue damage, gas emboli, membranous tissue blisters, and abnormal secretion of shell material were induced experimentally at elevated levels of gas supersaturation. Results indicate significant mortalities of surf clams and scallops held at 114% O-SUB-2- and 195% N-SUB-2-, and at higher levels of gas concentration. These values suggest a point of reference for the bivalve culturist in identifying potential problems which can be caused by gas-supersaturated seawater.

Goulletquer, P., Robert, R., Trut, G. 1999. Manila clam *Tapes philippinarum* culture: Sediment clam interaction. Aquat. Living Resour. /Ressour. Vivantes Aquat. Vol. 12, no. 1, pp. 45-46.

Manila clam (*Tapes philippinarum*) culture and sediment interactions were tested by comparing two rearing areas, including an oceanic (Le-Ferret) and a more estuarine (Les-Jacquets) sites in the Bay of Arcachon (France). The growth of calibrated clam population (10-mm spat) was monitored in these two areas with a concomitant sediment-water interface survey over a 1.5-year period. Two sites per area, including control and rearing plots, were sampled on a monthly basis. The potential clam farming impacts by bioturbation and interactions were examined at three sediment depths: O-1, 1-2 and 2-10 cm. The results demonstrate that clam rearing had only a limited effect on the environmental sediment parameters (i.e. water percentage, and phaeopigments and silt levels) from a spatio-temporal point of view. Therefore, a return to environmental conditions existing before the implementation of clam farming is likely to occur upon cessation of this activity.

Grant, J., Hatcher, A., Scott, D. B., Pocklington, P., Schafer, C. T., Winters, G. V. 1995. A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities. Estuaries. Vol. 18, no. 1A, pp. 124-144.

The impact of suspended mussel culture (*Mytilus edulis*, *M. trossulus*) on the benthos of a small Nova Scotia cove (7 m depth) was assessed using methods involving both benthic metabolism and community structure. Cluster analysis of macrofauna usually provided a clear separation between sites. Since the construction of a causeway (1968), foraminifera species composition showed a temporal response to temperature changes in the cove by shifting toward calcareous species, but assemblages downcore showed little or no relationship to aquaculture impacts. Although there is a shift toward anaerobic metabolism at the mussel lines, the impact of mussels falling to the sediments was more noticeable in benthic community structure than was any impact due to organic sedimentation or hypoxia. The impact of aquaculture on the benthos appeared to be minor.

Hasbrouck, E. G. 1998. The impact of a shellfish nursery on ambient chlorophyll-a concentrations. Journal of Shellfish Research. Vol. 17, no. 1, p. 355.

The Cornell Cooperative Extension Marine Program operates a shellfish hatchery and nursery in Southold, Long Island, NY, where they spawn, grow, and eventually release into the wild, a number of different types of shellfish. The nursery operation utilizes a flow-through system to draw in bay water with its associated microalgae as a food source for the shellfish. The nursery produced approximately 4 million hard clams, oysters and bay scallops during the 1997 growing season. This study was designed to determine the impact of the nursery's algal removal on the ambient algal concentrations of Cedar Beach Harbor. A chlorophyll-a sampling program was established Samples in this study were analyzed for only chlorophyll-a concentrations as an approximation of microalgal density.

Heath, W.A., Carroll, S., Devos, R., Provan, B. 2009. The assessment of impacts on the benthic environment from suspended oyster aquaculture in Baynes Sound, British Columbia, Canada. Aquaculture Canada super (OM) 2008: Proceedings of the Contributed Papers of the 25th super (th) Annual Meeting of the Aquaculture Association of Canada, no. 14, pp. 42-45.

A survey was conducted in Baynes Sound, BC, to assess potential benthic impacts of suspended culture shellfish farms. Benthic grab samples and underwater video images were collected at oyster longline and raft farms and reference sites. Sediment samples were analyzed for pH, porosity, sediment grain sizes, percent organic carbon and percent carbonates. Normalized data were analyzed by multivariate methods of clustering and Principal Components Analysis. Some differences between conditions at shellfish farms and reference sites were noted, although benthic sediment conditions were in the normal, oxic classification. The main benthic impact observed at oyster longline and raft sites was an increase in fish habitat complexity, related to introduction of shell material to the benthic environment and increased presence of macroalgae and macrofauna, such as sea stars and crabs.

Hilgerloh, G., O'Halloran, J., Kelly, T., Burnell, G. 2001. A preliminary study on the effects of oyster culturing structures on birds in a sheltered Irish estuary. Hydrobiologia. Vol. 465, no. 1-3, pp. 175-180.

This study investigated the species composition, numbers and behavior of birds in an intertidal oyster culture area in Cork Harbor. These data were compared to a nearby area free of aquaculture within the same estuary in March 1999. Species which occurred in the aquaculture free area were also observed in the trestle-area. The most abundant species were oystercatcher *Haematopus ostralegus*, redshank *Tringa totanus*, dunlin *Calidris alpina*, curlew *Numenius arquata*, black-headed gull *Larus ridibundus* and common gull *Larus canus*. Oystercatcher, curlew, black-headed gull and common gull occurred in significantly lower numbers in the trestle area, while for redshank and dunlin the differences were not significant. The percentage of birds feeding did not differ between the two areas. These preliminary observations at a single time period give some insight as to the potential interactions between shellfish aquaculture and intertidal birds.

Holsman, K.K., Armstrong, D.A., Beauchamp, D.A., Ruesink, J.L. 2003. The necessity for intertidal foraging by estuarine populations of subadult Dungeness crab *Cancer magister*: evidence from a bioenergetics model. Estuaries 26. pp. 1155-1173.

While the critical role of structured intertidal habitat for 0+ young-of-the-year Dungeness crab had been previously evaluated, little was known about use by sub-adult 1+ and >1+ crab. Abundance surveys indicated that these crab were most abundant in lower side channels in the estuary. A bioenergetics model suggested that the subtidal habitat in these areas could not possibly satisfy energetic demand and the crab must therefore use extensive intertidal flats to meet their daily requirements.

Horwith, M. PhD thesis research. Resilience of soft-sediment communities after geoduck (*Panopea abrupt*) harvest in Samish Bay. University of Washington. Project PI: Dr. Jennifer Ruesink.

The July 2009 survey associated with this project provides the first and only data suggesting spillover effects from the impact plot. The researchers found a significant positive correlation between *Zostera marina* size (measured as sheath length) and distance from the farm boundary, a significant negative correlation between *Z. marina* shoot density and distance from the farm boundary, and a significant positive correlation between *Z. marina* biomass and distance from the farm boundary. In short, *Z. marina* plants in the control plot were smaller, denser, and had less standing biomass nearer the impact plot.

Hosack, G.R., Dumbauld, B.R., Ruesink, J.L., Armstrong, D.A. 2006. Habitat associations of estuarine species: comparisons of intertidal mudflat, seagrass (Z*ostera marina*) and oyster (*Crassostrea gigas*) habitats. Estuaries and Coasts 29. pp. 1150-1160.

These authors compared densities of several types of organisms across habitat types in Willapa Bay. Density and diversity of epibenthos (small surface-dwelling invertebrates) was higher in structured habitats (eelgrass and oyster) than open mud. Infauna (invertebrates living in the sediment) were most abundant in eelgrass. Nekton (fish and crabs funneled into hoop nets set on the tideflat) densities did not differ by habitat type though patterns were apparent for some species and diversity was highest in structured habitats.

Hosack, G.R. 2008. Predicting the stability, equilibrium response, and nonequlibrium dynamics of ecological systems. Ph.D. Thesis. Oregon State University. Fisheries Science.

The use of intertidal habitats by juvenile pacific salmon. Density of juvenile salmonids (primarily Chinook, but also Coho and chum) caught using tow nets did not differ by habitat type (oyster, eelgrass, open tideflat) but varies instead by location within Willapa Bay estuary. Laboratory experiments with hatchery Chinook smolts and a mock heron predator suggest that structured habitat (particularly eelgrass) is important for protection from predators.

Inglis, G.J., Gust, N. 2003. Potential indirect effects of shellfish culture on the reproductive success of benthic predators Journal of Applied Ecology. Vol. 40, no. 6, pp. 1077-1089.

We investigated the potential indirect effects of long-line mussel *Perna canaliculus* farms on the demography of an important benthic predator, the sea star *Coscinasterias muricata*. Surveys beneath four active farms, an abandoned farm and three unfarmed areas of seabed in Pelorus Sound, New Zealand, described the direct effects of mussel culture on the distribution and abundance of sea stars and other benthic consumers. These data were used to calibrate a model that simulated the fertilization success of sea star populations in farmed and unfarmed areas of the bays. This study demonstrates the potential for significant bottom-up effects of aquaculture on surrounding ecological assemblages.

Islam, M., Wahab, M., Tanaka, M. 2004. Seed supply for coastal brackish water shrimp farming: environmental impacts and sustainability. Marine Pollution Bulletin. Vol. 48, no. 1-2, pp. 7-11.

The present paper provides a review of the environmental impacts of the wild shrimp seed fishery as well as the possibility of environmental degradation from artificial shrimp seed production in hatcheries.

Ji, R., Mao, X., Zhu, M. 1998. Impacts of coastal shellfish aquaculture on bay ecosystem. Journal of Oceanography of Huanghai and Bohai Seas/Huangbohai Haiyang. Qingdao. Vol. 16, no. 1, pp. 21-27.

The major ecological characteristics of high-density cultured shellfish including biodeposition and filter feeding control on phytoplankton and impacts on population of zooplankton and their ecological effect are described. The subsequent impacts on bay ecosystem is analyzed according to the recent literature in this field and our in situ investigation. The importance of this study on sustainable shellfish aquaculture development protection was pointed out and some techniques used in this field were proposed for further study.

Kaiser, M.J., Burnell, G., Costello, M. 1998. The environmental impact of bivalve mariculture: A review. Aquaculture '98 Book of Abstracts. pp. 81-82.

Bivalve cultivation can be broadly split into three main processes: (1) seed collection, (2) seed nursery and on-growing, and (3) harvesting. Here, we review the potential environmental effects that occur throughout the cultivation cycle, from collection of the seed to harvesting. We suggest that careful consideration of the techniques employed can effectively minimize environmental changes that might occur, and possibly ameliorate subsequent restoration of cultivated sites.

Klumpp, D.W., Bayne, B.L., Hawkins, A.J.S. 1992. Nutrition of the giant clam *Tridacna gigas (L.)*. 1. Contribution of filter feeding and photosynthates to respiration and growth. Journal of Experimental Marine Biology and Ecology. Vol. 155, no. 1, pp. 105-122.

The total carbon requirements (growth + respiration) of the host tissues of the giant clam *Tridacna gigas* from Davies Reef on the Great Barrier Reef were measured, and compared with rates with which nutrients were acquired from the two potential sources, translocated photosynthates and filter feeding. The giant clam is an efficient utilizer of particulate organic matter available in reef waters, retaining on average 75% of particles between 2 and 50 mu m, and absorbing from them 54% of C. The spectacular rates of growth in this clam are such that filter feeding is able to provide 65% of the total carbon needed both for respiration and growth in small clams (100 mg dry tissue wt), whereas large clams (10 g) acquire only 34% of their carbon from this source.

La Rosa, T., Mirto, S., Favaloro, E., Savona, B., Sara, G., Danovaro, R., Mazzola, A. 2002. Impact on the water column biogeochemistry of a Mediterranean mussel and fish farm. Water Research. Vol. 36, no. 3, pp. 713-721.

We investigated and compared the impact of organic loads due to the biodeposition of mussel and fish farms on the water column of a coastal area of the Tyrrhenian Sea (Western Mediterranean). Physico-chemical data, microbial variables and phytoplankton biomass were determined on a monthly basis. The results of this study indicate that both fish farm and mussel culture did not alter significantly dissolved inorganic phosphorus and chlorophyll-a values, while inorganic nitrogen concentrations were higher in mussel farm area. However, waters overlying the fish farm presented significantly higher DOC concentrations. The increased DOC concentrations determined a response of the heterotrophic fraction of < BR>picoplankton, while picophytoplankton and phytoplankton, did not display differences among fish or mussel farms and control site. It is possible to conclude that the impact of fish farms is evident only for the heterotrophic components. The comparative analysis of the mussel biodeposition and fish-farm impact revealed that mussel farms induced a considerably lower disturbance, apparently limited to an increased density and biomass of microbial assemblages beneath the mussel cultures.

Luckenbach, M. W., Wang, H. V. 2004. Linking watershed loading and basin-level carrying capacity models to evaluate the effects of land use on primary production and shellfish aquaculture. Bulletin of Fisheries Research Agency (Japan). no. Sup. 1, pp. 123-132.

Aquaculture production of hard clams, *Mercenaria mercenaria*, in the lower Chesapeake Bay, Virginia, U.S.A., has increased dramatically within the last decade. We describe an ongoing project linking a watershed-based loading model with a physical transport-based water quality model to simulate primary production and predict carrying capacity for clam aquaculture. In our present efforts, watershed loading models have been developed and tested for predicting both surface and groundwater inputs into the coastal waters. We are currently coupling the water quality and watershed loading models, and developing clam physiology and population-level sub-models. Also, under development is a sediment deposition/resuspension sub-model. Each of these components will be linked to estimate exploitation carrying capacity for clam production in this system. Our goal is to use the coupled models to predict how varying land use scenarios impact water quality, primary production and shellfish carrying capacity of coastal waters.

Mazouni, N., Gaertner, J. C., Deslous -Paoli, J. M. 1998. Influence of oyster culture on water column characteristics in a coastal lagoon (Thau, France). Hydrobiologia. Vol. 373-374, no. 1-3, pp. 149-156.

The aim of our study was to estimate (i) how much the composition and the abundance of the epifaunal species can influence the nutrient and oxygen fluxes recorded at the shellfish-water interface and (ii) how these fluxes modify water column characteristics. We used Principal Component Analysis with Instrumental Variables (PCAIV). Two analyses were carried out, using sets of data on fluxes, the specific composition of the cultivated communities, and on oxygen, nutrient and chlorophyll a concentrations in the water column. The highest fluxes at the OCU-water interface were measured when epifaunal species richness was maximum. However, at our measurement scale (i.e. the oyster frame) no influence of this filter-feeders assemblage was observed on the chlorophyll a level. Conversely, we found a significant influence of oyster culture on the oxygen and dissolved nitrogen concentrations in the water column. The use of this recent factorial analysis was helpful to estimate the influence of the biofouling species composition on the fluxes at the OCU-water interface, and to estimate the potential impact of oyster cultures on the conditions prevailing in the water column.

Mazouni, N., Gaertner, J.C., Deslous-Paoli, J. M., Landrein, S., Geringer d'Oedenberg, M. 1996. Nutrient and oxygen exchanges at the water-sediment interface in a shellfish farming lagoon (Thau, France). Journal of Experimental Marine Biology and Ecology. Vol. 205, no. 1-2, pp. 91-113.

The Etang de Thau (France) is a shallow lagoon characterized by the semi-intensive farming of oysters (*Crassostrea gigas*, Thunberg) cultured in suspension on frames. Analysis of the benthic fluxes of inorganic nutrients and oxygen over a period of a year has provided a basis for describing the dynamics of the water-sediment interface in the lagoon. Monthly measurements of fluxes at the water-sediment interface at two stations have been compared. One station (UC) is located under a culture table, and is subject to intensive accumulation of organic matter (biodeposition); the other (OC) is located outside the area directly under the impact of the culture activities.

Minjeaud, L., Michotey, V.D., Garcia, N., Bonin, P.C. 2009. Seasonal variation in di-nitrogen fluxes and associated processes (denitrification, anammox and nitrogen fixation) in sediment subject to shellfish farming influences. Aquat. Sci. 71. pp. 425–435.

Seasonal patterns of di-nitrogen fluxes together with denitrification, anammox, and N-fixation rates were studied in sediment in an area subject to strong human pressure via waste water, tributaries and shellfish farming in the Mediterranean Sea. Ammonium concentration demonstrated no seasonal variation, however, a large increase in its concentration was observed over a 10 years period due to intense biodeposition of organic matter. In contrast, nitrate concentration demonstrated no seasonal or long-term (10 years) variation. The main processes affecting di-nitrogen flux magnitudes were denitrification and N-fixation. Anammox was only detected occasionally, nevertheless it represented at times up to 39% of the N2-flux. Nitrate reducing processes were variable and denitrification showed a 20-fold increase over the past 10 years and might actually have reached its potential maximal activity. Rates of N2 production (denitrification and anammox) were generally higher than those of N-fixation, leading to elimination of nitrogen from the ecosystem.

Munroe, D., and McKinley, R.S. 2007. Commercial Manila clam (*Tapes philippinarum*) culture in British Columbia, Canada: The effects of predator netting on intertidal sediment characteristics. Estuarine, Coastal and Shelf Science 72. pp. 319-328.

Research has demonstrated that the use of predator netting in shellfish aquaculture increases sedimentation rates and productivity; here we examine the influence of netting on the west coast of Canada. Changes in percent silt (sediment particles <63 mm), percent gravel (sediment particles >2 mm), organic and inorganic carbon levels and temperature, and differences in clam populations were monitored on paired netted and non-netted Manila clam (*Tapes philippinarum*) plots on four farmed beaches at Baynes Sound, British Columbia in 2003 and 2004. For the locations and parameters monitored in this study, it appears that netting and clam farming in Baynes Sound British Columbia, has limited effect on the sediment.

Prins, T.C., A.C. Smaal, R.F. Dame. 2006. A review of the feedbacks between bivalve grazing and ecosystem processes. Aquatic Ecology. 31(4). pp. 349-359.

This paper gives an overview of interactions between bivalve grazing and ecosystem processes that may affect the carrying capacity of ecosystems for bivalve suspension feeders. These interactions consist of a number of positive and negative feedbacks. Bivalve grazing can result in local food depletion, which may negatively influence bivalve growth. On larger scale, it may induce a top-down control of phytoplankton biomass, and structural shifts in phytoplankton composition. In the case of harmful algal blooms, phytoplankton may negatively affect bivalve grazing rates. The processing of large amounts of particulate matter may change nutrient cycling on the scale of estuaries, and can result in changes in the inorganic nutrient pool available for phytoplankton, through regeneration and reduced storage of nutrients in algal biomass. This can reduce nutrient limitation of the phytoplankton and stimulate algal growth rates. Observations from mesocosms studies suggest that appositive feedback from bivalve grazing on phytoplankton growth may also change the physiological state of the algae and improve food quality.

Rheault, R.B. 2008. Report on Biological Impacts of Aquaculture. Coastal Resources Management Council. pp. 49-59.

See Section 1 references for abstract.

Rice, M.A. 2001. Environmental Impacts of Shellfish Aquaculture: Filter Feeding to Control Eutrophication. Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. pp. 77-84.

Filter feeding by populations of bivalve mollusks is reviewed with respect to their ability to act as an estuarine filter, increase clarity of coastal waters and facilitate the removal of nitrogen and other nutrients from eutrophic coastal waters. Most species of cultured bivalve mollusks clear particles from waters at rates of 1 to 4 L/h, and populations of shellfish in healthy assemblages can filter a substantial fraction of the water in coastal estuaries on a daily basis. Actively growing shellfish incorporate nitrogen and other nutrients into their tissues as they grow. On average, 16.8 g of nitrogen is removed from estuaries for every kilogram of shellfish meats harvested. In addition, shellfish beds may act to promote removal of nitrogen from estuaries by increasing organic nitrogen deposition to the sediments that stimulate denitrification processes. It is suggested that shellfish restoration projects and establishment of small-scale molluscan shellfish aquaculture operations may mitigate the effects of coastal housing development or other activities that promote excessive coastal eutrophication.

Richard, L.2004. Balancing marine aquaculture inputs and extraction: Combined culture of finfish and bivalve molluscs in the open ocean. Bulletin of Fisheries Research Agency (Japan) no. Sup. 1, pp. 51-58.

