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A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems

Volume I

Far-field Environmental Effects of Marine Finfish Aquaculture
(B.T. Hargrave)

Ecosystem Level Effects of Marine Bivalve Aquaculture
(P. Cranford, M. Dowd, J. Grant, B. Hargrave and S. McGladdery)

Chemical Use in Marine Finfish Aquaculture in Canada:
A Review of Current Practices and Possible Environmental Effects
(L.E. Burridge)

The complete papers can be found in the following document:

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FOREWORD

Context

The Government of Canada is committed to ensuring the responsible and sustainable development of the aquaculture industry in Canada. The Minister of Fisheries and Oceans' announcement of the $75 M Program for Sustainable Aquaculture (PSA), in August 2000, is a clear expression of this commitment. The objective of the PSA is to support the sustainable development of the aquaculture sector, with a focus on enhancing public confidence in the sector and on improving the industry's global competitiveness. Ensuring the sector operates under environmentally sustainable conditions is a key federal role.

As the lead federal agency for aquaculture, Fisheries and Oceans Canada (DFO) is committed to well-informed and scientifically-based decisions pertaining to the aquaculture industry. DFO has an ongoing program of scientific research to improve its knowledge of the environmental effects of aquaculture. The department is also engaged with stakeholders, provinces and the industry in coordinating research and fostering partnerships. As a contribution to the Federal government's Program for Sustainable Aquaculture, DFO is conducting a scientific review of the potential environmental effects of aquaculture in marine and freshwater ecosystems.

Goal and Scope

Known as the State-of-Knowledge (SOK) Initiative, this scientific review provides the current status of scientific knowledge and recommends future research studies. The review covers marine finfish and shellfish, and freshwater finfish aquaculture. The review focuses primarily on scientific knowledge relevant to Canada. Scientific knowledge on potential environmental effects is addressed under three main themes: impacts of wastes (including nutrient and organic matter); chemicals used by the industry (including pesticides, drugs and antifoulants); and interactions between farmed fish and wild species (including disease transfer, and genetic and ecological interactions).

This review presents potential environmental effects of aquaculture as reported in the scientific literature. The environmental effects of aquaculture activities are site-specific and are influenced by environmental conditions and production characteristics at each farm site. While the review summarizes available scientific knowledge, it does not constitute a site-specific assessment of aquaculture operations. In addition, the review does not cover the effects of the environment on aquaculture production.

The papers target a scientific and well-informed audience, particularly individuals and organizations involved in the management of research on the environmental interactions of aquaculture. The papers are aimed at supporting decision-making on research priorities, information sharing, and interacting with various organizations on research priorities and possible research partnerships.

Each paper was written by or under the direction of DFO scientists and was peer-reviewed by three experts. The peer reviewers and DFO scientists help ensure that the papers are up-to-date at the time of publication. Recommendations on cost-effective, targeted research areas will be developed after publication of the full series of SOK review papers.

State-of-Knowledge Series

DFO plans to publish 12 review papers as part of the SOK Initiative, with each paper reviewing one aspect of the environmental effects of aquaculture. This Volume contains three papers: Far-field environmental effects of marine finfish aquaculture; Ecosystem level effects of marine bivalve aquaculture; Chemical use in marine finfish aquaculture in Canada: a review of current practices and possible environmental effects.

Further Information

For further information on a paper, please contact the senior author. For further information on the SOK Initiative, please contact the following:

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FAR-FIELD ENVIRONMENTAL EFFECTS OF MARINE FINFISH AQUACULTURE

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EXECUTIVE SUMMARY

This review evaluates the existing knowledge and research needs required to determine the ability of coastal waters to support a sustainable marine finfish aquaculture industry. A central question is what methods, environmental observations and models exist, or are required, to determine the capacity of coastal areas to assimilate additional sources of dissolved and particulate matter released by cultured finfish.