While severe impacts have been documented in shallow, poorly flushed waters, proper siting of finfish sea cage operations generally results in only minor localized impacts to the benthic community on the sea floor directly beneath the cages In order for the industry to expand to meet the growing demand for seafood, measures to mitigate these impacts must be taken. One possible solution is to balance inputs of feed with extraction of biomass of organisms such as marine plants and bivalve molluscs that do not require external feed application. In 1999, the University of New Hampshire established the Open Ocean Aquaculture Demonstration Project. The project has produced harvests of several species of finfish using submersible sea cages and six crops of molluscan shellfish (primarily blue mussels) using submerged longlines in close proximity to the sea cages. While not considered true polyculture, the harvest of the filter feeding bivalve molluscs represents a net removal of nitrogen, carbon and phosphorus that can be used in mass balance to offset the addition of these nutrients from finfish feeding. In this paper, data the potential for balancing inputs associated with feed application and fish wastes with extraction of fish and bivalve biomass will be examined.

Richardson, N.F., Ruesink, J.L., Naeem, S., Hacker, S.D., Tallis, H.D, Dumbauld, B.R., Wisehart, L.M. 2007 Bacterial abundance and aerobic microbial activity across natural and oyster aquaculture habitats during summer conditions in a northeastern Pacific estuary. Hydrobiologia, in press.

Observational study of sediment properties, especially microbes, in six habitat types and along the estuarine gradient of Willapa Bay. Habitat types: eelgrass, unstructured, oyster hummocks (reefs), mechanically-harvested ground, hand-picked ground, and longline oyster aquaculture. [Funding: USDA WRAC, UW Bridges, Mellon Foundation].

Roycroft, D., Kelly, T. C., Lewis, L. J. 2004. Birds, seals and the suspension culture of mussels in Bantry Bay, a non-seaduck area in Southwest Ireland. Estuarine, Coastal and Shelf Science. Vol. 61, no. 4, pp. 703-712.

The main aim of this study was to examine the interactions, and assess the impacts (if any) of mussel suspension culture on the seabird and seal community, employing a simultaneous study of culture and control sites. The study spanned a 20-month period (from November 2001 to August 2003) and encompassed six sites in Bantry Bay (Southwest Ireland). The possible interactions between vertebrate predators and mussel suspension aquaculture are discussed and possible explanations for the increased seabird abundance observed in these areas are offered.

Ruesink, J.L., Feist, B.E., Harvey, C.J., Hong, J.S., Trimble, A.C., Wisehart, L.M. 2006. Changes in productivity associated with four introduced species: Ecosystem transformation of a "pristine" estuary. Marine Ecology Progress Series 311. pp. 203-215.

Estimates the annual production of 6 important native and non-native species in Willapa Bay ~1850 vs. ~2000 [Funding: Mellon Foundation, USDA WRAC]

Species	Scientific name	Native/ Non	1850 Prod'n (kg dry wt yr-1)	2000 Prod'n (kg dry wt yr-1)
Eelgrass	*Zostera marina*	Native	Similar to 2000	3.53 x 107
Dwarf eelgrass	*Zostera japonica*	Non	0	4.79 x 106
Spartina cordgrass	*Spartina alterniflora*	Non	0	1.31 x 107*
Native oysters	*Ostrea lurida***	Native	9.15 x 104	Small
Pacific oysters	*Crassostrea gigas*	Non	0	3.23 x 105
Manila clams	*Ruditapes philippinarum***	Non	0	6.94 x 103

* Value likely to have declined in recent years due to herbicide control
** Scientific name under review

Ruesink, J.L. and Rowell, K. 2007. Geoduck clam (*Panopea abrupta*) aquaculture as press and pulse perturbations to eelgrass (*Zostera marina*). Presentation at NW Workshop on Bivalve Aquaculture and the Environment. Sponsored by Washington Sea Grant.

Experimental study of the effects of geoducks and fertilizer on eelgrass density and growth, and the pace and manner of recovery of small (1 m^2) gaps created in an eelgrass bed. Eelgrass density was depressed in summer by space competition with geoducks; growth rates were not affected. Gaps recovered over 2 years exclusively by regrowth from the edges. When the geoducks were harvested at the end of the experiment, eelgrass shoot density dropped >70%. The results of this study should not be extrapolated widely because south Puget Sound tends to contain a very sensitive type of eelgrass – small, high-density plants with little sexual reproduction.

Rumrill, S.S. and Poulton, V.K. 2003. Ecological role and potential impacts of molluscan shellfish culture in the estuarine environment of Humboldt Bay, CA. Journal of Shellfish Research. Vol. 22, no. 2, p. 607.

The authors report on the first year of a 3-year project to identify and quantify the effects of commercial oyster mariculture in tideflat habitats, eelgrass beds, and invertebrate communities. Experimental oyster long-line spacing plots were established for comparison to a ground culture site and 6 reference sites (no oysters). We sampled study plots quarterly between Aug 2001-Aug 2002 for presence of eelgrass, oysters, and other cover types. We collected infaunal cores, deployed fish traps, and measured water quality, sedimentation, light intensity, and oyster growth characteristics.

Semmens, B.X. 2006. PhD, Department of Biology, University of Washington.

Hatchery-raised smolts of Chinook salmon were released into a large intertidal pen containing eelgrass (*Z. marina* and *Z. japonica*), oyster clusters, unstructured sediment, and Spartina cordgrass. They were implanted with acoustic tags that allowed their movements to be tracked in 2-dimensions at sub-meter accuracy. After effects of tidal elevation and enclosure were accounted for, smolts responded only to native eelgrass, where they moved more slowly than in other habitat types. Smolts never entered Spartina.

Sequeria, A., Ferreira, J.G., Hawkins, A.J.S., Nobre, A., Lourenco, P., Zhang, X.L., Yan, X., and Nickell, T. 2008. Trade-offs between shellfish aquaculture and benthic biodiversity: A modeling approach for sustainable management. Aquaculture 274. pp. 313–328.

Ecosystem modeling approach which focuses on natural benthic biodiversity and aimed to improve shellfish aquaculture management is used. The Wild species Integration for Shellfish Ecoaquaculture (WISE) approach helps to understand the baseline food requirements for maintaining natural benthic biodiversity of suspension-feeding organisms, thus informing managers on potential upper thresholds for shellfish aquaculture. WISE was tested in four coastal systems in Europe and China, with widely differing aquaculture activities. In the European systems, where the aquaculture industry is developing, species diversity and abundance are much higher and suspension feeding wild species play an important role in the consumption of food resources. In relative terms, wild populations play a more important role than cultivated shellfish in clearing suspended particles from the European systems due to the much lower aquaculture activity. There are trade-offs between commercial aquaculture and the conservation of biodiversity. Rates of and capacities for shellfish culture are reduced when both wild and cultured suspension-feeding species are considered in relation to the available section. When food resources are partitioned between wild and cultivated species, there is a decrease in individual length and weight resulting in a lower aquaculture production

Tallis, H.M., Ruesink, J.L., Dumbauld B.R., Hacker, S.D., and Wisehart, L.M. 2009. Oysters and aquaculture practices affect eelgrass density and productivity in a Pacific Northwest estuary. Journal of Shellfish Research. 28(2): 251-261.

Observational study of *Z. marina* density, biomass, and relative growth rates in 4 habitat types: mechanically-harvested ground, hand-picked ground, longline aquaculture, and nearby eelgrass beds in two regions of Willapa Bay. Eelgrass density was 30-70% lower on aquaculture beds than in nearby eelgrass beds. While aquaculture may promote eelgrass at the expense of burrowing shrimp at the landscape scale, eelgrass appears susceptible to space competition and disturbance at the bed scale. Statistical analyses are still on-going, so the numbers and relative values reported here should not be quoted yet.

Thuringer, P. L. 2004. Documenting Pacific sand lance (*Ammodytes hexapterus*) spawning habitat in Baynes Sound, east coast Vancouver Island, and the potential interactions with intertidal shellfish aquaculture. Masters Abstracts International. Vol. 42, no. 6, p. 2098.

This research documented characteristics of some of the beach spawning habitat in Baynes Sound and interactions between clam tenure operations and beach spawning activity, and evaluated potential approaches to managing these interactions. Pooled data (n = 5) indicates that *A. hexapterus* tend to spawn on medium (50%, 0.25-0.5mm grain size) to coarse sand (30%, 0.5-2mm) substrate with <3% finer material (silt/fine sand <0.25mm). The greatest potential for interactions between predator netting and sand lance beach spawning activity is in the lower limit of spawning range and the upper limit of net placement (tidal elevation +2.7m to +3.0m CD).

Van der Veer, H. W. 1989. Eutrophication and Mussel Culture in the Western Dutch Wadden Sea: Impact on the Benthic Ecosystem; a Hypothesis. Helgolaender Meeresuntersuchungen HEMEDC Vol. 43, No. 3/4, pp. 517-527.

Account of patterns in eutrophication and mussel culture in the western Dutch Wadden Sea is recorded. Due to a lack of data for the period until 1970 the impact of eutrophication and mussel culture cannot be assessed. From 1970 onwards an increased biomass and production of the macrofauna in the intertidal zone has been observed, which is attributed to eutrophication. The hypothesis is postulated that the introduction of mussel culture between 1950 and 1960 has resulted in an increased competition for food in the area, leading to a decreased stock of the macrofauna in the intertidal. Eutrophication from about 1970 onwards has improved the food conditions and as a result both the macrofauna in the intertidal and the mussel in the sublittoral area would have increased in biomass, allowing higher maximum yields of the mussel culture.

Vaudrey, J., Getchis, T., Britton, B. 2006. Assessing impacts of shellfish aquaculture on eelgrass populations in eastern Long Island Sound. Journal of Shellfish Research. Vol. 25, no. 2, p. 785.

Eelgrass beds provide critical ecological functions such as removing nutrients and stabilizing fine sediments. Beds also provide critical habitat to a myriad of marine organisms including juvenile fish, shellfish, and crustaceans, among others. Bivalve aquaculture, specifically the utilization of submerged cultivation and depuration gear such as cages, has been implicated as a potential source of negative impacts to eelgrass populations. However, shellfish aqua-culture gear has also been shown to provide an equivalent or greater degree of ecosystem services as submerged aquatic vegetation such as eelgrass. This study was conducted to determine the type and degree of impacts and benefits that oyster depuration bottom cages have on eelgrass and surrounding water and sediment quality. Preliminary results suggest an increase in eelgrass growth rate, measured as sheath length. No treatment effect was seen for water column properties, sediment % organics, or benthic microalgae concentrations.

Vaudrey, J.M.P., Getchis, T., Shaw, K., Markow, J., Britton, R., Kremer, J. N., 2009. Effects of Oyster Depuration Gear on Eelgrass (*Zostera marina L.*) in a Low Density Aquaculture Site in Long Island Sound. Journal of Shellfish Research. Vol. 28, no. 2, pp. 243-250.

The effects of short-term oyster depuration activity were gauged by comparing eelgrass reference sites and experimental plots (eelgrass areas containing oyster depuration cages with and without oysters) in triplicate. The aquaculture gear had no effect on this measure of growth rate of eelgrass in any of the deployments. Sediment characteristics (sediment chlorophyll, sediment % organics) in the cage footprint and 1m from the cages also failed to show an effect of the depuration cages on the local environment. Video monitoring of the footprints and local area indicated little physical damage to the eelgrass beds as a result of the short deployment of the aquaculture gear. The water column at all three sites was vertically well mixed and no effect of the cages on water column light and other characteristics was detectable. The results of this study indicated that at the current level of activity, short-term depuration of oysters has minimal effect on eelgrass growth, water quality and the sediment characteristics measured. However, if depuration activity expands in terms of the amount of gear and/or individual operations, it may result in measurable effects.

Watson-Capps, J.J., Mann, J. 2005. The effects of aquaculture on bottlenose dolphin (*Tursiops sp*.) ranging in Shark Bay, Western Australia. Biological Conservation. Vol. 124, no. 4, pp. 519-526.

Here we compare long-term ranging patterns of adult female bottlenose dolphins (*Tursiops sp*. in Shark Bay, Western Australia) before and during full-scale pearl oyster farming operations, to determine if they were displaced. Results suggest that shellfish aquaculture could have a large impact on small cetaceans. The analytical techniques discussed apply broadly to aquatic and terrestrial animals.

Weise, A.M., Cromey, C.J., Callier, M.D., Achambault, P., Chamberlain, J., McKindsey, C.W. 2009. Shellfish-DEPOMOD: Modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. Aquaculture 288. pp. 239–253.

By predicting the dispersal of particulate aquaculture wastes around farm sites, numerical modelling can provide an effective tool to assess the spatial extent of environmental effects. The present paper describes how the aquaculture waste model DEPOMOD (Cromey, C.J., Nickell, T.D., Black, K.D. 2002a. DEPOMOD — modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214. pp. 211–239.), originally developed for finfish aquaculture sites, was adapted and validated for suspended shellfish aquaculture. The relationship between modelled long-term biodeposition and benthic descriptors was assessed for the three farms. The potential application of Shellfish-DEPOMOD in terms of the management of shellfish aquaculture sites is discussed.

Whiteley, J.A. 2006. Macroinvertebrate community responses to clam aquaculture practices in British Columbia, Canada. Masters Abstracts International. Vol. 44, no. 1, p. 218.

Despite recent growth of shellfish aquaculture in B.C., Canada, very little is known regarding impacts of common practices. A pilot netting experiment found no observable effect of predation at small scales. A field study compared bivalve communities on clam farms with matched reference sites, using density and biomass data. *V. philippinarum* was the only species found in higher abundance on farm sites, consistent with values expected from clam seeding. Bivalve communities were not significantly different on farm sites, but were more similar on average than reference sites, leading to a loss of regional distinctness. These results are consistent with recent research suggesting that predation and competition may play minor roles in structuring communities in soft-bottom environments. Given the remaining uncertainties, a precautionary approach is recommended in future development of the intertidal for clam aquaculture.

Wisehart, L.M., Dumbauld, B.R., Ruesink, J.L., Hacker, S.D. 2007. Importance of eelgrass early life history stages in response to oyster aquaculture disturbance. Marine Ecology Progress Series 344. pp.71-80.

Compares seed production and germination in eelgrass, mechanically-harvested, and longline aquaculture in Willapa Bay. Seed production and germination were highest in dredged beds. Because the experimental removal of adults locally enhanced germination, the response on dredged beds is at least in part due to reduction of competition among eelgrass shoots.

Wisehart, L.M., Hacker, S.D., Dumbauld, B.R., Ruesink, J.L., 2006. Oyster aquaculture may positively affect eelgrass (*Zostera marina* L.) through enhanced seed production and germination. Journal of Shellfish Research. Vol. 25, no. 2, p. 792.

See Section 1 references for abstract.

Wisehart, L.M., Hacker, S.D., Tallis, H.M., Ruesink, J.L., Oyarzun, F., Dumbauld, B.R. 2004. The effects of different aquaculture techniques on *Zostera marina* biomass, density, and growth rates in Willapa Bay, Washington. Journal of Shellfish Research. Vol. 23, no. 2, p. 660.

In an effort to quantify possible positive and negative effects of shellfish aquaculture, we investigated the relationship between oyster culture type and eelgrass at three sites in Willapa Bay, Washington. At each site, we sampled an off-bottom long-line culture area, a dredged ground culture area, a handpicked ground culture area, and an area without aquaculture. We measured the standing biomass, percent cover and growth rate of eelgrass, as well as the density of vegetative and flowering shoots. In general, we found the largest growth rates in areas with off-bottom culture and those without aquaculture; these areas also had the greatest eelgrass biomass, density, and percent cover. Interestingly, there were significant site and culture type interactions for most variables suggesting that site-specific conditions may be as influential as culture technique in determining eelgrass growth.

Yang, S. PhD thesis research on the consequences of thinning eelgrass to different densities – especially in terms of water flow, epifauna/infauna, and eelgrass growth and reproduction. Working in Willapa Bay.

Yang, S., et al. in preparation.
Compares morphology and demography (flowering, recruitment) of *Z. marina* at 19 sites in Washington State at an ecologically equivalent tidal elevation, as well as the upper limit of eelgrass. Will allow predictions of resilience of populations to disturbance, based on asexual and sexual reproduction rates. Preliminary findings are that populations in Willapa Bay and on silty sediments in Puget Sound successfully recruit from seed.

Zydelis, R.N., Esler, D., Kirk, M., Boyd, W. S. 2009. Effects of off-bottom shellfish aquaculture on winter habitat use by molluscivorous sea ducks. Aquatic Conserv: Mar. Freshw. Ecosyst. 19. pp. 34–42.

The interaction between off-bottom, suspended oyster farming and wintering sea ducks in coastal British Columbia was studied. Specifically, the habitat use of surf scoters (*Melanitta perspicillata*) and Barrow's goldeneyes (*Bucephala islandica*), was evaluated in relation to natural environmental attributes and shellfish aquaculture. The extent of shellfish farming was the best-supported habitat variable explaining variation in surf scoter densities, and the only habitat attribute from the considered set that was a strong predictor of Barrow's goldeneye densities. In both cases, the findings indicated strong positive relationships between densities of sea ducks and shellfish aquaculture operations. These relationships are presumably the result of large numbers of wild mussels (*Mytilus trossulus*) that settle and grow on aquaculture structures and are preferred prey of these sea ducks. This offers a rare example in which introduction of an industry leads to positive effects on wildlife populations, which is particularly important given persistent declines in numbers of many sea ducks.

SECTION III: SHELLFISH AQUACULTURE OPERATIONS – GENERAL MANAGEMENT PRINCIPLES

Regulatory Compliance

West Coast shellfish farms are highly regulated by local, state, federal and, where applicable, international laws (Please refer to Regulations Section in this document for detailed information on permits and regulations that pertain to shellfish aquaculture operations). It is the expectation of the Pacific Coast Shellfish Growers Association that growers will comply with all laws and permit requirements that apply to their particular operations. Growers are encouraged to become involved in legislation and local policy making efforts to promote policies that help protect the environment and shellfish habitat.

Objective: Ensure operations meet or exceed regulatory and environmental standards.
Suggested Strategies:

1	Become knowledgeable about and keep current on all rules, regulations, certification, and permit requirements governing shellfish aquaculture operations (*See Regulations Section).
2	Compare all statutes and agency rules against shellfish activities to ensure compliance.
Objective: Promote sound environmental policies and innovative practices and techniques that help protect and restore the environment.	
Suggested Strategies:	
1	Identify opportunities for conserving and protecting natural areas, and for enhancing functions and values of growing areas and beaches.
2	Continue to experiment with and develop more efficient cultivation methods that also provide benefits or protections for the environment.
3	Incorporate environmental policies into employee training and orientation.
4	Become involved in local watershed and water quality improvement activities and support legislation and regulatory policies that promote environmental protection, such as water quality and shellfish habitat.

Farm Siting

In most cases on the West Coast, shellfish farming dates back several generations and operations are well established. In those instances where new operations are to be established, growers should attempt to locate their farms in areas where user conflicts and environmental impacts are least likely to occur, and impacts to pre-existing uses and activities will be minimized. Growers should document existing conditions, such as eelgrass presence, before cultivating an area. Waterfront property owners typically have a common law right to unimpeded access to and from their property at every point along the shoreline into deep water for the purposes of navigation and access to and passage along the foreshore, as does the public where rights-of-way exist along the waterfront.

There are several issues that should be considered prior to establishing a new aquaculture site, including existing land use zoning laws. Where potential adverse impacts may occur, corresponding mitigation measures should be determined.

Objective: Minimize adverse impacts to surrounding property owners, local residents and other users in and around shellfish farming areas.	
Suggested Strategies:	
1	Identify location of other land and water uses that may have potential to conflict or be conflicted by shellfish operations, such as recreational or commercial uses.
2	Where necessary, in order to gain access to farm site through other property, obtain prior approval from upland owners.
3	If operations impact normally traveled waterways, mark clearly following industry recommendations and Coast Guard requirements and alert other users to the extent possible.

4	Ensure site affords appropriate rate of water exchange and tidal currents that assures a good supply of food for shellfish crops while still maintaining a healthy environment for other marine organisms.
5	Ensure that seed storage piles and other temporary materials stored on intertidal sites are **neat and tidy**.

Solid and Hazardous Waste Management

Solid waste, such as netting, stakes, tags and bags, are generated in the normal course of farm operations and may be introduced into the environment accidentally as a result of weather or sea conditions or as ropes and culture gear age and break down. Plastic pollution in the ocean is a major international issue. It is a concern for shellfish growers in particular in light of emerging science on the potential effects micro and nano plastics may have on animal and human health. Many types of shellfish culture involve the use of considerable ropes and plastic gear. Farmers must ensure they are using gear designed to withstand the elements it is being deployed in and that it is being retired and recycled or disposed of properly before it degrades and contributes to plastic pollution. Farmers must attempt to minimize generation of waste by employing responsible waste reduction, recycle, and control measures.

Fuels and lubricants for boats and cleaning solutions are commonly used. Appropriate use, handling, storage and disposal of these materials and effective waste management practices assure these materials do not enter and potentially contaminate the marine environment.

Objective: Minimize generation of solid waste through re-use, recycling and reduction.	
Suggested Strategies:	
1	Minimize waste generation to the extent possible, practicing the principles of reduction, reuse, recycling and recovery.
2	Purchase materials with a long lifespan or which are reusable or recyclable.
3	Use only gear designed to withstand the elements is it being deployed in and that it is retired and recycled or disposed of properly before it breaks down in the environment.
4	Participate in volunteer clean-up efforts of the waters and coastline surrounding farms.
5	Encourage suppliers and manufacturers of shellfish equipment and packaging to develop and adopt recycling and disposal plans for the products they sell.
6	Encourage other marine resource user groups to be responsible in the collection and disposal of garbage and wastes.
Objective: Minimize the potential for adverse environmental impacts from waste produced by shellfish farming activities.	
Suggested Strategies:	
1	Use non-toxic, "environmentally friendly" bio-degradable lubricants and cleaning agents and minimize or eliminate use of chemicals that could harm the environment.

2	Take all possible precautions when using potentially hazardous materials, such as petroleum products, to avoid or minimize the potential for spills.
3	Properly dispose of any production-related chemicals through the use of appropriate hazardous waste collection facilities.
4	Prepare a spill prevention and response plan; participate in emergency oil-spill cleanup strategies and work with appropriate regulatory agencies in coordinating oil spill responses; train employees in spill prevention and clean up.
5	In Washington, consider enrolling vessels in the Department of Ecology Vessel of Opportunity Program for potential use in the event of a spill in your area.
6	In the event of a spill or other pollution event, notify the Coast Guard and other pertinent regulatory authorities and immediately begin cleanup.
7	Keep oil-absorbing materials and containers on-site for proper disposal of hazardous and toxic materials.
8	Prevent direct or indirect contact of toxic chemicals and compounds including creosote, wood preservatives, paints, etc. with the marine environment.
9	Discourage other marine users against the use of toxic chemicals and compounds.
10	Separate fuel containers from product holding areas on marine vessels.
11	Maintain only the minimum reasonable necessary quantity of fuels and lubricants on site to carry out operations.

Growers are advised that documenting baseline shellfish tissue, sediment and water quality on their farm sites is a useful defense in the event of an oil or other spill, such that there is evidence established that could be used in the event that a claim settlement must be litigated.

Wastewater Management

Wastewater, typically from washing shellfish and equipment, is generated in the normal course of farm operations. A significant concern to shellfish farm operators is the hazard posed by sewage contamination on or near their site. Farmers should minimize their contribution to the wastewater stream by employing responsible wastewater reduction, reclamation, recycle, and control measures. Farmers must be diligent in ensuring that their sewage handling methods, whether onshore or onboard, are maintained at the highest standards and should encourage all other marine resource users to meet these same standards.

Objective: Minimize the potential for adverse impacts from wastewater.	
Suggested Strategies:	
1	Reuse wastewater through recycling, conversion to irrigation systems, in environmental enhancement projects, or other approved means.
2	Use water conservation methods, such as stopping water flow when processing is interrupted.
3	Provide approved upland sanitary facilities for employee and visitor use.
4	Have a sewage plan and adequate facilities for all vessels and/or sites.

5	Ensure employees working on the shellfish farms are trained to understand the importance of proper disposal of human waste.
6	Ensure that the contents of portable toilets are emptied only into approved disposal systems, and that they are cleaned before return to the site.
7	Encourage all other resource users (marine and upland) to be responsible in their handling of sewage; assuring it is not discharged into the marine environment.

Vehicle and Vessel Operation

Motorized vehicles are a vital component in the transportation required for the safe and efficient handling of shellfish products. In addition to transport of product on the highways, vehicles may also be used to transport employees, equipment and shellstock over beaches and intertidal areas. Vehicles operating in the intertidal zone can cause environmental impacts, so care should be taken to avoid beach driving to the extent possible. When such transport is necessary, operators should develop appropriate routes for vehicle traffic that minimizes impact. Farmers should be aware of local or state restrictions for vehicle use in these areas and comply with any applicable laws.

Marine vessels and equipment of assorted descriptions are commonly used in shellfish farming operations. This equipment is necessary for the safe and efficient transport of employees and equipment and the seeding, handling, cultivation and harvesting of product. However, there is the potential for environmental impact as a result of the operation of this equipment in an inappropriate manner.

Objective: Minimize adverse impacts from operating vehicles in intertidal areas.	
Suggested Strategies:	
1	Avoid or minimize the use of vehicles and other heavy equipment on sensitive intertidal areas and beaches.
2	Where driving on the beach is unavoidable, restrict route in intertidal areas to hard surfaces along the upper intertidal zone to the extent feasible. Crossing the shore at a designated place each time and choosing the shortest route possible can be effective at localizing this source of disturbance to a discrete area[2]. In no case should vehicles be driven across documented forage fish spawning grounds on the upper beach during periods when spawn is present.
3	Ensure vehicles are routinely serviced and appropriate for the type of terrain to be crossed.
4	Have a contingency plan for addressing vehicle breakdowns in the intertidal zone.

[2] In some locations, based on the underlying substrate type and its saturation and compaction, the use of a set path can create deep ruts in the beach causing a chronic impact as long as farming operations continue on the site. Using multiple access paths in such cases may cause less damage to foreshore habitat. It should be recognized, however, that the use of multiple paths would avoid spreading the spatial extent of impact from vehicle use only if the frequency of such use on the beach is low enough that no evidence of vehicle activity could be identified afterwards (i.e., in the next accessible tide cycle). If multi-access routes create discernible impacts to physical habitat along each point of access, then the use of a single discrete path is preferable to minimize the overall spatial extent of impact from vehicle operations.

Objective: Minimize adverse impacts from operating vessels and marine equipment, including risks of spills of contaminants.	
Suggested Strategies:	
1	Provide environmental training in areas such as contaminated spill cleanup, bilge water disposal, and sewage disposal from boats.
2	Provide adequate and appropriate training in the operation and maintenance of all marine equipment.
3	Regularly maintain vessels and equipment to ensure seaworthiness.
4	Adjust vessel speed to reduce the impact of wake on other marine users and the foreshore area.
5	Use biodegradable or food grade oils and products when available.
6	Minimize the risk of spills of substances from vessels and equipment through appropriate design, employing appropriate containment devices (such as drip pans), and prompt cleanup of all spills and leaks.
7	When upgrading consider engines that use less fuel and lubrication.
8	Report hazards and obstructions to safe navigation to appropriate authorities.

Navigational Safety Around Shellfish Aquaculture Structures

Navigable waters are generally described as any body of water over which any description of vessel may operate. Virtually all shellfish farming operations occur in navigable waters. Approval from the Army Corps of Engineers is required prior to the construction of all works located below the high water mark in any navigable waters that may constitute a significant interference with navigation.

A "work" is commonly defined as any structure, device, or thing on, in or under the water that may interfere with navigation. Concrete clam bed boundary markers that are flush with the tideland, for example, are not considered a hazard to navigation, but a raft would be. Anything installed in navigable waters must be marked and maintained in accordance with the guidelines of the Ports and Waterways Safety Act administered by the U.S. Coast Guard.

All works and site plans must be approved prior to the commencement of construction. As a condition of approval, the use of private aids and markers may be required (i.e., lights). When required, the operator must establish and maintain navigational aids in accordance with regulations and all applicable standards. Depending on the circumstances, the operator may be required to mark the site or obstacle by day, and by adequate light at night.

Many farmers experience significant loss or damage as a result of accidental or negligent marine vessel operation around their sites. The potential for accidents and personal injury to other marine vessel operators is increased during periods of limited visibility. By ensuring their sites and equipment are clearly marked at all times, farmers will reduce the potential for commercial and recreational marine traffic to approach or enter their site in an unsafe manner.

With increased shoreline development, shoreline lights are becoming a significant issue in regard to glare and preventing existing navigational aids to be seen. Homes with lights that are unshaded project this light onto estuarine waters which increases light pollution and elevates the danger of collision and grounding because navigation aids cannot be distinguished from these other lights at night.

Objective: Maintain safe navigation around shellfish farms and structures.	
Suggested Strategies:	
1	Ensure anchors securing rafts, vessels, floating structures and culture apparatus are properly sized and set to prevent dragging.
2	Ensure lights are installed according to US Coast Guard requirements.
3	Mark aquaculture structures properly to assure safe navigation within farmed areas.
4	Keep all portions of farm structure within site boundaries.
5	Promote public awareness of the need for caution when operating vessels around shellfish operations.
	Ensure anchor lines and cables are clearly marked or submerged to prevent obstruction.
7	Ensure floating equipment is securely fastened and regularly maintained.
8	Repair storm damaged equipment in a timely fashion.
9	Use material to secure predator netting that is least likely to cause accidents or injury, for example "U" shaped rebar.
10	Ensure that predator nets are tightly secured to prevent them from floating away and quickly repair tears that occur.
11	Post and maintain speed limits in shellfish growing areas.
12	Encourage other marine users to reduce speed in congested marine areas for safety purposes.
13	Report shoreline lighting that interferes with navigation to the coast guard or other appropriate authority.
14	Participate in policy development that required shading of shoreline lights.

Equipment and Construction Standards

The shellfish farming industry is rapidly developing new equipment, techniques and construction standards to enhance efficiency and productivity. With this development, a variety of equipment and designs are being researched and constructed while older less efficient methods are steadily being replaced. Pacific Coast shellfish farmers have a tradition of innovation in equipment design, and continue to pioneer new culture techniques.

Continuing this tradition is critical if the industry is to continue flourishing in the future, but it must be balanced with aesthetics and impacts on the environment, with a focus on lifespan, durability and safety. Farmers should avoid the use of materials that rapidly break up, decompose, or have limited, short-term single use, or the use of damaged or abandoned equipment.

Objective: Continue to improve standards of equipment and culture apparatus design and construction to improve lifespan and appearance.	
Suggested Strategies:	
1	Arrange placement of culture apparatus in the most environmentally compatible manner feasible.
2	Keep equipment well maintained and perform periodic checks of equipment and machinery for efficient operations and use of energy.
3	Maintain high efficiency energy systems including fluorescent lighting and high R-value insulation in areas requiring refrigeration.
4	Perform periodic grounds and facilities inspections.
5	Equipment should be designed and constructed to withstand the most extreme weather conditions anticipated at the site over time.
6	Should the protective covering over polystyrene foam flotation become damaged, it should be repaired or replaced as soon as practical.
7	Manufacturers of shellfish farming equipment should be encouraged to develop a plan to reuse or recycle materials they manufacture.
8	Equipment should be designed and constructed with a view to long-term durability.

Visual Impacts

Maintaining farm sites in a clean and orderly manner facilitates acceptance of operations by the public, as well as improving efficient farm operation and safety. The individual interpretation of aesthetic appeal is subjective, however, and may vary considerably from one individual to another. Farmers need to acknowledge and be prepared to address visual quality issues (aesthetics), which are often the single biggest source of opposition for shellfish farming operations and the underlying source of public concern.

Recognizing that some marine resource users will never be satisfied with any visual impact on the water, farmers must nonetheless be prepared to make reasonable efforts to minimize the visual impact of their operations for their own sake and for other farmers. For guidance on aesthetics issues, consult the "Visual Impact Analysis" developed by the Washington State Department of Ecology.

In general terms, an orderly, well-maintained and uniformly laid-out site indicates a responsible and efficient farm operation.

Sharing Resources

A significant challenge facing shellfish farmers is educating the general public about our activities in a manner that affirms commitment to protecting and enhancing the marine environment. In most instances, growers share similar concerns with other user groups regarding the impacts of human activities on the marine environment. By promoting better understanding of shellfish farming and common interests, support as a legitimate marine resource user group will improve.

At the same time, the public is largely unaware of the detrimental impact many of their activities may have on the marine environment and sensitive shellfish growing areas. Most people are willing to improve their practices when they understand their impacts. Farmers must encourage positive efforts and lead by example in this area. Public support for the continued growth and development of shellfish aquaculture will be facilitated by a "good neighbor" policy that includes recognition of the concerns of others and attempts to achieve reasonable compromise. In some cases, farmers have encouraged the public's access to their farms in the interest of encouraging awareness and acceptance of shellfish aquaculture activities.

In farm siting or changes in cultivation practice it is also necessary to consider how these changes may impact existing farm operations. Growers must consider impacts on current flow, siltation, navigation, etc. to assure an existing operation is not impacted.

Objective: Minimize adverse impacts to surrounding property owners, local residents and other users of coastal marine areas.	
Suggested Strategies:	
1	Identify areas of potential user conflicts.
2	Communicate with upland owners and other resource users and work to develop and maintain cooperative relationships.
3	Inform adjacent landowners of operations and ongoing activities. Take complaints from adjacent landowners seriously and respond appropriately and in a timely fashion.
4	Maintain dialogue with upland owners and neighbors to resolve concerns and conflicts at a personal level.
5	Report the abuse of natural resources by pollution, poaching, illegal fishing, etc. to the appropriate authorities.
Objective: Foster a public attitude of protecting and enhancing our marine environment and resources.	
Suggested Strategies:	
1	Participate in community events and activities to promote environmental protection.
2	Participate on national, state and local policy panels, watershed groups, and other forums that promote environmental protection, especially water quality.
3	Set a positive public example of environmental stewardship in the conduct of all activities.
4	Participate in efforts to increase public awareness of the importance of marine environmental stewardship.
Objective: Foster public good will toward shellfish aquaculture by demonstrating the benefits of aquaculture in the marine environment.	
Suggested Strategies:	

1	Provide educational materials to the public and adjacent landowners.
2	Provide opportunities to increase public awareness of farming operations and the benefits of shellfish aquaculture, such as farm tours or donating product to conservation groups and water quality advocacy organizations.
3	Make boaters aware of the availability of farmers along the coast to provide assistance in the event of marine emergencies.
4	Make recreational harvesters aware of ongoing shellfish monitoring efforts that growers support and advise of information available regarding the closure of areas due to contaminants or naturally occurring marine bacteria or toxins.
5	Advertise or post your name and contact number of your operation to facilitate communication directly with those who have concerns, are looking for assistance or need information.
Objective: Construct and maintain farm sites and facilities in a manner that minimizes reasonable public aesthetic concerns.	
Suggested Strategies:	
1	Remove all unnatural materials used in cultivation activities (such as mark stakes, nets and buoys) as soon as practical after they are no longer necessary.
2	Use the most environmentally compatible and aesthetically appealing materials feasible for culture apparatus.
3	Install pipe and other culture apparatus in the most aesthetically appealing manner as possible.
4	Maintain facilities in such a way as to minimize adverse impacts to views from the water.
5	Where possible, use decorative and attractive additions to building fronts in areas exposed to the public.
6	Ensure that site layout and construction complies with submitted development plans.
7	Floating buildings and structures should be constructed and maintained in a fashion that will minimize visual impact and comply with local zoning where applicable.
8	With the exception of navigational safety aids, select subdued natural colors for materials used for floatation, culture apparatus and structures.
9	Where reasonably possible select flotation of uniform shape and color.
10	Equipment not in use should be stored in an orderly manner to minimize visual impact.
11	Ensure that all equipment including structures, culture apparatus, storage areas and anchor lines are within site boundaries.
12	Remove unserviceable or damaged equipment from site.
Objective: Consider impact of farm siting or changes existing farms operation to minimize impact.	

1	Prior to any work occurring, meet with neighboring grower to discuss plans.
2	Design and install cultivation structure so as not to alter existing water/food flow, so siltation is not increased, and so the new activity does not cause navigation to be altered in such a way as to damage the existing farm(s).
3	Review existing area drainages and document to assure new site can be adjusted in the event any new sloughs begin to develop that impact existing farm operations in the area.

Noise, Lights, Odors

Noise. Shellfish farmers are steadily improving the productivity and efficiency of their operations and reducing employee injuries through increased reliance on motorized equipment. A consequence of the necessary use of more equipment is the incidental noise generated by their operation.

On the West Coast, generally from September to March, tides are low enough to permit beach farming operations only at night. Impacts from noise include operating equipment and vessels, and communicating verbally. Some shellfish nurseries (e.g. floating upwelling systems or FLUPSYS) use diesel, electric or propane power to operate paddlewheels, or airlifts to promote water circulation to young seed. These systems typically run continuously (24 hours a day, year - round) generating noise that has the potential to travel outside the farm site, since noise travels well across water, especially at night.

Lights. Shellfish farming is conducted year- round, regardless of weather or visibility, therefore artificial lights (generated by battery, fuel, or generator) are required at times to comply with navigational and safety requirements as directed by law, and to provide security and safety for workers. A strong light that is poorly directed or reflecting from the water can create an annoyance to vessel operators and upland owners several miles away. The use of some lights may create a hazard to ocean navigation depending on how they are directed, and neighbors may be affected by lights during periods when they would normally be asleep.

Odors. Normal farm operations generate some odors related to the handling of their stocks and the natural biofouling that coexists with them. In high concentrations, some farm odors can be offensive to persons outside the farm site.

Objective: Minimize adverse impacts from noise on employees, local residents and other marine resource users.	
Suggested Strategies:	
1	Conduct night time operations in a manner that is respectful of adjacent home owners. Minimize noise at night to the extent possible.
2	Ensure vessels and marine equipment is maintained in good working order to keep noise levels to a minimum.
3	Maintain facilities in a manner that minimizes outdoor noise.
4	When possible, schedule activities on site from 7:00 am to 8:00 pm.

5	When possible, employ well-maintained sound suppression devices including mufflers, barriers and baffles, while operating equipment.	
6	Minimize the impact of recreational radios while working on site, particularly at night.	
7	Reduce vessel speed along near-shore areas and observe safe operating practices to reduce noise levels and minimize shore disturbances.	
8	Caution employees to reduce verbal communication to the minimum necessary level at night in areas with nearby upland residents.	
Objective: Minimize adverse impacts from artificial lighting outside the farm site.		
Suggested Strategies:		
1	Bright lights should not be shown seaward in a manner such that they interfere with safe navigation.	
2	Conduct nighttime operations in a manner that is respectful of adjacent homeowners. Minimize external lights at night to the extent possible.	
3	Point directional lights away from the upland area to the extent feasible given safety considerations.	
4	Where possible, lights should be shielded from all but essential directions. If spotlights must be used, they should be positioned as high above the water as possible so that penetration is maximized and reflection is minimized.	
Objective: Minimize impacts of farm generated odors outside the farm or facility site.		
Suggested Strategies:		
1	Store and dry equipment in areas where odors generated don't impact adjacent land owners or users.	
2	Keep all vessels, equipment and vehicles clean and well maintained at all times.	
3	Keep shell piles isolated to minimize odor.	

Annotated Bibliography—Section III

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See Section 2 references for abstract.

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Creswell, R.L.R., McNevin, A.A. 2008. Chapter 11: Better Management Practices for Bivalve Molluscan Aquaculture. Environmental Best Management Practices for Aquaculture. Oxford, UK: Blackwell Publishing Ltd. pp. 427-486.