Pillay (1992) provided an early review of major environmental effects of all types of aquaculture on a worldwide basis. Over the past decade, several international groups have considered various environmental issues surrounding the development of marine finfish aquaculture (Rosenthal 1988, 1994; GESAMP 1991, 1996; Buerkly 1993; Stewart et al. 1993; Ervik et al. 1994a, 1997; Stewart 1994, 2001; Rosenthal et al. 1995; Silvert and Hargrave 1995; Burd 1997; Goldberg and Triplett 1997; Milewski et al. 1997; Fernandes et al. 2000; Harvey 2000; Milewski 2000; EVS 2001; Holmer et al. 2001). Much of the information on environment-finfish aquaculture interactions in publications cited above is focused on measurable near-field changes in water and sediment variables sensitive to organic matter and nutrient additions.

Despite the difficulties of observing far-field effects, published literature shows that in some locations, measurable effects attributable to finfish aquaculture development have been observed at the ecosystem level. The impacts may be categorized into three types of broad-scale changes distant from farm sites: eutrophication, sedimentation and effects on the food web.

It is a common observation that the amount of suspended particulate matter increases in the immediate vicinity of finfish net-pens. When feed pellets are distributed by hand or automatic mechanical feeders, a fine dust may potentially be transported in the air or trapped in the water surface film and spread over a broad area. Unconsumed feed pellets and fish feces usually contribute to increased local concentrations of suspended and sedimented particulate matter. While much of the released material is assumed to settle rapidly at or near cage sites (Gowen et al. 1994; Silvert 1994e; Findlay et al. 1995; Findlay and Watling 1997), there is potential for horizontal transport and widespread dispersion, particularly in areas with high currents (Sutherland et al. 2001; Cromey et al. 2002). Holmer (1991) collected material, directly attributable to a finfish aquaculture source, at distances up to 1.2 km from a farm site in Danish coastal water. The extent to which resuspension and lateral transport increase sedimentation at locations remote from farm sites depends on both physical and sedimentological processes. Tidal flow, residual

circulation, patterns of turbulence, wind and wave energy, and flocculation (aggregation) will determine large-scale patterns of particle dispersion. The distances and locations of accumulation are highly site-specific and depend on bottom topography, currents, erosion and flocculation processes that affect the residence time of material both in the column (Sutherland et al. 2001) and on the bottom (Milligan and Loring 1997).

Specific compounds associated with organic matter, such as fatty acids, digestible proteins, sterols, elemental sulfur, pristane and stable carbon/nitrogen isotopes (Li-Xun et al. 1991; Johnsen et al. 1993; Findlay et al. 1995; McGhie et al. 2000) and trace elements such as zinc that might be used as tracers of fish feed pellets, have been measured in surface sediments to determine far-field dispersion patterns (Ye et al. 1991; McGhie et al. 2000; Sutherland et al. 2002; Yeats 2002). Alteration of bottom type to more fine-grained sediments through enhanced deposition of flocculated, fine-grained material may also account for the speculation that a population of lobsters was displaced from their historic spawning ground after a salmon farm was located at the site (Lawton and Robichaud 1991). However, an opposite effect of salmon farm operations causing aggregations of lobster may also occur. Salmon farm sites may be a refuge for lobsters from harvesting.

Eutrophication is the process of natural or anthropogenic enrichment of aquatic systems with inorganic nutrient elements (Jørgensen and Richardson 1996; Strain and Yeats 1999; Cloern 2001). Long-term eutrophication of coastal and estuarine waters results from the additions of both dissolved inorganic and organic nutrients and increased biological oxygen demand (BOD) from oxygen-consuming material from all sources (Rosenberg 1985; Costa-Pierce 1996; Johannessen and Dahl 1996; Cloern 2001). Dissolved inorganic nutrients released by finfish culture and regenerated from sediments enriched with sedimented organic matter under fish pens may stimulate phytoplankton production and increase oxygen demand. It is often difficult to accurately estimate the magnitude of additions of nutrients and organic matter from finfish aquaculture when many environmental factors and possible sources of addition occur (Einen et al. 1995; Strain et al. 1995). Models can help determine the relative amounts of organic loading from aquaculture from all natural sources (river discharge, tidal exchange, rainfall, phytoplankton and macroalgal production) and human inputs (Valiela et al. 1997). The degree of nutrient enrichment is influenced by the scale of aquaculture, local hydrographic characteristics, the magnitude of other sources relative to aquaculture and internal processes, such as uptake by phytoplankton, algae, internal recycling, resuspension of fine material, and uptake by biofouling communities that colonize net-pens.