In the United States, cultured shellfish remains one of the most successful and stable forms of aquaculture. Bivalve mollusk aquaculture production in the United States exceeds 220,000 tonnes (FAO 2005). Oysters are the most common bivalve mollusk cultured in the United States, accounting for approximately 61% of cultured shellfish. Clams account for 31% of shellfish aquaculture production, and the remaining 8% is divided among mussel, geoduck, and scallop culture. Production of bivalves in the United States is concentrated in three main areas: the Gulf of Mexico, the mid- to north-Atlantic seaboard, and the Pacific Northwest. Washington State accounts for the greatest production, followed by Virginia, Louisiana, California, and Oregon (USDA-NASS 2006). Although many species of bivalve mollusks are under various stages of aquaculture development in the United States, only about 20 species currently are in commercial production using methods described in this chapter. Because gastropods such as abalone (*Haliotus spp*.) account for less than 4% of total mollusk aquaculture in the United States, this chapter will focus on environmental best management practices for bivalve species.

Dolmer, P., Frandsen, R.P. 2002. Evaluation of the Danish mussel fishery: suggestions for an ecosystem management approach. Helgol Mar Res 56. pp. 13–20.

See Section 1 references for abstract.

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.B. 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model. Aquaculture 264. pp. 160–174.

This paper describes a model for assessment of coastal and offshore shellfish aquaculture at the farm-scale. The Farm Aquaculture Resource Management (FARM) model is directed both at the farmer and the regulator, and has three main uses: (i) prospective analyses of culture location and species selection; (ii) ecological and economic optimization of culture practice, such as timing and sizes for seeding and harvesting, densities and spatial distributions (iii) environmental assessment of farm-related eutrophication effects (including mitigation). The modelling framework applies a combination of physical and biogeochemical models, bivalve growth models and screening models for determining shellfish production and for eutrophication assessment. FARM currently simulates the above interrelations for five bivalve species: the Pacific oyster *Crassostrea gigas*, the blue mussel *Mytilus edulis*, the Manila clam *Tapes phillipinarum*, the cockle *Cerastoderma edule* and the Chinese scallop *Chlamys farreri*. Shellfish species combinations (i.e. polyculture) may also be modelled. The model has been implemented as a web-based client–server application and is available at http://www.farmscale.org/.

Ferreira, J.G., Sequeria, A., Hawkins, A.J.S., Newton, A., Nickell, T.D., Pastres, R., Forte, J., Bodoy, A., Bricker, S.B. 2009. Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species. Aquaculture 289. pp. 32–41.

The Farm Aquaculture Resource Management (FARM) model has been applied to several shellfish species and aquaculture types. The performance of the FARM model, developed to simulate potential harvest, key financial data, and water quality impacts at the farm-scale, was tested in five systems in the European Union: Loch Creran, Scotland (Pacific oyster), Pertuis Breton, France (blue mussel), Bay of Piran, Slovenia (Mediterranean mussel), Chioggia, Italy (Mediterranean mussel) and Ria Formosa, Portugal (Manila clam). These systems range from open coasts to estuaries, and are used for shellfish aquaculture by means of different cultivation techniques (e.g. oyster bottom culture in Loch Creran and mussel longlines and poles in Pertuis Breton). The drivers for the FARM model were supplied by measured data, outputs of system-scale models or a combination of both.

Filgueira, R., Grant, J. 2009. A Box Model for Ecosystem-Level Management of Mussel Culture Carrying Capacity in a Coastal Bay. Ecosystems 12. pp. 1222–1233.

See Section 2 references for abstract.

Liu, J., Wang, Z., Lin, W. 2010. De-eutrophication of effluent wastewater from fish aquaculture by using marine green alga *Ulva pertusa*. Chinese Journal of Oceanology and Limnology. Vol. 28 No. 2, pp. 201-208.

The de-eutrophication abilities and characteristics of *Ulva pertusa*, a marine green alga were investigated in Qingdao Yihai Hatchery Center from spring to summer in 2005 by analyzing the dynamic changes in NH_4^+, NO_3^-, NO_2^- as well as the total dissolved inorganic nitrogen (DIN). The results show that the effluent wastewater produced by fish aquaculture had typical eutrophication levels with an average of 34.3 □mol L-1 DIN. This level far exceeded the level IV quality of the national seawater standard and could easily lead to phytoplankton blooms in nature if discarded with no treatment.

MacFarlane, S., Flimlin, G. 2005. Shellfish aquaculture on the East Coast: A snapshot. Journal of Shellfish Research. Vol. 24, no. 1, p. 327. Jan 2005. ISSN 0730-8000

The authors conducted a survey of all East Coast states through their extension agents to determine the extent and diversity of the East Coast shellfish aquaculture industry. The survey was conducted for the East Coast Shellfish Growers Association as a prelude to developing best management practices or an environmental management system for the shellfish aquaculture industry. Survey revealed that the shellfish industry on the East Coast is diverse in size and scope of operations, but there are common threads as well that overlap state jurisdictions.

Vaudrey, J.M.P., Getchis, T., Shaw, K., Markow, J., Britton, R., Kremer, J. N. 2009. Effects of Oyster Depuration Gear on Eelgrass (*Zostera marina L.*) in a Low Density Aquaculture Site in Long Island Sound. Journal of Shellfish Research. Vol. 28, no. 2, pp. 243-250.

See Section 2 references for abstract.

Weise, A.M., Cromey, C.J., Callier, M.D., Archambault, P., Chamberlain, J., McKindsey, C. W. 2009. Shellfish-DEPOMOD: Modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. Aquaculture 288. pp. 239–253.

See Section 2 references for abstract

SECTION IV: PEST AND PREDATOR CONTROL

Pest and Predator Control

Shellfish farming operations are conducted in an environment that is naturally rich in diverse populations of wild plants and animals, both terrestrial and aquatic. The health and safety of these animals is necessary to preserve the biodiversity of an area. Most natively occurring plants and animals have no adverse effects on farming operations, and some have beneficial effects. There are, however, some organisms in the marine environment that can have a significant negative impact on shellfish and the overall marine environment. PCSGA encourages growers as well as public and private land managers to assure pests are not harbored on their lands and appropriate agricultural laws are adhered to in regard to invasive and agricultural pest species management.

Farmers take reasonable steps to prevent the destruction of their crops and farm lands by agricultural pests, predators and disease, as stated in the Federal Environmental Pest Control Act of 1972 (an amendment to the Federal Insecticide, Fungicide, and Rodenticide Act of 1947 (FIFRA)). FIFRA was further amended in 1996 by the Food Quality Protection Act, which provided a uniform safety standard for pesticide-related risks in raw and processed foods as "a reasonable certainty of no harm from aggregate exposure to the pesticide chemical residue" (Osteen 2000). In many cases, the proper design, construction and management of farm operations will reduce the need for significant efforts for after-the-fact control. Combinations of avoidance, prevention and exclusion methods are utilized, depending on the particular species present, cultivation methods employed, and time of year. Actions of shellfish growers to control pests have been demonstrated to assist in sustaining the ecology of the areas where they farm as compared to other areas not managed for pests. Formal Integrated Pest Management (IPM) plans developed as aligned with agricultural definitions are encouraged.

Aquatic Nuisance Species, Pest and Disease Transfer Prevention

The ability to grow healthy, disease-free shellfish is of basic importance to any successful commercial shellfish operation. Certain aquatic nuisance or invasive species and pests, such as oyster drills, Japanese eelgrass, burrowing shrimp, sand dollars, Spartina, etc. are firmly established in many West Coast locations. Other species with a potential to do harm have not yet been introduced to the region and rigorous steps must be taken to prevent such an occurrence.

West Coast shellfish are widely considered to be free of serious pests and diseases. To maintain this reputation and the competitive advantage of producing quality shellfish, growers must ensure seed stock for their farms comes from facilities with health-monitoring programs that take into consideration enzootic pathogens, notifiable organisms and OIE-listed pathogens. Regulation requirements for transfer and movement of shellfish between and within states and foreign locations are in place and must be strictly complied with, and detailed interstate transport records maintained.

Failure to adequately monitor for pests and disease can have disastrous consequences. Growers already live with the consequences of earlier generations that inadvertently brought nuisance species into Pacific Coast waters. Today, shellfish growers abide by rigorous protocols for the certification and inspection of imports and transplants to avoid repeating these earlier mistakes (See Regulatory Section, USDA, Animal and Plant Health Inspection Service.)

Pest and Predator Controls

Control methods may include prevention such as planting at times when predation is least likely to occur, hand removal and relocation of pests, permitted pesticides, or simply scaring competitors away. Netting and other predator exclusion devices may be used to shield shellfish, especially during their most vulnerable, juvenile stage. In all cases, growers are encouraged to develop and adhere pest management strategies based on the formal agricultural definition. This approach is part of a strategy referred to as Integrated Pest Management (IPM), also known as Integrated Pest Control (IPC). IPM is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Lethal controls including pesticides are used only after monitoring indicates they are necessary according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest control methods and materials are selected and applied in a manner that minimizes risks to human health, beneficial and nontarget organisms, and the environment.

Many shellfish predators have developed special adaptations to be able to penetrate the shells of their victims to feed on the meat inside. Japanese oyster drills, starfish, crustaceans and moon snails are some common examples of shellfish predators. Netting and hand removal are the two most common methods utilized for control. Nonnative predators such as Japanese oyster drills should be removed to the uplands and disposed of properly. When effective exclusion methods are not available or practical at preventing harm from native pests and predators they should be collected and relocated to areas they will survive and not cause harm to crops.

In some areas, predation by shore birds is significant, especially Scoter ducks that favor Littleneck and Manila clams. Measures including substrate covers, fencing, the use of PVC tubes and netting are the preferred methods of control in most areas. Hazing is also used with some degree of success, but can be ineffective in the long term. Timing farm activities when birds are most likely to be present has proven effective in scaring them away from sites.

Ghost shrimp (*Neotrypaea californiensis*) and mud shrimp (*Upogebia pugettensis*) (collectively referred to as "burrowing" shrimp) are native species found in significant concentrations in some Oregon and Washington coastal estuaries. In significant numbers, the shrimp alter substrate dramatically, making it "soupy" and especially harmful to shellfish production, eelgrass, and other fauna and flora.

For reasons not fully understood by scientists, the populations of these species began rapidly increasing and expanding beyond their historically centered population areas in the 1940s to levels that have seriously impacted the natural habitat of bays in coastal Washington and Oregon, and that has seriously impacted farming operations. Among the theories that have been developed to explain this phenomenon is the potential that higher salinity levels throughout the year, caused by the damming of the Columbia River, have created an optimum environment for the shrimp which have limited tolerance for the low salinity that is associated with maximum spring freshwater outflows. Another possibility is reduction of natural predators such as green and white sturgeon, due to overfishing, spawning habitat loss, etc. Changing weather patterns, such as El Nino events, have also been posited as a possible factor in this environmental imbalance. Whatever the cause, the shrimp populations have reached levels that have resulted in significantly altered substrates in affected estuaries.

Since the late 1940s, various physical means for controlling the shrimp have proven largely ineffective, including efforts to harden the substrate through rolling, shell placement, harrowing, etc. Growers are continuing to search for effective control methods through an IPM process initiated in the early 1990s. An IPM Plan for Burrowing Shrimp was developed by the Willapa-Grays Harbor Oyster Growers Association in 2003 which was updated in 2007. The plan subscribes to the legal definition(s) of IPM as presented to Washington State agencies with pest control responsibilities: "a coordinated decision-making and action process that uses the most appropriate pest control methods and strategy in an environmentally and economically sound manner to meet agency programmatic pest management objectives..." (RCW 17.15.010, 1997).

The Plan also views IPM development in terms of 3 levels that are functions of the ecological, socio-economic, and agricultural communities that increase in scale and complexity from level 1 to level 3 (Kogan,1998). The burrowing shrimp control program meets the first level of IPM integration, but will hopefully become more complex if other alternative control tactics can be found. Burrowing shrimp populations fluctuate over time. They have historically been most problematic in Washington coastal estuaries but also at times in Puget Sound. Significant general habitat and crop losses occur when populations exceed 10 burrows per square meter. The Willapa-Grays Harbor Oyster Growers Association is working to secure the necessary permitting for the use of imidacloprid, a pesticide with proven efficacy, for use by a group of its members. This tool has been in research since 1996. The EPA registration under the Federal Insecticide, Fungicide, and Rodenticide Act was secured in 2013. An Environmental Impact Statement (EIS) was completed for the use in 2015 and a Supplemental EIS is being completed.

Spartina alterniflora is an invasive plant species from the East Coast that arrived on Washington's coastal beaches over 100 years ago. In Washington State it is formally listed as a Class-A noxious weed and eradication is required by law. It has proven to be a hardy competitor for space, converting approximately 20,000 acres of tidelands to Spartina meadows that once had supported a diverse spectrum of flora and fauna, including shellfish and shorebirds. Efforts to mow or pick the plant proved inadequate for keeping up with the pace of its expansion. The application of the herbicide Rodeo had also failed to stop the plant's progress onto tideflats. Through research efforts focused at the Washington State University, the herbicide imazapyr was identified as an effective eradication tool and a risk assessment that considers its impacts on non-target species concluded minimal risk from application at the prescribed application rates (Fisher et al. 2003). The *Spartina* eradication program has resulted in reducing the *Spartina* infestation in Washington State to single plants and isolated clonal populations. The critical path to eradication will require growers to diligently report any sighting of plants so they can be located and removed. Due in great deal to the dedicated involvement of shellfish growers, this eradication program will be recorded as one of the most successful eradication efforts of an invasive species in US history. At the time of this writing, concerns are increasing by public state agencies in regard to increasing Spartina populations in Northern Puget Sound.

Japanese eelgrass, (*Zostera japonica*) is an invasive weed that was first documented on the West Coast in approximately 1957. For many years this invasive was limited to high intertidal areas, and was very limited in its annual density. Within the last approximately 20 years it has expanded its range and density in the Willapa Bay estuary so that it now "carpets" many areas that once consisted of bare sand/mud substrate. It has also become more widespread and dense in the Puget Sound region, as well as in Grays Harbor. PCSGA encourages growers to report new sightings as well as expansion or regression of existing beds of *Z. japonica* to state and local agencies responsible for managing invasive species on public and private lands. This high level of infestation has caused large impacts from the increased sedimentation it facilitates, and impacts to water and sediment chemistry through annual decomposition of stem wrack. The impacts to shellfish farms, especially Manila clam beds, has been high due to interference with seed recruitment and growth, refuges it provides for invasive shellfish predators and, siltation, and water retention on the beds. *Zostera japonica* has been added to the Washington State noxious weed list as a class-C noxious weed. Washington Department of Fish and Wildlife (WDFW 2011) and Washington Department of Natural Resources (Mach et al. 2010) both acknowledge that it is an invasive species. As an invasive species, it would follow that it should not be protected as beneficial habitat for fish, invertebrates, and wildlife.

California has listed *Zostera japonica* as a noxious weed per Title-3 California Code, section 4500 due to its destructive nature. California states that *Zostera japonica* is a marine, annual forb from Asia and occurs in shallow estuarine and marine habitats off the west coast of Oregon, Washington, Alaska and British Columbia. It was likely introduced with oyster shipments from Japan. The rhizomes creep or ascend, and produce roots and shoots at the nodes to facilitate local spread, but colonization of new sites is primarily by seed. *Z. japonica* may replace the native eelgrass, *Z. marina*. The introduction of *Z. japonica* in Washington has changed the physical habitat where it has colonized by slowing water flow and increasing sedimentation, which has also affected species richness and abundance of resident fauna. Larned (2003) demonstrated that *Z. japonica* invasions alter water column-benthos nutrient fluxes. The author found that *Z. japonica* is removing dissolved inorganic nitrogen and dissolved reactive phosphorus from the Yaquina Bay water column. Continued expansion of *Z. japonica* in the estuary could lead to substantial reductions in nutrient availability. It is estimated that in Willapa Bay alone the economic impact to the Manila clam farming community is approximately $4,000/acre/year, or $4 million for every 1,000 acres infested (Fisher et al. 2011).

Sand dollars (*Dendraster excentricus*) are a native species that can present difficulties in aquaculture operations. Relocation of some of the sand dollar bed may be necessary in some instances, such as when sand dollars are covering a bed of geoduck clams, so that the companies can plant or harvest their crops. When planting in a sand dollar bed, the most benign approach is to not move them. During grow-out, growers have found that geoduck clams and sand dollars can co-exist and that sand dollars in some cases provide the geoduck protection from predation. However, if the sand dollars are so thick as to inhibit planting or full harvest, then relocating the sand dollars onto existing areas of the sand dollar bed from which they originated and which will not interfere with the growing of shellfish would be the next best option. If leaving them in place or moving them to a part of the existing sand dollar bed is not economically practical, the next method would be to relocate them to other suitable habitat in which they normally grow and where they can survive. Such new habitat should be as similar as is practically possible to the habitat from which they originated.

Relocation has been shown to maintain the integrity of a shellfish bed while not harming native species. Sand dollars, once relocated, were able to migrate back to their preferred habitat after harvest activities were completed. This migration strategy is typically associated with food availability and has been noted by studies that track sand dollar movement in the intertidal environment (Merill and Hobson 1970, O'Neill 1978, Smith and Brumsickle 1989).

Biofouling Control

During the normal course of farming operations, naturally occurring biofouling, including mussels, barnacles, marine plants and other marine invertebrate animals, can collect on shellfish and equipment. The types and frequency of biofouling varies considerably depending on factors such as location of the site, type of crop and equipment, depth, seasonality, flow and water temperature.

Most "fouling" species produce planktonic or free swimming larvae that are carried around by tides, currents and waves. Eventually, they settle on a suitable surface and grow through the next stages of development.

Almost any object placed into the water will soon be colonized by these species. For the shellfish grower, this can pose a major problem if the abundance of these organisms becomes so great that they outcompete the crop for available food, smother it, attract predators or otherwise interfere with the culture effort. Among the fouling organisms that can have a detrimental effect are mussels, barnacles, tunicates, tube worms (polychaete annelids), bryozoans (either branching or flat and encrusting), hydroids (a small branching organism related to jellyfish and sea anemones) and encrusting sponges.

While biofouling may have no significant direct adverse impact on the crops being cultured, it can create significant indirect negative impacts including competing with crops for food, restricting flow to the crop, increasing cleaning required at harvest, providing a food source for predators that could later threaten crops, and significantly increasing the weight of floating crops and equipment necessitating higher maintenance, fuel, and capital costs. There is strong economic incentive for farmers to develop management practices that reduce the impact and requirement to discard non-target species on their crops and equipment.

Maintenance of crops and equipment may include removal or washing of fouling organisms on-site. At harvest, growers often complete a preliminary wash of the shellfish on-site to ensure product is delivered to the processing plant as clean as possible. Under normal circumstances, and when maintenance is carried out at regular intervals, most sites should be capable of absorbing the impact of the biofouling generated from, and released to, the farm site (Brooks, 2000).

Marine Mammals

The only known cases of predation of farmed shellfish by marine mammals on the West Coast have involved sea otters and more recently sea lions have been documented preying on farmed geoduck in Southern Puget Sound. The protected status of the animals under the Marine Mammal Protection Act limits the ability of farmers to deal with marine mammal predators.

Sea otters have raided lantern nets of oysters repeatedly in some locations in Prince William Sound. Some of the growers responded by switching from lantern nets to wire mesh trays, while others wrapped nets in seine web. Both methods have been successful in keeping otters out of the nets. Most growers report having no problems with otters and say the animals actually are helpful by grazing on mussels setting on lantern nets and other gear – a mutual environmental benefit of aquatic farming.

Interactions with marine mammals can have serious consequences for shellfish farmers. Harassment of marine mammals is not allowed by the MMPA, effectively prohibiting a farmer so inclined from even scaring away visiting sea otters. Even the perception that marine mammals are adversely affected by aquatic farming operations may lead to restrictions on the siting of new operations or relocation of some existing farming activities.

Shellfish farmers operating in areas with high sea otter populations are encouraged to experiment with methods of exclusion to prevent the animals from accessing the crops under cultivation. Growers must endeavor to avoid any harmful interactions with marine mammals.

Integrated Pest Management

In all cases of pest and predator control, growers should attempt to formulate pest and/or nuisance species management plans that integrate knowledge of the life history and ecology of species involved, their natural predators and competitors, and that adhere to more formal agricultural pest management methodologies. Integrated Pest Management (IPM) is the coordinated decision-making and action process that utilizes the most appropriate pest and predator control methods and strategies in an environmentally and economically sound manner and in coordination with appropriate regulatory agencies. Growers are encouraged to develop knowledge on the economic impact thresholds that necessitate pest management activities for each species and culture method used in their farm operations.

Growers are also encouraged to review the Pest Management Strategic Plan (PMSP) for bivalves completed in 2010. This document was developed through a joint regulatory, academia, and industry process to develop strategies for pest management. The intent was to better inform stakeholders on pest management strategies so as to promote education to a broader array of regulatory managers, growers, the science community, political groups, and citizens.

Elements of IPM include prevention of pest and predator problems at the onset; monitoring for the presence of and damage caused by pests and predators; establishing densities of pest and predator populations that can be tolerated and the correlated damage level sufficient to warrant treatment based on health, safety, economic or aesthetic thresholds; and evaluating the effects and efficacy of pest and predator control options. A focus on the conservation of agricultural lands is also an aspect of an IPM plan as aligned with goals of WSDA, conservation groups, etc. Shellfish lands are extremely valuable habits for an array of species. The IPM plan subscribes to the legal definition(s) of IPM as presented to Washington State agencies with pest control responsibilities: "a coordinated decision-making and action process that uses the most appropriate pest control methods and strategy in an environmentally and economically sound manner to meet agency programmatic pest management objectives..." (RCW 17.15.010, 1997). The Plan also views IPM development in terms of 3 levels that are functions of the ecological, socio-economic, and agricultural communities that increase in scale and complexity from level 1 to level 3 (Kogan, 1998).

Avoidance

Avoiding fouling and predation is sometimes possible by properly timing farming activities. This involves monitoring the site for pests and predators and timing events in the production cycle to avoid the worst predation. Juvenile shellfish seed put out in the spring or early summer for nursery rearing may be particularly vulnerable to such fouling organisms. A "fouling line," with oyster shell attached at spaced intervals, hung in the water from the surface down to the lower limits of fouling can be used to detect when setting occurs, quantities and types of fouling and predatory organisms, with planting or setting of seed timed accordingly.

Prevention

There are steps which can be taken in the rearing process that will aid in preventing problems at the onset, for example, starting with good quality seed and promoting high growth rates from nursery to grow-out helps prevent colonization of fouling and predatory organisms. Intertidal nursery rearing of oysters and clams is another means for controlling predation and fouling problems. Daily exposure to air results in starfish and crabs retreating with the tide and organisms such as hydroids and tunicates do not tolerate drying. While some mobile pests, such as crabs and starfish, may retreat at low tide, often times they remain on the bed and continue preying on shellfish on the next high tide. During a longer grow out period these pests can colonize a bed and actually reproduce to greatly increase that population. It's critical that effective measures be taken to remove these pests to avoid substantial crop loss.

Control Measures

Several control measures can be taken simply through normal maintenance. For example, in nursery systems regular maintenance of screens, containers and seed helps to eliminate or minimize fouling and predation. In deep water systems such as tray oyster culture where stock is regularly pulled up and graded, the removal from the water, handling and restocking help prevent buildup of soft fouling organisms and allows the grower to hand-remove larger organisms such as mussels and starfish. In systems where tubes or shell cultch are hung from rafts or longlines, fouling control takes place when stringing the shellfish stock.

Another means of fouling control consists of dipping stock in fresh water, heavily salted water, hot water or a solution of lime that kills the fouling organisms without having a negative effect on the shellfish stock or the environment.

Areas of Concern

Given the potential for negative impacts, farmers must make a great effort to conduct pest and predator control measures that have the lightest touch on the environment, taking into account seasonal fluctuations, weather, and other conditions that may aid or hamper their efforts in controlling pests and predators. A significant problem for growers is that shellfish beds provide great habitat for the colonization of various algae once those beds are cultivated. It's normal for a bed once void of any significant plant life to become completely colonized after shellfish are cultivated on the bed. This dense plant life provides excellent cover for pests and predators. In addition, the high density of plant life acts to reduce water drainage from the bed at low tide, so that predators can colonize the bed and continue to feed through low tide. To the extent practical, growers should control nuisance macroalgae, such as *Ulva*, to provide natural water drainage characteristics reflective of baseline conditions. It is therefore recommended that growers document existing conditions prior to cultivation with photos or other documents in the event any ESA or other issues arise.

Biofouling organisms are largely natural to the marine environment, so there is no intrinsic environmental impact associated with their presence. The main concern here is the massing of organisms that may occur as a result of attachment to the three-dimensional structure created by shellfish, such as alteration of the benthos or improper disposal upland. When the organisms are removed from shellfish stocks, in the course of tending or harvesting, care must be taken to avoid or minimize disruption of the ecosystem.

An assessment of flora and fauna present prior to shellfish cultivation can provide a base from which to determine how methods being employed are affecting the natural environment. This is an area where more research and continued innovations in cultivation technology are needed. As stated above, this assessment should be recorded and maintained in bed records.

Objective: Minimize the potential for disease and invasive species transfers.

Suggested Strategies:	
1	Conduct periodic pathology screens and when significant mortality events occur have a qualified pathologist examine the shellfish to ensure it has not been caused by enzootic pathogens, notifiable organisms and OIE-listed pathogens.
2	Store oyster shell used for cultch on an upland site for an appropriate period of time as required by transfer permit prior to returning to marine waters to control pest transfers.
3	Ensure, through compliance with regulations and company policies, that pests and diseases are not transferred from one estuary or area to another.
4	Keep shellfish culture and harvest gear from invasive species infested areas separated, and take other precautions to avoid transfer of pests, disease and aquatic nuisance species.
5	Continue to support research into improved methods for control of introductions.
6	Store all products, including waste products such as empty shell, appropriately before transferring to appropriate waste facility or other ecosystem.
7	Do not transfer pests from beds known to contain these pests, to beds in areas without significant pest populations, such as when transplanting seed from areas with known Japanese drill populations.
Objective: Minimize adverse impacts from intentional introductions and transfers.	
Suggested Strategies:	
1	Obtain proper permits for transferring shellstock from one body of water to another.
2	Ensure seed stock is sourced from facilities with health-monitoring programs that take into consideration enzootic pathogens, notifiable organisms and OIE-listed pathogens
3	Conduct periodic pathology screens.
4	Out-plant only stock and species approved for the growing area and keep records that identify the source of shellstock planted.
5	Support the development of practical and scientifically responsible regulations regarding transporting shellstock.
6	Avoid genetic interactions of selectively bred and cultured native species with naturally occurring wild stocks.
7	Consider using triploid shellfish or other technology when also cultivating indigenous native stocks to assure cultured stocks are sterile and will not interact with native stock.
8	Stay abreast of and utilize the best available science for maintaining the genetic integrity of the natural populations of shellfish in farmed areas.
Objective: Minimize impacts from predator exclusion and pest control apparatus and methods.	
Suggested Strategies:	

1	Secure predator exclusion devices (such as predator netting on clam beaches and vertical fencing) to ensure they do not present a risk to boaters or other users of marine and intertidal areas.
2	Install predator nets and other control apparatus in a manner that is as unobtrusive and neat as possible.
Objective: Minimize the amount and impacts from organic material that must be discarded.	
Suggested Strategies:	
1	Where biofouling must be washed or removed on the farm site, attempt to reduce its impact by spreading the debris over a larger area within the site.
2	If biofouling is disposed of on upland areas, place where harbor for pests will not be provided and odor will be minimized.
3	Monitor the benthic environment of the site to observe for potential impact of biofouling control measures and adjust practices as required to ensure sustainability.
4	Document bed conditions prior to cultivating through photographs, assessments, etc. and maintain this documentation for proof of baseline conditions.
Objective: Develop and use an Integrated Pest Management Program.	
Suggested Strategies:	
1	Employ mitigation sequencing — use lowest impact control methods first, graduating to higher impact methods only as needed — when employing pest and predator controls.
2	Time activities to avoid predation to the extent possible.
3	Promote non-lethal predator control methods such as exclusion and other physical deterrents.
4	Schedule farming activities to coincide with times when birds are most likely to be present.
5	Implement "scaring" or hazing techniques on sites prone to bird predation prior to production of any shellfish and immediately upon arrival of early migrating birds.
6	Adopt operating and maintenance practices, such as regular cleaning, air drying or other practices which reduce the potential for non-target fouling species to become a significant factor.
7	Facilitate probiotic control measures (for example, polyculture of sea urchins) to reduce fouling impact.
8	Follow guidelines established in existing formal IPM plans and PMSP documents

Annotated Bibliography—Section IV

Berry, A. W. 1996. Aquaculture and sea loch nutrient ratios: a hypothesis. Aquaculture and sea lochs. pp. 7-15.

See Section 2 references for abstract.

Buhle, E.R., Margolis, M., Ruesink, J.L. 2005. Bang for buck: cost-effective control of invasive species with different life histories. Ecological Economics 52. pp.355-366.

Matrix population model representing *Ocinebrina inornata* (Japanese oyster drill), which demonstrates that manual control of this invasive species is most cost-effective when it targets several life-history stages simultaneously – both adults and egg capsules (but during the summer when the latter are found easily). An additional manuscript in preparation compares *O. inornata* with *Urosalpinx cinerea*, the eastern oyster drill, which has higher adult survival, lower reproduction, and overall similar population growth rate.

Buhle, E.R. and Ruesink, J.L. 2009. Impacts of invasive oyster drills on Olympia oyster (*Ostrea conchaphila Carpenter*) recovery in Willapa Bay, Washington, USA. Journal of Shellfish Research. 28(1): 87-96.

Potential role of two introduced predatory gastropods, the Japanese drill (*Ocinebrina inornata*) and the eastern drill (*Urosalpinx cinerea*), in limiting Olympia oyster recovery. Bay-wide sampling revealed differences in spatial distribution of the two drill species, with *U. cinerea* more abundant toward the head of the estuary and *O. inornata* more abundant toward the mouth. Includes estimates of feeding rates on both cultured and native oysters, showing preferences for smaller oysters and per capita consumption rates of ~2 oysters/week.

Carswell, B., Cheesman, S., Anderson, J. 2006. The use of spatial analysis for environmental assessment of shellfish aquaculture in Baynes Sound, Vancouver Island, British Columbia, Canada. Aquaculture 253. pp. 408–414.

The Baynes Sound area accounts for a large proportion of shellfish aquaculture production in British Columbia. In response to non-industry concerns regarding impacts from this inter-tidal farming on bird populations in Baynes Sound, a quantitative inventory of aquaculture infrastructure, more specifically clam netting, was done. These techniques offer a cost-effective method of assessing inter-tidal resource utilization and provide a basis for time-series evaluation and a useful tool for adaptive resource management in Baynes Sound. More generally, these techniques can be used in any region where a shoreline classification system is complete to quantify the extent of intertidal habitat modification and be used as a decision support tool.

Carver, C.E., Chisholm, A., Mallet, A.L. 2003. Strategies to mitigate the impact of *Ciona intestinalis (L.)* biofouling on shellfish production. Journal of Shellfish Research. Vol. 22, no. 3, pp. 621-631.

A sudden increase in the population of the solitary ascidian *Ciona intestinalis (L.)* is causing serious biofouling problems for shellfish growers on the Atlantic coast of Nova Scotia, Canada. The objective of the present study was to document the growth, spawning, and recruitment patterns of this species, and to develop strategies to minimize its impact on the culture of European oysters at two locations in Lunenburg Bay, Nova Scotia.

Cook, N.A., Bendell-Young, L.I. 2006. Using Prey Preference and Feeding Rates to Examine the Role of a Potential Shellfish Aquaculture Predator in Structuring Bivalve Communities. EOS, Transactions, American Geophysical Union. Vol. 87, no. 36, suppl., [np]. suppl.

Euspira lewisii (Lewis's moonsnail) is a predator of bivalves found in intertidal and subtidal soft sediment habitats along the west coast of North America, from southeastern Alaska to southern California. The objectives of this study were to gain basic understanding of the ecology of *E. lewisii* and to apply this ecology to best manage this species in relation to the shellfish aquaculture industry. The feeding ecology of moonsnails was studied using cages dug into the sediment in Baynes Sound, British Columbia. This study highlights the importance of having baseline ecological knowledge and applying that knowledge to manage ecosystems.

Cook, N.A.. 2008. Feeding ecology and bioturbation: Determining the ecological role of *Euspira lewisii*. Masters Abstracts International. Vol. 47, no. 04, p. 104.

The burrowing, predatory snail *Euspira lewisii* is being removed from intertidal habitats due to its reputation as an economically damaging species to shellfish aquaculture. Here, the objectives were to examine feeding ecology and determine the functional role of a poorly understood species. Feeding experiments and shell assemblages showed distinct prey preferences, avoidance of the commercially valuable Manila clam, a low, species-dependent feeding rate and a limited yearly consumption of the clam population.

Davis, R.P. 2000. James River market sized oysters have their late summer survival rates doubled by marl treatment of their water. Journal of Shellfish Research. Vol. 19, no. 1, pp. 569-570.

James River oysters, market sized at about 250 per bushel, are not normally expected to survive another summer. The cause of death is usually attributed to either MSX or Dermo. This experiment appears to reproduce conditions under which oysters thrived abnormally well. A lot of those older oysters were given water that was run through a mesh bag of fossil shell hash. Twice the proportion of oysters survived in the treated water as did in the untreated water. Approximately, 20.8% of the no-marl oysters survived and 41.7% of the marled oysters survived. Given the sample size and the binomial nature of the survival statistic there is a 1:16 chance that the marl treatment made no difference.

DeFrancesco, J., K. Murray, and D. Clarke. 2010. Pest management strategic plan for bivalves in Oregon and Washington. Western Integrated Pest Management Center, U.S. Department of Agriculture, National Institute of Food and Agriculture. Workshop held on March 11, 2010. Long Beach, Washington.

In a proactive effort to identify pest management priorities and lay a foundation for future strategies, bivalve farmers, commodity group representatives, pest control advisors, regulators, university specialists, and other technical experts from Oregon and Washington formed a work group and assembled this document. Members of the group met on March 11, 2010, in Long Beach, Washington, where they drafted a document containing pest management activities, critical needs, activity timetables, and efficacy ratings of various management tools for specific pests in bivalve production. The work group, including additional members who were not present at the meeting, reviewed the resulting document. The final result, this document, is a comprehensive strategic plan that addresses many pest-specific critical needs for the bivalve aquaculture industry of Washington and Oregon.

Dumbauld, B.R., Booth, S., Cheney, D., Suhrbier, A., and Beltran, H. 2006. An integrated pest management program for burrowing shrimp control in oyster aquaculture. Aquaculture 26. pp. 976-992.

See Section 2 references for abstract.

Dumbauld, B.R., Wyllie-Echeverria, S. 2003. The influence of burrowing thalassinid shrimps on the distribution of intertidal seagrasses in Willapa Bay, Washington, USA. Aquatic Botany 77. pp 27-42.

See Section 2 references for abstract.

Dumbauld, B.R., Ruesink, J.L., Rumrill, S.S. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. Aquaculture 290. pp. 196–223.

See Section 2 references for abstract.

Elston, R.A., Hasegawa, H., Humphrey, K.L., Polyak, I.K., Haese, C.C. 2008. Re-emergence of *Vibrio tubiashii* in bivalve shellfish aquaculture: severity, environmental drivers, geographic extent and management. Diseases of Aquatic Organisms. Vol. 82, no. 2, pp. 119-134.

During 2006 and 2007, we documented the re-emergence of severe episodes of vibriosis caused by *Vibrio tubiashii* in shellfish hatcheries on the west coast of North America. Lost larval and juvenile production included 3 previously undescribed hosts, Pacific (*Crassostrea gigas*) and Kumamoto (*C. sikamea*) oysters and geoduck clams *Panopea abrupta*, with a 2007 decline in larval oyster production of similar to 59% in one hatchery. Losses of larval and juvenile bivalves were linked to *V. tubiashii* blooms in the coastal environment, which were associated with the apparent mixing of unusually warm surface seawater and intermittently upwelled cooler, nutrient- and *Vibrio spp*.-enriched seawater.

Epelbaum, A., Pearce, C.M., Barker, D.J., Paulson, A., Therriault, T.W. 2009. Susceptibility of non-indigenous ascidian species in British Columbia (Canada) to invertebrate predation. Mar Biol 156. pp. 1311–1320.

We identified potential predators of four non-indigenous ascidians (*Styela clava, Botryllus schlosseri, Botrylloides violaceus*, and *Didemnum vexillum*) in British Columbia (BC), Canada in order to: (1) assess the potential for biotic interference to limit the establishment and/or spread of these ascidian species in BC, and (2) identify candidate species to be used as ascidian biofouling control agents in shellfish aquaculture.

Gómez R., Geovanny D., Balcázar, J.L., Ma, S. 2007. Probiotics as Control Agents in Aquaculture. Journal of Ocean. University of China (Oceanic and Coastal Sea Research). Vol.6, No.1, pp.76-79.

Infectious diseases constitute a limiting factor in the development of the aquaculture production, and control has solely concentrated on the use of antibiotics. Probiotics, live microorganisms administered in adequate amounts that confer a healthy effect on the host, are emerging as significant microbial food supplements in the field of prophylaxis.

Leavitt, D. 2008. Report on Biological Impacts of Aquaculture. Wakefield, RI: Coastal Resources Management Council. 64 pp.

It is in the best interest of all users of the aquatic environment to expand the oversight of practices that can result in the introduction of exotics into Rhode Island waters. The following recommendations will provide a better base of operations to reduce the risk of introductions of new aquatic nuisance species: A standard protocol of evaluating and permitting the movement of shellfish and all other aquatic species into and within the state when being moved for fishery management purposes, such that both aquaculturists and fisheries managers are held to the same standard, Increase the oversight and authority of the Biosecurity Board to include all restoration and importation activities. Initiate an educational campaign to raise public awareness of ANS issues in Rhode Island, and Curtail intentional introductions by utilizing a strategy similar to that recommended by the International Council for the Exploration of the Seas. Marine biofouling is a natural process that imposes technical operational problems and economic losses on marine-related activities. Marine biofouling communities are complex, diverse, highly dynamic ecosystems consisting of a range of organisms. The need to control biofouling on underwater surfaces has given rise to many different technologies. Conventional antifouling strategy employs the use of biocidal surface coatings. Insights into the larval sensory recognition of physical cues and adhesion resulted in the development of foul release coatings based on low surface energy phenomenon. Another alternative approach for control of biofouling and inhibition of larval settlement lies in inhibiting the neurophysiological processes involved in larval settlement. Several pharmacological compounds, natural products and synthetic analogues that inhibit the metabolic processes underlying settlement have been identified through laboratory bioassays.

Munroe, D., McKinley, R.S. 2007. Commercial Manila clam (*Tapes philippinarum*) culture in British Columbia, Canada: The effects of predator netting on intertidal sediment characteristics. Estuarine, Coastal and Shelf Science 72. pp 319-328.

See Section 2 references for abstract.

Richardson, N.F., Ruesink, J.L., Hacker, S.D., Tallis, H.M., Dumbauld, B.R., Wisehart, L.M. 2007. Bacterial abundance and aerobic microbial activity across natural and oyster aquaculture habitats during summer conditions in a northeastern Pacific estuary. Hydrobiologia, in press.

See Section 2 references for abstract.

Southworth, M., Mann, R. 2003. Decadal scale changes in seasonal patterns of oyster recruitment in the Virginia sub estuaries of the Chesapeake Bay. Journal of Shellfish Research. Vol. 22, no. 1, p. 355.