The effects of eutrophication may extend into shallow water littoral and intertidal zones. Intertidal areas, subject to daily movements of water and sediment, are locations influenced by broad-scale processes affecting chemical fluxes of mass and dissolved material throughout an inlet system. Nutrient enrichment can stimulate the extensive development of macroalgal beds (Soulsby et al. 1982; Petrell et al. 1993; Campbell 2001), which have a large capacity for nutrient uptake (Chopin and Yarish 1999; Chopin et al. 2000) and may affect benthic fauna through changes in the rates and nature of deposition of particulate organic matter (Bourget et al. 1994). However, few studies have unequivocally linked the establishment of aquaculture farm sites to environmental or ecological changes in intertidal areas.

Eutrophication can alter the ratio between essential nutrients (carbon: nitrogen:phosphorus), as well as absolute concentrations by causing a shift in phytoplankton species assemblages. It has proven difficult to directly relate the occurrence of harmful algal blooms (HAB) to finfish farms. As with other types of plankton blooms, many environmental factors appear to control the formation of HABs. Water column mixing and stratification that maintain cells in the photic zone with an adequate nutrient supply are critical variables. In contrast to numerous studies of localized benthic effects of finfish aquaculture at farm sites, there have been very few observations of effects on plankton communities (Burd 1997). Reductions in zooplankton standing stock with oxygen depletion could allow standing stocks of phytoplankton to increase. With sufficient nutrient and light supplies, higher rates of primary production and increased sedimentation would result in even further oxygen depletion in deep water.

There is an extensive literature documenting changes in benthic infauna community structure associated with high levels of nutrient and organic matter additions (Burd 1997). Only fauna (e.g. nematodes and polychaetes) tolerant of low oxygen conditions and reduced sulfides are able to survive under conditions of high organic sedimentation (Hargrave et al. 1993, 1997; Duplisea and Hargrave 1996). The presence/absence of these 'indicator' species or faunal groups may show transitions from lower (background) levels of organic matter supply to high deposition rates caused by unconsumed feed pellets and fish feces in areas subject to low transport (Weston 1990; Pocklington et al. 1994; Burd 1997). Moderate increases in organic matter supply may stimulate macrofauna production and increase species diversity; however, with increasingly higher rates of organic input, diversity and biomass decrease.

Widespread changes in species community composition of benthic macrofauna distant from farm sites are more difficult to detect and have been less studied. Temporal and spatial scales of changes in benthic macrofauna species composition and biomass have been measured over the past decade in some areas as part of long-term monitoring programs near net-pens to determine if organic enrichment effects from aquaculture can be detected (Burd 1997; Brooks 2001). Most studies have shown that the local extent of altered benthic community structure and biomass is limited to less than 50 m. Water depth and current velocity are critical factors determining patterns of sedimentation around cage sites (Weston 1990; Pohle et al. 1994; Silvert 1994e; Henderson and Ross 1995; Burd 1997; Pohle and Frost 1997; Brooks 2001; Cromey et al. 2002), and therefore impacts of benthic fauna differ at different farm sites. In southwest New Brunswick, organic enrichment effects at newly established farm sites were localized to within 30 m of cages. After approximately five years, changes were measurable over greater (>200 m) distances. Macrofaunal community diversity was most reduced close to a farm site that had been in operation for 12 years, but significant declines in diversity also occurred throughout the inlet system. Benthic epifauna and infauna at two intertidal sites at varying distances from aquaculture sites showed that the diversity of infauna was significantly higher away (>500 m) than near (<500 m) farm sites (Wong et al. 1999).

Loss of diversity at distances less than 500 m may indicate that benthic infauna are more sensitive to organic matter additions than epifauna (Warwick 1986, 1987), possibly reflecting changes in sediment physical structure (grain size), oxygen supply and sulfide accumulation associated with increased organic matter supply.

Another far-field effect of local sources of organic matter produced by finfish farm sites involves the use of chemotherapeutants. Antibiotics in medicated fish feed have the potential to induce drug resistance in natural microbial populations on an inlet-wide scale. Concentrations of a commonly used antibiotic, oxytetracycline (OTC), largely disappeared within a few weeks, but traces of the antibiotic were detectable for up to 18 months (Samuelsen et al. 1992). In Puget Sound, the highest numbers of bacteria (as colony-forming units) in sediments generally occurred at farm sites (Herwig et al. 1997), but the proportion of OTC resistant bacteria declined exponentially with increasing distance from a farm. Ervik et al. (1994b) also observed antibiotics in fish and wild mussels near a farm site after medicated food had been administered, and OTC resistance has been observed in bacteria cultured from sediments up to 100 m away from salmon farm sites in inlets in the Bay of Fundy where salmon farms are concentrated (Friars and Armstrong 2002).

GAPS IN KNOWLEDGE

1. There is a need to determine sustainable levels of salmon production within coastal regions, inlets or embayments where marine finfish aquaculture is currently practiced in Canada.

2. Mass balance models of nutrient loading (inorganic and organic) from all sources (natural and anthropogenic) may be used to assess potential additions from finfish aquaculture. Budgets must take into account internal nutrient recycling as well as external sources.

3. General circulation models can be developed and improved to resolve combined effects of tidal and wind-driven forcing and that reflect complex topography and intertidal drying zones.

4. New methods are required to quantify processes of resuspension that redistribute fine material produced locally by finfish aquaculture sites over large areas.

5. New methods are required to quantify processes, such as flocculation and aggregation, that affect dispersion of particulate matter from finfish farm sites.

6. Studies are required to determine if the frequency and location of HAB or plankton blooms are related to the expansion of finfish aquaculture.

7. New studies are required to determine changes in water column variables in areas of intensive finfish aquaculture. In comparison to benthic studies, there have been very

few investigations of changes in planktonic communities around finfish aquaculture sites.

8. Further studies are required to document environmental or ecological changes in intertidal areas and to determine if these can be linked unequivocally to the establishment of aquaculture sites.

9. Mass balance and numerical models are required to link production and external loading with aerobic and anaerobic oxidation of organic matter (pelagic and benthic), sedimentation and sulfide accumulation in sediment.

10. Further studies are required to determine the extent of far-field effects on ecological and biological impacts of antibiotic resistance induced in microbial and other wild populations in areas of intensive finfish aquaculture.

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ECOSYSTEM LEVEL EFFECTS OF MARINE BIVALVE AQUACULTURE

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EXECUTIVE SUMMARY

This paper reviews the present state of knowledge on environmental issues related to bivalve aquaculture, with emphasis on suspended mussel culture. Material reviewed includes Canadian and international studies on the role of wild and cultured bivalve populations in controlling ecosystem-level dynamics. The focus is on identifying potential changes in ecosystem processes (material and energy fluxes, and nutrient cycling) at the coastal ecosystem scale. Potential mechanisms for ecosystem-level effects include the utilization of particulate food resources by cultured bivalves and associated fauna, the subsequent release of unutilized materials in dissolved (urine) and particulate (feces and pseudofeces) form, and the removal of minerals from the system in the bivalve harvest. The potential consequences to coastal ecosystems from intensive bivalve aquaculture are summarized in the following sections.