Reproductive periodicity of sessile estuarine invertebrates reflects local seasonality of both environmental (temperature, salinity) and biological (food) parameters. Analysis of long term trends in oyster settlement periodicity since 1960 in three major sub estuaries (James, Piankatank and Great Wicomico Rivers) of the Chesapeake Bay show marked changes in this periodicity within the 40 year time frame with the 50th percentile of cumulative recruitment occurring between day 194 and 250 of the year depending on year and location. Significant coherence in interannual variation is observed across a wide range of sites. These are discussed in relation to pre- and post-disease (both MSX and Perkinsus) events, periods characterized by high and low river flow, varying harvest pressure, and trends arguably associated with global warming.

Sriyutha-Murthy, P., Venugopalan, V.P., Nair, K.V.K., Subramoniam, T. 2009. Larval Settlement and Surfaces: Implications in Development of Antifouling Strategies. Springer Series on Biofilms. Volume 4: Marine and Industrial Biofouling. Springer Berlin Heidelberg.

Marine biofouling is a natural process that imposes technical operational problems and economic losses on marine-related activities. Marine biofouling communities are complex, diverse, highly dynamic ecosystems consisting of a range of organisms. The need to control biofouling on underwater surfaces has given rise to many different technologies. Conventional antifouling strategy employs the use of biocidal surface coatings. Insights into the larval sensory recognition of physical cues and adhesion resulted in the development of foul release coatings based on low surface energy phenomenon. Another alternative approach for control of biofouling and inhibition of larval settlement lies in inhibiting the neurophysiological processes involved in larval settlement. Several pharmacological compounds, natural products and synthetic analogues that inhibit the metabolic processes underlying settlement have been identified through laboratory bioassays.

Therriault, T.W., Herborg, L.M., Clarke, C.L. 2007. Predicted changes in the distribution of the non-indigenous tunicate *Styela clava* along the west coast of North America with emphasis on Canadian waters. The Changing North Pacific: Previous Patterns, Future Projections and Ecosystem Impacts. p. 152.

Various ecological models ranging from simple to complex have been applied to predict the potential distribution of an invader with varying levels of success. Tunicates have received much attention, largely due to their negative impacts on shellfish aquaculture operations In addition to informing risk assessments, these predictions can be used to focus monitoring activities, including vectors that could transport *S. clava* to favorable environments.

Whiteley, J. 2006. Macroinvertebrate community responses to clam aquaculture practices in British Columbia, Canada. Masters Abstracts International. Vol. 44, no. 1, p. 218.

See Section 2 references for abstract.

Whiteley, J.A., Bendell-Young, L.I. 2006. Intertidal Community Structure and Clam Aquaculture Practices in British Columbia, Canada. EOS, Transactions, American Geophysical Union. Vol. 87, no. 36, suppl., [np]. suppl.

Potential effects of aquaculture practices are poorly understood. Clam farmers employ two primary practices to increase production of the commercial species (*Venerupis philippinarum*) on tenures: (1) juvenile seed clams are added to intertidal sediments and (2) nets are laid on the sediment surface. We conducted large-scale field surveys with the goal of assessing possible consistent differences between clam tenures and matched reference sites, while controlling for physical and environmental factors. Intertidal macrofaunal communities are compared in terms of species richness, evenness, and composition using multivariate techniques of ordination and hypothesis-testing. The commercial species *Venerupis philippinarum* is the only bivalve to show consistently higher abundance on farm sites. Clam farms otherwise show few differences to reference sites, on average.

Whitlatch, R.B., Osman, R.W., Shumway, S.E. 2005. Invasive ascidian biofouling in aquaculture: An increasing problem and can it be controlled? Journal of Shellfish Research. Vol. 24, no. 2, pp. 682-683.

Data and observations strongly suggest that the increasing number and high abundances of introduced fouling species, especially ascidians, represent an increasing threat to cultured populations of shellfish. There currently exists a variety of options for removing, killing, or controlling the invaders, but any method must be targeted at the invaders while avoiding deleterious effects to the shellfish. An alternate and preferred treatment approach is to eliminate the problem before it starts and involves some form of biological control (e.g., predators and parasites) agent. To be effective these species should remain with the shellfish population and continually remove the invaders. Recent studies suggest that several species of small (4-15 mm) gastropods might be effective candidates for controlling the abundance newly settled invasive ascidians.

WDOE "Final Environmental Impact Statement Control of Burrowing shrimp using Imidacloprid on Commercial oyster and Clam Beds in Willapa Bay and Grays Harbor, Washington".

WDOE "Final Environmental Impact Statement: Management of *Zostera Japonica* on Commercial Clam Beds in Willapa Bay, Washington".

SECTION V: HATCHERY AND NURSERY OPERATIONS

Seed and Broodstock Collection

Shellfish farmers require a consistent supply of quality seed on a continuous basis. Traditionally, West Coast shellfish growers relied on catching wild seed through a variety of methods. Commonly, "cultch" consisting of used, washed and bundled oysters shells, have been set out in areas where oyster seed, in their free-swimming larval mode, would be likely to occur. The free-swimming larval oysters, naturally attracted to the "mother" shell, grab on and permanently attach themselves. The farmers take this seeded cultch and transport it to grow-out sites.

More recently, since the 1980's, shellfish hatcheries have drastically reduced dependence on wild seed capture, although some farms have historically relied on this source for seed to lesser or greater degrees. Hatchery technology is the primary reason the West Coast shellfish industry has grown two-fold since the mid 1980's.

Objective: Minimize adverse environmental impacts from seed and broodstock collection or sourcing methods.	
Suggested Strategies:	
1	Comply with all applicable wildlife transfer regulations.
2	Ensure broodstock sources are disease-free by inspecting all animals upon arrival and conducting periodic pathology screens.

Primary Shellfish Hatchery and Nursery Operations

Reared species include Manila and Geoduck clams; Pacific, Kumamoto, European, Olympia and Eastern oysters; and two species of mussel: *Mytilus trossulus*, known as the Blue Mussel, and *Mytilus galloprovincialis*, known commonly as the Mediterranean or Gallo mussel.

Research and development activities to determine the feasibility of culturing other molluscan species, including scallops and various abalone species, are currently underway. According to Shumway and Parsons (2006), using offshore platforms for rock scallop culture is being investigated in California and experimental breeding has occurred in Oregon and Washington. In Alaska, seed is now produced routinely in a hatchery, and rock scallop production is being pursued by at least three companies.

Hatchery and nursery operations can be divided into distinct sectors: algal production, larval rearing, nursery seed culture, and broodstock maintenance. Nursery rearing is carried out in special systems to achieve the highest survival rates possible. During the juvenile stage, most shellfish are particularly vulnerable to water quality, disease, parasites and predators.

Algal production involves culturing a variety of single cell algae species for use as feed for larvae, seed, and broodstock. Algal tanks are filled with seawater, which is treated by filtering and then either heating or cooling, followed by sterilization either through heat pasteurization or by the addition of chlorine to kill microflora, which is followed by neutralization with sodium thiosulphate. A variety of species of microalgae are then added to the seawater and grown in isolated cultures of graduated sizes (Figure 5.1). These are then used as inoculants to start larger cultures for use as feed. Algal cultures are grown under natural and artificial light.

Larval culture involves the rearing of bivalve larvae in the phase of life from the time the gametes are spawned by adult shellfish, until the larvae set, or "settle out," when they lose their ability to swim. The larvae are raised in tanks filled with filtered, heated seawater that is changed every few days or continuously refreshed.

Nursery seed production is the rearing of larvae from the time they near the settle-out or setting phase, to the time they are ready for planting. Mature larvae are placed in tanks where they are allowed to settle out onto screens or cultch. Seawater and microalgae are pumped to the newly set larvae ("seed") to feed them. When the seed reaches a suitable size, depending upon species, the time of year and the end use, it is taken to a secondary nursery for further controlled growth, or delivered to farms for planting.

Clam larvae do not require cultch, but can be set on screens in a downwell system and later in an up-well or flow-through system. Mussel larvae may also be set on screens in a downwell, but are generally set on ropes prearranged in a large setting tank. Single set oyster seed are produced by inducing the larvae to set on tiny cultch fragments. This is usually made from grinding shells and then screening them to obtain uniform fragment sizes. The optimum size is large enough for one larva to settle on it, but small enough so two or more cannot. Once they have been set this way, oyster and clam single seed is commonly boosted in size by using a secondary nursery system such as a Floating Upwell System (FLUPSYS).

Some alternative nursery structures are currently being tested by geoduck farmers in Washington State. These include, floating nursery pools, weighted nursery pools, or some other way to use small individual trays (i.e., ones that can be picked up by 1-2 people). Floating nursery pools consist of rafts that are anchored to a log boom and in-water pilings, which allow the rafts to float up and down with the tide. Each raft supports perforated plastic trays stacked on top of each other and filled with washed sand. The weighted nursery pools are similar to the floating pools in that they are anchored to a raft above subtidal habitat. The weighted pools occur within a single structure that is mostly protected from wave action and the geoduck seed are grown in mesh bags and trays. Each of these systems utilize natural nutrients that are transported with tidal exchange. The use of "kiddie pools" or intertidal pools are no longer a viable option due to the restrictions placed upon the sediment and water flow within an intertidal system by the pools.

Broodstock maintenance consists of the care and feeding of adult bivalves used for propagating future generations of various shellfish species. Shellfish hatcheries operate under the "High Health Program" for broodstock maintenance, which has been adopted by the U.S. Department of Agriculture's Animal Plant Health Inspection Service (APHIS) as best management practice for meeting national and international standards for bivalve health.

Objective: Minimize adverse environmental impacts of hatchery operations.	
Suggested Strategies:	
1	Utilize management practices to avoid or make minimal use of antibiotics in treating bacterial contamination in larval and algal cultures.
2	Keep broodstock from different growing areas separated in the hatchery when working with genetically isolated stocks.
3	Ensure that species cultured are listed as acceptable for culture within the entire range of the commerce area.
4	Isolate specialized species not widely cultured within the commerce area.
5	Equip and outfit hatchery facilities to avoid harming the natural flora and fauna of the surrounding marine environment. For example, use fish-friendly screens to avoid pumping fish and invertebrates in with the seawater.

Secondary Nurseries: Seed Floats and Floating Upwell Systems (FLUPSY)

To offset the added costs and potential adverse environmental impacts of raising clam and oyster seed to a commercially viable size in primary nurseries, some companies have developed secondary floating and tideland nursery methods placed in the natural marine waters to take advantage of abundant naturally occurring algae (Figure 5.1).

Figure 5.1 – FLUPSY system
Source: Fisher Island Oysters 2007

Upland upwellers, used primarily for oyster seed, take advantage of abundant natural algae, but still require pumping large amounts of seawater to upland tanks.

Seed floats, normally used for clam seed, are underwater platforms covered with a sand substrate. The juvenile clams feed on naturally occurring algae borne on the tidal flows.

The Floating Upwell System, (FLUPSY), an integral part of many companies' seed production systems, is a highly efficient method for growing seed out to a larger size. In essence it translates the technique of the tank-enclosed upweller to a much larger scale by moving the upwellers into a floating structure that continuously draws natural seawater through the system.

Juvenile clams and oysters, one to two millimeters in length, are transported to FLUPSYs from shellfish primary hatcheries and nursery settings. The seed is placed in bins with screened bottoms that are lowered into openings in a floating frame and suspended in the seawater. Several bins are placed in a row on either side of a central enclosed channel that ends at a paddlewheel. The rotation of the wheel draws water out of the central channel creating an inflow of seawater through the bottom of the seed bins, continuously feeding the juvenile shellfish. The outflow from the bins is through a dropped section on one side of the bin facing the central channel. Typically, the FLUPSY platform is equipped with overhead hoists so the bins can be cleaned and moved. Once seed have reached a suitable size, they are removed from the FLUPSY and transplanted to a grow-out site.

Objective: Minimize adverse environmental impacts of nursery operations.
Suggested Strategies:

1	Periodically inspect the seafloor under FLUPSY and remove any unnatural, nonbiodegradable materials that have fallen from rafts and work areas.
2	Design and build FLUPSY platforms to minimize effects from shading to allow light to penetrate to the subtidal zone.
3	Design FLUPSY mechanisms to prevent accidental injury to other animals from moving parts such as paddlewheels.

Oyster Cultch Preparation and Remote Setting Sites

Cultch Preparation. Many farmers raising ground or longline cultured oysters, or focused on shellstock production for shucking houses, prepare or purchase oyster cultch for remote setting. Oyster cultch is generally prepared by bundling washed and aged Pacific oyster shells ("mother shells") in plastic mesh bags. Hundreds to thousands of cultch bags are required to sustain farm inventories. There is usually a considerable amount of waste with broken shell and debris being discarded prior to the bagging operation. Broken shell and shell grit is recycled for use as clam or other substrate, while other debris is disposed of through proper recycling or taken to refuge collection centers.

Natural Seed Collection. Natural seed is collected on bags of cultch, stakes or other substrate, and placed in the intertidal zone prior to spawning season. Once the oysters have set on the substrate, they are kept until a suitable size for planting.

Remote Setting Operations. Cultch bags, are placed in large remote setting tanks containing well-mixed controlled temperature seawater. Ready-to-set larvae are added to the seawater, sometimes with a small quantity of algal "paste." The larvae then rapidly set onto the mother shell and metamorphose into tiny juvenile oysters. The set cultch bags are then usually placed on the beach until the seed is large enough or "hard" enough (firmly cemented onto the mother shell) to withstand being moving onto the culture beds.

Objective: Minimize adverse environmental impacts of oyster cultch preparation, storage and remote setting operations.	
Suggested Strategies:	
1	Site shell washing and bagging operations so that water, shell fragments and grit, and other debris are contained in the work area. Dispose of debris properly.
2	Control excess runoff from the site to avoid or minimize sedimentation and turbidity.
3	Ensure shell piles are not a pest problem for your neighbors.
4	Make sure outdoor setting tanks are empty and cleared of debris, or are covered, when not in use.

Oyster Emergency Project

The unpredictable oyster seed supply continues to pose a serious threat to Pacific Coast shellfish growers. Hatchery problems vary and continue to affect the shellfish hatcheries that serve the West Coast, and very limited recruitment of natural-set oyster seed in Willapa Bay has led to growing concern among growers that typically rely on natural set.

In 2010, Congress awarded funds to PCSGA, through NOAA, to provide assistance to hatcheries and growers in finding the causes and potential solutions to the seed mortality problems, and specifically to:

1. Enhance understanding of the environmental conditions that lead to natural wild set larval shellfish mortalities; and
2. Improve hatchery management and technology to mitigate for water conditions that are conducive to mortality events.

The project includes three basic components:

- systematic monitoring of water quality in bays outside each hatchery;
- detailed monitoring of water quality in the hatchery setting;
- evaluation of seawater treatment systems and direct monitoring of conditions in larval tanks.

The project provided technology to several hatcheries to monitor all known water chemistry parameters. From research and observations conducted to-date, it is known that Vibrio *tubiashii*, a naturally occurring marine bacteria, is symptomatic of ocean acidification caused by low aragonite saturation levels in incoming hatchery waters and can cause, or contribute, to oyster larvae mortalities. Other factors are suspected to contribute to mortality events as well, and possibly certain combinations of constituents within the water cause stunted growth or mortality of seed. On the outer coast, lower than normal water temperatures and low aragonite saturation levels which coincide with upwelling events have persisted for years and leave reliance on significant natural sets as very unpredictable.

Correlating larval responses to various water conditions is key to developing strategies to mitigate for changes in ocean chemistry that may occur as a result of upwelling events, storms, algal blooms, and increasingly corrosive (low pH) waters with insufficient minerals necessary for oysters to develop through the larval stage.

The ongoing water monitoring at four key shellfish growing sites, monitoring of larval development both in hatcheries and in Willapa Bay (the largest natural oyster setting site on the U.S. West Coast), and small-scale water treatment systems will allow hatchery personnel to experiment to determine the most effective treatment systems under a variety of water conditions.

Annotated Bibliography—Section V

Dumbauld, B.R., Ruesink, J.L., Rumrill, S.S. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. Aquaculture 290. pp. 196–223.

See Section 2 references for abstract.

Elston, Ralph A; Hasegawa, Hiroaki; Humphrey, Karen L; Polyak, Ildiko K; Haese, Claudia C. 2008. Re-emergence of *Vibrio tubiashii* in bivalve shellfish aquaculture: severity, environmental drivers, geographic extent and management. Diseases of Aquatic Organisms. Vol. 82, no. 2, pp. 119-134.

See Section 4 references for abstract.

Ferreira, J.G., Hawkins, A.J.S., Bricker. S.B. 2007. Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model. Aquaculture 264. pp. 160–174.

See Section 3 references for abstract.

Philippart, C.J.M., van Aken, H.M., Beukema, J.J., Bos, O.G., Cadee, G.C., Dekker, R. 2003. Climate-related changes in recruitment of the bivalve *Macoma balthica*. Limnology and Oceanography. Vol. 48, no. 6, pp. 2171-2185.

In this study, we examine temperature-induced effects on reproductive output (eggs m super (-2)), onset of spawning (day of the year), and the juvenile instantaneous mortality rate (per day) of *M. balthica*. Data analysis was based on an extensive long-term data set (1973-2001) originating from the western Wadden Sea. Our results strongly suggest that rising seawater temperatures affect recruitment by a decrease in reproductive output and by spring advancement of bivalve spawning.

Southworth, M., Mann, R. 2003. Decadal scale changes in seasonal patterns of oyster recruitment in the Virginia sub estuaries of the Chesapeake Bay. Journal of Shellfish Research. Vol. 22, no. 1, p. 355.

See Section 3 References for abstract.

Whiteley, J.A. 2006. Macroinvertebrate community responses to clam aquaculture practices in British Columbia, Canada. Masters Abstracts International. Vol. 44, no. 1, pp. 218.

See Section 2 references for abstract

Whiteley, J.A., Bendell-Young, L.I. 2006. Intertidal Community Structure and Clam Aquaculture Practices in British Columbia, Canada. EOS, Transactions, American Geophysical Union. Vol. 87, no. 36, suppl., [np]. suppl.

See Section 4 references for abstract.

SECTION VI: SHELLFISH CULTIVATION OPERATIONS AND PRACTICES

Clam Culture

Although there is minor commercial production of Butter (*Saxidomus gigantea*) and Littleneck (*Protothaca staminea*) clams, Manila clams are the predominant clam species farmed along the West Coast. In Alaska, however, the only clam currently farmed is the native Littleneck. Methods of cultivation include ground culture, where clams are grown directly in the substrate of the beach at the intertidal range, and bag culture, where clams are grown in bags where they are set on the beach in the intertidal zone, or in bags suspended from racks or trays either subtidally or intertidally. On-bottom subtidal cultivation techniques are currently in the early experimental phase.

Ground Culture

Bed Preparation. Prior to planting clam seed on the tidelands, beds are prepared in a number of ways depending on the location. Bed preparation increases the chances of seed survival and allows for full use of available land. Types of preparatory work may include raking debris; adding shell and/or washed gravel to the clam beds to create more suitable substrate; cleaning the beds of mussel mats and other growth; and conducting environmental assessments of conditions, such as salinity and water quality.

When shelling or graveling, a method termed “frosting” (Figure 6.1), is used where several light layers of shell and/or washed gravel are spread -over many days and/or months. In addition to these types of activities other preparations may include laying down netting to protect against predators such as crabs and ducks; and marking boundaries. Some growers remove the predator netting within a few days of planting clam seed, giving the clams enough time to burrow sufficiently into the substrate to avoid most predators, while minimizing the chances that netting will escape into the environment.

Figure 6.1 – “Frosting” a Clam Bed
Note: Light material on raft is crushed shell; dark material is washed gravel.

Seeding. Typically, clam seed is planted in the spring and early summer. Most of the clam seed used comes from West Coast hatchery and nursery facilities, although in some areas natural sets of clams occur. Clam seed sizes and methods of seeding vary, depending on site-specific factors such as predators present and weather conditions. Planting methods include: hand-spreading seed at low tide upon bare, exposed substrate; hand-spreading seed on an incoming tide when the water is approximately four inches deep; hand spreading seed on an outgoing tide when the water is approximately two to three feet deep; or spreading seed at high tide from a boat.

Bed Assessment and Maintenance. After each growing season, surveys and samplings are typically conducted to assess seed survival and spreading adequacy, and to estimate harvest yield for the upcoming year. Surveys determine whether additional seeding is required to supplement a natural set or poor hatchery seed survival. The goal is to maintain the optimum sustainable productivity of the growing ground.

Where predator exclusion netting is used it requires periodic maintenance. Periodic maintenance includes inspecting periodically to ensure it is secure to the beach and effectively excluding predators and not floating up creating a potential hazard to boaters. During summer months macroalgae growing on nets requires periodic net cleaning or exchanging to improve water flow and avoid suffocation of the clams. In many areas that experience diving duck predation, predator exclusion nets can be removed during the summer months after the ducks have left for their arctic migration.

Harvesting. Before harvest begins, bed boundaries are typically staked and any remaining predator netting is folded back or removed. Harvesting crews typically hand-dig clams using a clam rake.

Each digger is responsible for going back and smoothing over the beach upon completion of the dig. Market-size clams are selectively harvested, put in buckets, bagged, tagged, and transported to processing plants. Undersized clams are left in beds for future harvests.

Technology has recently been developed to harvest clams mechanically. Lack of and/or costs associated with manual labor make this alternative attractive to some shellfish farms. The machines are used at low tide and bring the beach material and clams up onto a shaking perforated table that separates the clams from the substrate. Many of the machines are modified tulip bulb harvesters or have been custom built using similar technology. Research has been conducted in Samish Bay and British Columbia on potential impacts from mechanical harvesting. Results indicated the effects are minimal and comparable to the effects from hand raking.

Multiple crops may be in the ground at any time, depending upon the level of productivity of the ground. Beds may be dug annually, or as infrequently as once every four years, depending on growth rates and market demands.

Harvested clams are generally left in net bags, trays or totes in wet storage, either in the marine waters or upland tanks filled with seawater, to purge sand for at least 24 hours.

Bag Culture

Bed Preparation. Prior to setting bags on the tidelands, debris, such as driftwood, is removed from the area to be planted. Shallow (typically 2 to 4 inches) trenches may be dug with rakes or hoes to provide a more secure foundation for setting down the clam bags.

Grow-out. Bags are monitored throughout the grow-out cycle to make sure they are properly secured, and turned occasionally to optimize growth.

Harvesting. When the clams reach market size, the bags are removed from the growing area by hand. Harvesting may occur when there is one to two feet of water over the bags, so that sand and mud can be sieved from the bags. Bags are then brought to the processing site, and like ground-cultivated clams, are generally left to hang in wet storage to purge sand for 24 hours.

Objective: Minimize adverse environmental impacts of clam culture.	
Suggested Strategies:	
1	Minimize physical alteration of the culture area.
2	Emphasize the use of netting or similar passive measures to exclude predators.
3	When transplanting or seeding clams, take precautions to avoid introducing diseases and parasites.
4	Use biodegradable hydraulic fluid in harvesting machines. Inspect for and repair any fluid leaks prior to deploying machinery on beach. When possible fuel machinery on shore and take appropriate precautions to avoid spills. Have spill clean-up materials onsite where machinery is used and refueled.
5	Ensure predator exclusion nets and/or clam bags are secure to the beach and maintained so they are not dislodged in storms, trapping fish or floating up and hazardous to boaters or other types of recreation. Consider removing predator exclusion nets during times of year when they may not be necessary.

Geoduck (Giant Clam) Culture

Native geoduck, (*Panopea generosa*) the largest known clam, is a relatively new species for culture, and techniques are rapidly evolving and changing. At the present time, Washington and Alaska are the only U.S. states actively farming geoducks, although British Columbia, Canada is very actively involved in substantial geoduck cultivation as well. Currently, broodstock are collected from wild geoduck. Farms are typically located in both intertidal and subtidal. New and evolving geoduck farming techniques are expected to continue to arise as more data and research is developed.

Setting. Geoduck broodstock are conditioned and spawned in shellfish hatcheries. The larvae are reared through metamorphosis in tanks. Following metamorphosis, the juveniles are placed in nurseries until they reach approximately five millimeters long, at which point they are transported to beds for out-planting.

Seeding. Sections of protective gear is pushed into the substrate, leaving two-to-five inches of gear exposed. Depending on the tube circumference, two to seven seed clams are placed in each tube, where they will burrow into the substrate. The top of each protective gear is either covered with a plastic mesh net and secured with a rubber band to exclude predators, or alternatively, the entire field of tubes may be covered by a single large "canopy" net.

An alternative tube material is being tested by a few farms, which uses flexible extruded plastic mesh (Vexar) tubes instead of PVC pipe. The tubes are installed by hand using low volume and low pressure pumped seawater to a depth of six to seven inches and extend about four to five inches above the substrate (Figure 6.2). The tubes are then secured with a biodegradable bamboo skewer to close the opening at the top for predator exclusion. In observations to-date, the flexible tubes seem to have better

Figure 6.2 – Geoduck Clam Flexible Extruded Plastic Mesh Culture Tubes

Source: Allen Shellfish, LLC

retention in the substrate, allow for more water and sediment exchange, and produce better survival rates of geoduck clams compared to the PVC tubes. However, it should be noted that this is based on only a few samples and for a short duration of time. This methodology is still in the "testing" phase, but could become a viable alternative in the future for more farms.

Another alternative method includes the use of rigid netting material that is formed to create "tunnels." Seed is placed on the substrate in rows with the net tunnels placed over them to protect them from predators.

Grow-out. Once the young clams have buried themselves to a depth adequate to evade predators, normally about fourteen inches, the grow-out tubes are removed. With some exceptions, this generally occurs after one to two growing seasons. The tubes and nets are saved to re-use at another planting. Gear that is broken or deteriorated is disposed of in upland waste facilities. Once the clams reach market size in five to six years, the crop is harvested.

Harvesting. Geoducks are harvested both at low and high tide using a pump and hose to inject seawater next to the clam to loosen the substrate enough that the clam can be pulled easily to the surface without damaging the animal (Figure 6.3). The effect on the substrate itself is of short duration. Within one or two tidal cycles, the disrupted areas have been observed to fill back in. Clams are carried to transportation via land or brought to shore by boat on a flood tide then transported to processing plants.

Figure 6.3 – Geoduck Clam Harvest at Low Tide

Objective: Ensure that no synthetic material is lost into the marine environment.	
Suggested Strategies:	
1	Retrieve all excess, non-biodegradable material used during planting operations for reuse when possible. Non-reusable materials should be transported to an appropriate land-based disposal facility.
2	Farmers shall routinely inspect growing areas to collect dislodged tubes, caps and nets from the site. This material shall be disposed of at an approved land-based disposal site.
3	Utilize biodegradable materials to the extent possible and support innovations in development of biodegradable cultivation materials.
4	All tubes, nets and other material should be clearly marked with the company name and contact information.

Objective: Minimize adverse environmental impacts of routine geoduck harvesting to non-persistent effects of short duration.	
Suggested Strategies:	
1	Conduct harvest activities in a manner that minimizes offsite sedimentation, for example during low tidal cycles for beach harvest or periods of low current flow for subtidal harvest.
2	Time harvesting activities to a period when species of concern will not be present.
3	Train employees in use of equipment and planting and harvesting techniques to assure minimal disruption to the natural environment.

4	Use ball valves on hoses to prevent free flow of pumped water onto beach surface when not directly harvesting.

Mussel Culture

Two species of mussels are farmed on the West Coast: *Mytilus trossulus*, commonly known as the Blue Mussel and *Mytilus galloprovincialis*, commonly known as the Mediterranean or Gallo Mussel.

Farm Structure. Most mussels on the West Coast are grown suspended from rafts or surface longlines in the subtidal zone. Raft structures and surface longlines are visible all daylight hours, unlike intertidal culture of other species, which are only visible during daylight low tides in the spring and summer. Consequently, extra efforts must be made to continually maintain mussel farms in a neat and orderly fashion to minimize adverse aesthetic impacts.

Raft platforms are typically constructed of lumber, galvanized steel, and plywood. Flotation is generally made from coated or vinyl-wrapped polystyrene foam or reclaimed polyurethane food-grade barrels. Raft structures and longlines are anchored in place, frequently with concrete anchors attached with nylon or polypropylene line. Rafts may be periodically wrapped with nets to exclude predators.

Surface longlines are typically made of heavy polypropylene or nylon rope suspended by floats or buoys attached at intervals along the lines and anchored in place at each end (Figure 6.4). Anchors are frequently made of concrete, and floats are either foam filled or recycled food-grade containers.

Figure 6.4 – Longline Mussel Farming
Source: Environment Waikato 2010

Seeding. Typically, naturally spawned mussel seed sets on lines or metal screen frames in net cages that are suspended in the water during the late spring spawning season. Hatchery seed is set on lines or screen frames at the nursery, and then transported to the mussel farm for planting. Once the seed reaches a manageable size of six to twelve millimeters long, which can take several months in winter or several weeks in summer, it is scraped from the frames or stripped from the lines and transplanted on to culture ropes or into polyethylene net -like tubes, called "socks," each with a strand of line threaded down the length of the sock for strength. Concrete weights with stainless steel wire hooks are hung on the bottom end of each mussel sock for tension. Mussel discs are often inserted into the sock to help support the mussels on the line as they grow. The socks are then lashed to the raft, longlines or stakes, and suspended under the water.

Grow-out. When the mussels reach about one inch in length, the weights are often removed from the socks and saved for reuse. If the predator exclusion nets become excessively fouled, blocking the flow of microalgae to the mussels, the nets may be removed, and shell or other debris cleaned off.

Harvesting. When the mussels reach market size, socks or lines of mussels are freed from the longline, stake or raft structure for cleaning and grading. Depending upon the equipment available, the mussels are stripped from the lines or socks on which they are growing, after which they are bulk bagged and tagged for transport to shore and the processing plan, or they are cleaned, graded, and bagged on a vessel and then taken to shore for packing and shipping. Weights and discs are reclaimed for re-use, and used socking and lines are re-used, recycled, or disposed of at an appropriate waste facility, depending on the condition of the equipment.

Objective: Minimize adverse short and long-term environmental impacts of mussel farming operations.	
Suggested Strategies:	
1	Establish system that assures to the extent possible no synthetic materials, such as mussel lines, mussel discs and socking, are lost in the marine environment.
2	Use harvesting methods that minimize disruption to the water column and benthos.
3	Periodically conduct benthic sampling under mussel farms to determine potential adverse or beneficial impacts to the benthic flora and fauna.
4	Take measures to minimize visual impacts (such as keeping area clean).
5	Ensure predator nets, if used, do not impede or block current flow or rest on the sea floor.
6	Support efforts to assess effects on local marine biota and carrying capacity.

Oyster Culture

Several species of oysters are cultured on the West Coast including the Pacific oyster (*Crassostrea gigas*), Native oyster (*Ostrea lurida*), Kumamoto oyster (*Crassostrea sikamea*), Eastern oyster, also known as the American oyster, (*Crassostrea virginica*), and the European flat oyster (*Ostrea edulis*).

Productive oyster ground is dependent on a number of variables including salinity, temperature, substrate quality, water quality and types of predators present. Oyster ground is often classified or referred to by its use, such as seed ground, grow-out ground or fattening ground.

Different approaches can be taken to oyster grow-out, depending upon target market, beach characteristics and environmental conditions. For instance, bag, rack and bag, and suspended culture methods are typically employed to supply single oysters destined for the half-shell market. For the shucked meat market, however, oysters can be grown in clusters, so the method used is determined primarily by environmental conditions, such as substrate composition and the presence or absence of certain predators. Suspended cultures, such as longline and stake culture, are primarily used in areas that are not suitable for bottom culture.

Bottom Culture

Bed Preparation. Prior to planting a new crop of oysters, oyster beds may be cleaned of debris and drills and other pests by hand, or by use of a chain or net bag. The bag removes any oysters remaining on the bed after a harvest as well as some pests, and debris. If the substrate is too soft or muddy and not naturally suitable for planting oysters, it may be enhanced, typically by spraying shell, often mixed with washed gravel, from the deck of a barge using a pump and hose. Several passes are made over marked ground to ensure the material is spread evenly.

Seeding. Seed oysters attached to cultch shell may be sprayed from the deck of barges or cast by hand onto marked beds at an even rate to achieve optimum densities. The natural set method relies on naturally occurring oyster larva attaching to shells placed on beds. This natural seed is then allowed to grow out on the seed bed, and then normally transplanted to a grow-out bed.

Grow-out. The oysters are left on the beds and tended to remove pests and any natural debris until harvest. Seed may also be harrowed to lift it out of mud or sand caused by natural siltation or by winter storms shifting sands and mud/silt.

Transplanting. Oysters may be transplanted from one site to another at some point during grow-out. For example, oysters may be moved from an initial growing area to "fattening" grounds where higher levels of nutrients are found, allowing the oysters to grow more rapidly for market. Growers must abide by all transfer permits, regulations and requirements when transplanting oysters from one area to another to assure pests (such as oyster drills) are not accidentally introduced into growing areas.

Harvesting. Bottom culture oysters are harvested by hand during low tide or with a mechanical harvester during high tide. There is also a lesser use of oyster tongs to harvest small quantities of oysters.

In the case of hand harvesting, workers hand-pick oysters into large containers or baskets. Large containers are sometimes equipped with ropes and buoys so they can be lifted with a boom crane onto the deck of a barge at high tide. Smaller baskets are hand carried off the beach, or loaded onto a scow or boat for transport at high tide.

For mechanical harvesting, a harvest bag is lowered from a barge or boat by boom crane or hydraulic winch at high tide and pulled along the bottom to scoop up the oysters. This type of harvest apparatus is arranged to provide for adjustment so that minimal negative impact occurs on sensitive bottom substrate layers as tidal levels change. Where feasible, the area may be hand harvested at low tide afterward to obtain any remaining oysters.

After harvest, oysters are tagged and transported to processing plants.

Longline Culture

Bed Preparation. In some areas, silt may build up as a result of reduced current flow over the longline area and need to be leveled manually at the end of a growing cycle. Most residual oysters (i.e., "drop-offs" dislodged from the lines during the previous growing cycle) are removed from the ground prior to replanting.

Seeding. Stakes of metal or PVC pipe are stuck in the ground in rows. Long polypropylene or nylon lines with a piece of seeded oyster cultch attached approximately every foot are suspended above the ground by stakes. Unseeded shell may also be used if using the natural set method. Rows of stakes should be spaced so as to avoid adverse impacts from shading, silt buildup and alteration of currents (Figure 6.5).

Figure 6.5 – Oyster Longlines at 2.5-foot Spacing

Grow-out. The oysters grow in clusters supported by the longlines, which keep them from sinking into soft substrate and protect them from certain pests and predators. During grow-out diverse habitat is typically created due to the attachment sites offered by oyster shells and longlines (Figure 6.6).

Figure 6.6 – Diverse habitat created by intertidal oyster longline habitat in Samish Bay

Source**: Pacific Coast Shellfish Growers Association**

Harvesting. Longlined oysters may be harvested by hand or by machine. Typically, hand harvesting involves cutting oyster clusters off the lines by hand at low tide and placing the clusters in harvest tubs equipped with buoys for retrieval by a vessel equipped with a boom crane or hydraulic hoist at high tide. The oysters are then barged to shore. Smaller operations might hand-carry the tubs off the beach. For mechanical harvesting, buoys are attached at intervals along the lines at low tide. On a high tide, the buoys are hooked to a special reel mounted on a vessel that pulls the lines off the stakes and reels them onto the boat. The oyster clusters are cut from the lines, then barged to shore and transported to processing plants or market.

After a harvest, some growers pull all the pipe stakes from the bed in order to harvest residual drop-off oysters and to address any silt built up during the crop cycle due to reduced flow across the long line area. With the pipes pulled, the residual oysters can be harvested using a harvest bag, which can also help remove built up silt. The bed could also be hand harvested, and then harrowed to remove silt and return the bed to its natural level before putting the stakes back for the next cycle.

Another method used to control silt build up is to simply allow the bed to lie fallow for a time so current and waves can naturally return a bed to pre-cultivation elevation. Other growers leave the stakes in place from cycle to cycle, depending on the conditions of the bed after a crop cycle.

Bag and Rack-and-Bag Culture

Bed Preparation. Beds are prepared by removing debris such as driftwood, and pests such as oyster drills. In some cases, the substrate might be enhanced with oyster shells to harden the ground. The ground may be marked with stakes for working purposes. Some operations may install longlines and PVC pipe or metal stakes to secure the bags. Wood or metal racks may be used to support the bags off the ground. Racks with legs may be placed directly on the bottom, or supports may be driven into the bottom. Bags are typically attached to racks with reusable plastic or wire ties.

Seeding. Single-set seed is placed in re-usable plastic net bags closed with plastic ties or metal rings. The bags are placed in the intertidal zone directly on the ground, if suitable, but sometimes lashed to longlines, hooked to stakes, or placed on racks.

Grow-out. The bags are periodically turned and tended, and predators removed by hand.

Harvesting. Bags are released from supports, if any, loaded into a boat or wheelbarrow for transport to shore, and then transported to processing plants or market.

Stake Culture

Bed Preparation. Beds are prepared in the intertidal zone by removing debris such as driftwood, and pests such as drills and starfish. In some areas, the substrate may occasionally be enhanced with oyster shells to harden the ground, but usually soft mud or sand bottoms require little or no enhancement. Stakes made of hard - surfaced non-toxic materials, such as PVC pipe, are driven into the ground approximately two feet apart to allow good water circulation and easy access at harvest. Stakes are typically limited to two feet in height to minimize obstruction to boaters.

Seeding. Stakes can be seeded in hatchery setting tanks before being planted in the beds, or bare stakes might be planted in areas where there is a reliable natural seed set. Bare stakes might be planted some months before the natural spawning period to allow barnacles and other organisms to attach to the stakes, increasing the surface area available for setting oyster spat. An alternative method of seeding is to attach from one to several pieces of seeded cultch to each stake.

Grow-out. Stakes are left in place through a two to four year growing cycle. Each piece of seeded cultch attached to stakes grows into a cluster of market-size oysters suspended above the mud and most pests. In areas where natural spawning occurs, multiple year classes of oysters grow on the stakes, with smaller, younger oysters growing on top of older oysters. Gear and bed maintenance takes place during harvest when stakes are repositioned, straightened or replaced, and the oysters are thinned to relieve overcrowding. Stakes may be removed to allow mechanical methods to be used to eliminate silt build up during the crop cycle due to reduced flow across the stake bed.

Harvesting. Oysters are selectively hand harvested during low tide by prying clusters of market-sized oysters from the stakes, or removing the clusters and the stakes, and placing them in baskets or buckets. The containers are tagged and either hand carried off the beach or loaded into a boat at a higher tide for transport to shore.

The clusters are separated into singles, sorted, culled and rinsed if destined for the single oyster market, or left as clusters if intended for the shucked oyster market, and transported to processing plants. Undersized single oysters from the clusters are transplanted to a bottom culture bed for grow-out, since they cannot reattach to the stakes, and are harvested using bottom culture methods when they reach market size.

Oysters that fall from or are knocked off the stakes are harvested periodically using bottom culture methods. Market-sized drop-offs that have not been lost due to sinking into the mud are harvested along with those pried from the stakes, and those that have settled into the mud are periodically picked and transplanted to bottom culture beds to improve their condition for harvest at a later time.

Tumble Bags or Baskets on Longlines

Bed Preparation. Beds are prepared in the intertidal zone by removing debris such as driftwood, and pests, such as oyster drills. Upright supports, usually PVC or galvanized metal, are installed every 6 to 10 feet, usually 2 to 4 feet above the surface of the substrate. Nylon or polypropylene line is strung across and secured to the tops of the uprights, and tensioned using t-stake, galvanized pipe or screw anchors.