CONTROL OF SUSPENDED PARTICLE DYNAMICS

Dense bivalve populations may exert a strong influence on suspended particulate matter (including phytoplankton, detritus, and some auto- and heterotrophic picoplankton and microzooplankton) in some coastal systems through their huge capacity to clear particles from the surrounding water (Dame 1996). Grant (2000) studied 15 embayments in Prince Edward Island (PEI) and concluded that the mussel biomass under culture in 12 of these embayments was potentially capable of removing food particles much faster than tidal exchange could replace them. Similarly, Meeuwig et al. (1998) concluded that mussel culture operations in many PEI embayments significantly reduce phytoplankton biomass through grazing. Similar conclusions have been reached for numerous international coastal regions (reviewed by Dame 1996). These relatively simple calculations of the time required for bivalve populations to clear the water column of particles indicate that intensive bivalve aquaculture has the capacity to alter matter and energy flow at the coastal ecosystem scale. However, gaps in knowledge exist regarding a number of important processes that could potentially mitigate the suspected impact of bivalve feeding. These include the following: (1) the effects of physical processes such as water column stratification, mixing and flow velocity, and spatially dependent tidal flushing; (2) the replenishment of food particles through primary production within the embayment; (3) bivalve-mediated optimization of primary production (Prins et al. 1995);

and (4) the large flexibility of bivalve feeding responses to environmental variations (Cranford and Hill 1999).

A strong indication that bivalve filter-feeders are able to control suspended particulate matter in some coastal systems comes from documented ecosystem changes that occurred after large biomass variations in natural and cultured bivalve populations. Population explosions of introduced bivalve species in San Francisco Bay and dramatic reductions in oyster populations in Chesapeake Bay have been implicated as the cause of large changes in phytoplankton biomass and production experienced in these systems (Nichols 1985; Newell 1988; Nichols et al. 1990; Alpine and Cloern 1992; Ulanowicz and Tuttle 1992). Research on the whole-basin environmental effects of bivalve aquaculture in France and Japan indicate that intense bivalve culture in these regions led to changes in particulate food abundance and quality, resulting in large-scale growth reduction and high mortalities in the cultured bivalves (Héral et al. 1986; Aoyama 1989; Héral 1993). Speculation that intense bivalve culture can affect coastal ecosystems by reducing excess phytoplankton associated with eutrophication have been supported by some laboratory and field observations, but have not been rigorously proven.

DIVERSION OF MATERIALS TO BENTHIC FOOD WEBS

The feeding activity of bivalve filter-feeders results in the packaging of fine suspended material into larger feces and pseudofeces that rapidly settle to the seabed, especially under conditions with slow or poor water flushing and exchange. These activities divert primary production and energy flow from planktonic to benthic food webs. While the dynamics of bivalve feces deposition (settling velocity, disaggregation rate and resuspension) are poorly understood, enhanced sedimentation under shellfish culture is well documented. Mortality and fall-off of cultured bivalves, induced by seasonal colonization by fouling organisms, can result in additional acute benthic organic loading.

The spatial scale and degree of seabed organic enrichment effects caused by the increased vertical flux of naturally occurring particles is dependant on the biomass of cultured bivalves, local hydrographic conditions, and the presence of additional organic inputs from other natural and anthropogenic activities. The recycling of organic biodeposits under suspended mussel culture operations in PEI, and at several other international regions, has been shown to have local to inlet-wide benthic impacts (Dahlback and Gunnarsson 1981; Tenore et al. 1982; Mattsson and Linden 1983; Kaspar et al. 1985; Shaw 1998; Stenton-Dozey et al. 1999; Mirto et al. 2000; Chamberlain et al. 2001). The increased oxygen demand in sediments from mussel biodeposits can, under certain conditions, result in the generation of an anaerobic environment that promotes ammonification and sulfate reduction, increased sediment bacterial abundance, and changes in benthic community structure and biomass. Aquaculture is not solely responsible for such impacts in PEI, as many basins are also stressed by nutrient enrichment from agricultural run-off. Observations of seabed impacts under mussel lines in PEI are, therefore, not directly transferable to bivalve culture sites in many other regions of Canada. Biodeposition patterns and the dispersion of bivalve biodeposits are also controlled by water depth and local water movement. Slight differences in these physical properties can result in marked differences in the degree of impact observed on seabed geochemistry and communities under different suspended mussel culture sites (Chamberlain et al. 2001). Further research is needed to assess the ability of different coastal regions to resist or assimilate the effects of increased organic enrichment through a variety of physical and biogeochemical processes.