Seeding. Single-set seed is placed into re-usable plastic net bags or baskets, which are self-closing or are closed with zip-ties or metal rings. Bags or baskets are attached to lines using metal or plastic clips or ties. Sometimes, floats are attached to individual bags/baskets to accentuate wind and wave tumbling, which improves shell quality.

Grow out. Lines are checked periodically and re-tensioned, if necessary.

Harvesting. Bags/Baskets are released from the supporting lines and loaded into shallow draft vessels, or carts/wheelbarrows, depending upon location.

Suspended Culture

Farm Structure. Oysters are farmed in the subtidal zone by using lantern nets, bags, trays, cages, or vertical ropes or wires suspended from surface longlines, or to a lesser extent, rafts (Figure 6.7).

Surface longlines are **Figure 6.7 – Oyster Suspended Culture using Rafts and Trays**
Source: Northwest Aquaculture Ltd. 2003

heavy lines suspended by floats or buoys attached at intervals along the lines, anchored in place at each end. Lantern nets, adopted from Japanese shellfish culture, are stacks of round mesh-covered wire trays enclosed in tough plastic netting. The nets, bags, trays, cages, or vertical ropes or wires are hung from the surface longlines under the floats or buoys, or from rafts.

Seeding. Single set oyster seed is placed on the trays or in the bags and suspended in the water. Seed set on cultch is attached to the vertical ropes or wires.

Grow-out. The oysters are regularly sorted and graded throughout the growth cycle. Every three or four months the trays are pulled up, the stacks taken apart, oysters put through a hand or mechanical grading process, the trays restocked, stacks rebuilt and de-fouled and returned to the water. Oysters grown on vertical lines are in clusters and receive little attention between seeding and harvesting.

Harvesting. A vessel equipped with davits and winches works along the lines, and the trays, nets or bags are detached from the line one by one and lifted into the boat. The gear is washed down as it is pulled aboard. Oysters are emptied from the gear and placed into tubs, then cleaned and sorted on board the harvest vessel, on an on-site work raft, or at an offsite processing facility.

Oysters grown using suspended culture are generally transplanted to an intertidal bed for two to four weeks to "harden." Hardening extends the shelf-life of suspended culture oysters by conditioning them to close their shells tightly when out of the water, retaining body fluids; and abrasion on the beach substrate literally hardens the shell making it less prone to chipping, breakage and mortality during transport. After hardening, the oysters are re-harvested using bottom culture harvest methods.

Objective: Minimize adverse environmental impacts of oyster culture.	
Suggested Strategies:	
1	Take measures to prevent synthetic materials, such as oyster seed and grow-out bags, from escaping into the marine environment.
2	Adopt grow-out and bed management methods that enhance the habitat value of the shellfish.
3	Adopt harvesting methods that reduce bottom disturbance and turbidity.
4	Prior to siting new cultivation plots, review and document topographical layout to identify existing sloughs, low areas, etc., with goal of maintaining topographical integrity.
5	Review data for prevailing wind direction and site operations to minimize redirection of flow.
6	If placing cultivation gear, such as longlines, in navigational routes, lay out operations to minimize impact. Work with neighboring property owners and other users of the surrounding waters to mitigate any impacts.
7	Remove all culture gear from area after harvest unless it will be reused shortly thereafter.
8	Where cultured areas are located along navigational routes, select marking devices that will provide optimum visibility both day and night.

Scallop Culture

Scallop culture for any of several commercially important species remains in its infancy on the West Coast. Commercial aquaculture for the Japanese-Weathervane hybrid is currently practiced in British Columbia, though efforts there have been hampered by low seed survivorship in recent years. Interest is building for establishing commercial scallop aquaculture in Washington and California focusing on the purple-hinged rock scallop, *Crassadoma giganteus*. Commercial rearing techniques are under development in Washington State. These include optimizing hatchery and nursery techniques and further developing tray-based growout methods. The economic viability of scallop cultivation is also being investigated, as culture methods for scallops tend to be labor intensive, unless automated. However, commercial scale studies have demonstrated that rock scallops are extremely hardy and relatively fast growing in culture, making this species an ideal candidate for commercial cultivation.

Several factors continue to constrain the development of the U.S. aquacultured scallop industry, however. These include the relative scarcity of hatchery produced seed and lack of established suspended aquaculture facilities and farm locations. A lack of suitable, permitted aquaculture sites on the US west coast also hinders development as do possible regulatory restrictions regarding the utilization of wild broodstock for hatchery production of juveniles or collection of wild spat.

Hatchery. Rearing and setting of scallops is accomplished in a hatchery. Growers may also use setting tanks on-site supplied with seawater and suitable settlement substrates. Seed collectors may also be used. These consist of either hanging collectors vertically in the water column or filling spat bags with a collection material (such as artificial seaweeds or fuzzy rope). Particular care must be taken during the larval rearing stage to ensure that nutrition supplied via cultured live algae is adequate for successful settlement and metamorphosis to the juvenile stage. The early nursery stage for rock scallops may also be protracted, lasting up to 2-3 months, due mainly to undeveloped ctenidia that hamper their ability to feed on suspended seston. This stage is also the bottleneck for survivorship to the juvenile (seed) stage though recent work has demonstrated that up to 10% survivorship from pediveliger to seed stage is possible.

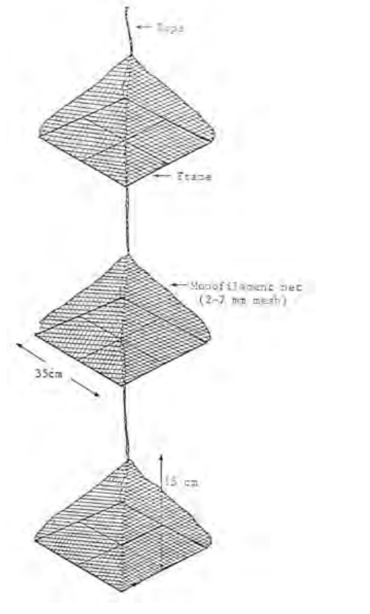

Figure 6.8 – Pearl Net used in Scallop Culture

Once scallop seed are 2mm in shell length they are transferred from the setting system to a suspended aquaculture site. There, seed are contained in 2mm mesh pearl nets (Figure 6.8). Once stocked, pearl nets are fastened, one on top of the other and a line of approximately 15 nets is then tied to a longline at a depth of at least 3 meters to avoid fouling and temperature/salinity fluctuations. Juveniles remain in the pearl nets until they reach about 20 mm. Scallops have a low tolerance to temperature and salinity fluctuations during early life stages. When scallop spat are transferred to an open water nursery site it is important to place them deep enough to be free of temperature and salinity fluctuations, yet still have adequate plankton in the water for feeding on.

Grow-out. Once scallops reach the appropriate size (20-30mm), they are removed from the pearl nets, graded and placed into trays for continued growout. Stocking density is important and should be no more than 150 scallops per square meter. Later, when they approach commercial harvest size (100-120mm), the density should be reduced to 50 per square meter.

Farm Structure. Long-line systems are usually constructed either in a surface or subsurface array. Subsurface longlines can be built so that the entire system (floats and horizontal longline) is submerged below the surface. This is commonly done in scallop farming to prevent surface agitation from affecting the nets or cages, and to place scallops in deep water where temperature and salinity are relatively stable. Subsurface longlines are also constructed so that the flotation is on the surface but the horizontal longline is 15 to 30 feet or more below the surface.

Pressurized or foam-filled floats are used to support the horizontal longline. The line is often counter-weighted to stabilize the system. This may involve weights hung on the lantern nets for example, and down-lines spaced regularly along the lines attached to weights resting on the bottom.

Objective: Monitor for and minimize adverse environmental impacts of scallop farming operations.	
Suggested Strategies:	
1	Establish system that assures no synthetic materials, such as seed collection materials or spat bags, are lost in the marine environment.
2	Use harvesting methods that minimize disruption to the water column and benthos.
3	Periodically conduct benthic sampling under scallop farms to determine potential adverse or beneficial impacts to the benthic flora and fauna.
4	Take measures to minimize visual impacts.

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The British Columbia coastline is under increasing pressure from competing coastal zone utilization (urbanization, recreation and aquaculture) and potential climate change impacts, highlighting the need for effective diagnostic tools of coastal ecosystem health and function. For cultured and wild shellfish, a variety of environmental, biological and human factors have been identified that could have significant effects on these populations. Within the Myt-OME Project genomic information and tools for study marine mussels (*Mytilus spp*.) are being developed. In addition to their importance to Canadian shellfish aquaculture, mussels are widely used as bioindicators of ecosystem health. Libraries will be generated from mussels exposed to a variety of stressing agents, producing sequence information in the form of expressed sequence tags and identifying genes involved in environmental stress responses. From these libraries a cDNA microarray will be developed for use in gene expression analysis, to examine the nature and magnitude of the stress response to these agents.

Heath, W.A., Carroll, S., Devos, R., Provan, B. 2008. The assessment of impacts on the benthic environment from suspended oyster aquaculture in Baynes Sound, British Columbia, Canada. Aquaculture Canada super (OM) 2008: Proceedings of the Contributed Papers of the 25 super (th) Annual Meeting of the Aquaculture Association of Canada. , no. 14, pp. 42-45.

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Inglis, G.J., and Gust, N. 2003 Potential indirect effects of shellfish culture on the reproductive success of benthic predators Journal of Applied Ecology. Vol. 40, no. 6, pp. 1077-1089.

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Luckenbach, M. W., Wang, H. V. 2004. Linking watershed loading and basin-level carrying capacity models to evaluate the effects of land use on primary production and shellfish aquaculture. Bulletin of Fisheries Research Agency (Japan). no. Sup. 1, pp. 123-132.

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MacKenzie, C.L.Jr. 1997. The natural history and habitat characteristics of softshells (*Mya arenaria*) in northern New Jersey. Journal of Shellfish Research. Vol. 16, no. 1, p. 310.

The natural history and habitats of softshell clams (*Mya arenaria*) in Raritan Bay and the Navesink and Shrewsbury Rivers, NJ, were studied from 1993-96. In beds with no evident causes of mortality after the clams had attained a length of at least 15 mm, the survival rate was about 50% in 21 months, September 1993 to June 1995. The clams attained market size about 2 years after settlement.

Philippart, C.J.M., van Aken, H.M., Beukema, J.J., Bos, O.G., Cadee, G.C., Dekker, R. 2003. Climate-related changes in recruitment of the bivalve *Macoma balthica*. Limnology and Oceanography. Vol. 48, no. 6, pp. 2171-2185.

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Raman-Nair, W., Colbourne, b., Gagnon, m., Bergeron, P. 2008. Numerical model of a mussel longline system: Coupled dynamics. Ocean Engineering 35. pp. 1372– 1380.

The numerical model may be used to predict the dynamics of longline systems using drag coefficients determined from field measurements. We expect that the results will be useful for checking and optimizing shellfish aquaculture designs prior to installation and for modifying existing designs to safeguard against failure.

Richard, L. 2004. Balancing marine aquaculture inputs and extraction: Combined culture of finfish and bivalve molluscs in the open ocean. Bulletin of Fisheries Research Agency (Japan). no. Sup. 1, pp. 51-58.

See Section 2 references for abstract.

Richardson, J., Newell, C., Angel, D., Getchis, T., Suhrbier, A., Davis, J., Cheney, D. 2006. CFD analysis of shellfish aquaculture gear used in inter-tidal and sub-tidal locations. Journal of Shellfish Research. Vol. 25, no. 2, p. 768.

An environmental and technical assessment of alternative methods used to cultivate bivalve shellfish. Of particular interest are the use of fractional volume techniques to model nets and bags, and the use of a kinetics algorithm to calculate phytoplankton consumption within the culture units. These techniques allow the practitioner to accurately simulate three-dimensional flows through the different types of culture units and to estimate food availability within the culture units. The methods developed for this study can also be used as an aid to evaluate siting concerns and to customize gear designed to work optimally at specific locations.

Richardson, N.F, Ruesink, J.L., Naeem, S., Hacker, S.D., Tallis, H.M., Dumbauld, B.R., Wisehart, L.M. 2007. Bacterial abundance and aerobic microbial activity across natural and oyster aquaculture habitats during summer conditions in a northeastern Pacific estuary. Hydrobiologia, in press.

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Roycroft, D., Kelly, T. C., Lewis, L. J. 2004. Birds, seals and the suspension culture of mussels in Bantry Bay, a non-seaduck area in Southwest Ireland. Estuarine, Coastal and Shelf Science. Vol. 61, no. 4, pp. 703-712.

See Section 2 references for abstract.

Ruesink, J.L. and Rowell, K. 2007. Geoduck clam (*Panopea abrupta*) aquaculture as press and pulse perturbations to eelgrass (*Zostera marina*). Presentation at NW Workshop on Bivalve Aquaculture and the Environment. Sponsored by Washington SeaGrant.

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Southworth, M., Mann, R. 2003. Decadal scale changes in seasonal patterns of oyster recruitment in the Virginia sub estuaries of the Chesapeake Bay. Journal of Shellfish Research. Vol. 22, no. 1, p 355.

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Stevens, C., Plew, D., Harstein, N., Fredricksson, D. 2008. The physics of open-water shellfish aquaculture. Aquacultural Engineering 38. pp. 145–160.

Here we review issues relating to the design and mechanics of shellfish longline structures in relation to the offshore marine environment. Two main facets are explored: (i) the effect of the flow (waves and currents) on the farm and (ii) the reverse perspective of the impact of the farm on the flow.

Stevens, C.L., Plew, D. R., Smith, M.J., Fredricksson, D.W. 2007. Hydrodynamic Forcing of Long-Line Mussel Farms: Observations. J. Wtrwy., Port, Coast, and Oc. Engrg. Volume 133, Issue 3, pp. 192-199.

The first detailed observations of the motion and loading of a mussel (shellfish) aquaculture long-line are described in order to identify the dominant modes of flow-structure interaction and provide a baseline for prediction of future structures.

Tallis, H.M., Ruesink, J.L., Dumbauld, B.R., Hacker, S.D., Wisehart, L.M. 2009. Oysters and aquaculture practices affect eelgrass density and productivity in a Pacific Northwest estuary. Journal of Shellfish Research. 28(2): 251-261.

See Section 2 references for abstract.

Vaudrey, J., Getchis, T., Britton, B. 2006. Assessing impacts of shellfish aquaculture on eelgrass populations in eastern Long Island Sound. Journal of Shellfish Research. Vol. 25, no. 2, pp. 785.

See Section 2 references for abstract.

Vaudrey, J.M.P., Getchis, T., Shaw, K., Markow, J., Britton, R., Kremer, J. N. Effects of Oyster Depuration Gear on Eelgrass (*Zostera marina L.*) in a Low Density Aquaculture Site in Long Island Sound. Journal of Shellfish Research. Vol. 28, no. 2, pp. 243-250.

See Section 2 references for abstract.

Weise, A.M., Cromey, C.J., Callier, M.D., Archambault, P., Chamberlain, J., McKindsey, C.W. 2009. Shellfish-DEPOMOD: Modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. Aquaculture 288. pp. 239–253.

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Whiteley, J. A. 2006. Macroinvertebrate community responses to clam aquaculture practices in British Columbia, Canada. Masters Abstracts International. Vol. 44, no. 1, p. 218.

See Section 2 references for abstract.

Wisehart, L.M., Dumbauld, B.R., Ruesink, J.L, Hacker, S.D. 2007. Importance of eelgrass early life history stages in response to oyster aquaculture disturbance. Marine Ecology Progress Series 344. pp. 71-80.

See Section 2 references for abstract.

Zydelis, R.N., Esler, D., Kirk, M., Boyd, W. S. 2009. Effects of off-bottom shellfish aquaculture on winter habitat use by molluscivorous sea ducks. Aquatic Conserv: Mar. Freshw. Ecosyst. 19. pp. 34–42.

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SECTION VII: SHELLFISH PROCESSING AND SHIPPING OPERATIONS

Processing and Shipping

Transportation

After harvest, shellfish are transported by land, air or sea, depending upon the location of the farm, to a processing house. The most energy efficient method that also meets the health department and certification requirements for time and temperature guidelines tend to be the most cost effective method of transport.

Receiving

Shellstock are transported in harvest containers or totes to the processing plants under strictly regulated time/temperature controls. All product received by processing plants is maintained in separate lots, identified by harvest tags, and great care is taken to assure no co-mingling occurs, as required by law. Once received, shellstock may be processed directly or placed in cold dry storage or wet storage until ready for processing.

Wet Storage

Wet storage is the temporary storage of shellstock in water after harvest from growing areas and before shipping or processing. The shellstock is placed in containers or floats in natural bodies of water or in tanks containing natural or synthetic seawater, and this is the last body of water the live shellfish are suspended in before processing or shipping. Water may also be aerated and/or chilled to provide an optimum environment for shellfish health.

Shellfish that are to be stored live in a wet storage system are washed and culled prior to placement in the system. Product removed from wet storage is washed and culled prior to shipping. For wet storage in tanks, plastic or fiberglass tanks are filled with seawater, and water is pumped through them.

The water used may be synthetic (made from potable water with salts added), or pumped from an adjacent water body. The water is typically filtered and disinfected using UV light. Systems can be run in a flow-through mode with water released back to the adjacent water body, but are usually run in a recirculating mode. Regular cleaning of the tanks occurs. Any shell fragments or other solid wastes are disposed of in upland facilities. Water is released back to the source water body, or allowed to leach into upland gravel fields.

Processing

Wastewater, both fresh and saline, is a byproduct of offloading, storing and rewashing shellfish in processing facilities. Wastewater resulting from processing operations should be collected and reused or recycled. State regulations and the nature of the processing operations dictate the specific requirements for wastewater disposal.

Shellfish to be sold live are washed with approved potable water, or an approved seawater system, then culled, graded, packaged, and placed in coolers or wet storage to await shipment.

Shellfish intended for the jarred meat market are shucked and meats are then packed in containers for shipment. Prior to packing, shucked meats might be rinsed with water from an approved potable water source, and then may be chilled, frozen, or processed further using other approved processing methods, such as canning, smoking or breading.

Shell and shell fragments are the main byproduct of processing shellfish. Whole oyster shell may be reclaimed for use as cultch. Shell may also be crushed for other uses. For example, the U.S. Army Corps of Engineers has used oyster shell as substrate in restoration projects, and growers often use old oyster shell to improve beach substrate for shellfish beds.

Handling Harvest Tags

Harvest tags, made by necessity of a non-permeable material to withstand saltwater conditions, are carefully disposed of in an appropriate waste facility. The shellfish industry is working with the FDA (which currently requires non-destructible tag material) to establish other possible tag systems that could be recyclable. It is important to know the how long you must retain your shellfish tags, as most cases it is at least 90 days.

Packaging

Shellfish products may be packed in a variety of materials, including plastic mesh bags, glass jars, plastic cups, bag-in-box, cooler boxes or cans. Examples of packaged products are frozen whole meats, shucked fresh-pack meats, or in the case of single oysters, flash-frozen top-off.

Shipping

All shellfish products are transported to wholesale dealers, retail outlets and airfreight carriers under approved time/temperature controls.

Objective: Minimize adverse environmental impacts from shipping, receiving, storage, washing, processing and packaging operations.	
Suggested Strategies:	
1	Assure practices comply with wastewater permit requirements.
2	Implement a reduce/reuse/recycle program for all solid waste from processing and packaging operations, such as cardboard, metal, wood, plastic, glass, polystyrene foam, light bulbs, and batteries.
3	Recycle shells and shell fragments resulting from processing operations by using for cultch or crushing for other uses.
4	Capture shell fragments and other solid wastes from processing operations and dispose of them properly in upland waste facilities.
5	Include proper removal and disposal of shellfish harvest tags in processing procedures to prevent accidental return to bay.