The increased coupling of planktonic and benthic food webs by cultured bivalves has the potential to change energy flow patterns in coastal ecosystems, including altering food availability to zooplankton and larval fish (Horsted et al. 1988; Newell 1988; Doering et al. 1989). Bivalve filter-feeders have a competitive advantage over zooplankton for food resources because they are able to respond immediately to increased food availability, while zooplankton must go through a complete life cycle before being able to fully exploit increased food resources. Direct ingestion of zooplankton by bivalves may also reduce zooplankton abundance (Horsted et al. 1988; Davenport et al. 2000). However, effects of bivalve culture on zooplankton communities are largely speculative owing to the limited research conducted.

ALTERED COASTAL NUTRIENT DYNAMICS

The consumption and deposition of suspended particulate matter by bivalves, as well as the excretion of dissolved nutrients, can play a significant role in controlling the amounts and forms of nitrogen in coastal systems and the rate of nitrogen cycling (reviewed by Dame 1996). This transformation and translocation of matter by bivalves appears to exert a controlling influence on nitrogen concentrations in some coastal regions (Dame et al. 1991) and can provide a means of retaining nutrients in coastal areas, where they are recycled within detrital food chains, rather than being more rapidly exported (Jordan and Valiela 1982). Benthic nutrient mineralization can increase at culture sites as a result of the increased organic matter sedimentation, greatly speeding up the rate of nitrogen cycling (Dahlback and Gunnarsson 1981; Kaspar et al. 1985; Feuillet-Girard et al. 1988; Barranguet et al. 1994; Grant et al. 1995). The high flux of ammonia excreted from dense bivalve populations may have a major effect on phytoplankton production (Maestrini et al. 1986; Dame 1996) and may potentially contribute to more frequent algal blooms, including those of the domoic-acid-producing diatom *Pseudo-nitzschia multiseries* (Bates 1998; Bates et al. 1998). Aquaculture-induced changes in the relative concentrations of silica, phosphorus and nitrogen (e.g. Hatcher 1994) may also favor the growth of other harmful phytoplankton classes (Smayda 1990), but this has yet to be observed in nature. Bivalve aquaculture may also play a significant role in nutrient cycling in coastal systems, as nutrients stored in the cultured biomass are removed by farmers and the nutrients are no longer available to the marine food web. Kaspar et al. (1985) suggested that the harvesting of cultured mussels may lead to nitrogen depletion and increased nutrient limitation of primary production, but there is little direct evidence of environmental effects. The retention and remineralization of limiting nutrients in coastal systems is necessary to sustain system productivity, but the potential impacts of bivalve cultures on coastal nutrient dynamics is poorly understood.

CUMULATIVE ENVIRONMENTAL EFFECTS

Any attempt to assess ecosystem-level effects of bivalve aquaculture must consider the complexity of natural and human actions in estuarine and coastal systems. Infectious diseases associated with intense bivalve culture, as well as exposure of cultured organisms to 'exotic' pathogens introduced with seed or broodstock, can have a significant and perhaps more permanent impact on ecosystems than the direct impact of the bivalves themselves (Banning 1982; ICES 1995; Bower and McGladdery 1996; Hine 1996; Renault 1996; Minchin 1999; Miyazaki et al. 1999). The presence of additional ecosystem stressors can also influence the capacity of bivalves to impact the ecosystem. The effects of chemical contaminants and habitat degradation are complex, but are well documented as having the potential to adversely affect bivalve health. Bivalve neoplasias show strong correlations to heavily contaminated environments (Elston et al. 1992), and the severity of infection is related to sub-optimal growing conditions (Elston 1989). Dissolved contaminants are frequently scavenged onto particulate matter, a mechanism which increases their availability for wild and cultured filter-feeders to ingest. Weakened bivalves with impeded feeding activity, along with spawning failure or poor quality spawn, can all contribute to morbidity, mortality and fall-off.

Land-use practices that transport sediments into estuaries can impact coastal water quality. Cultured bivalves and their support structures could alter sedimentation patterns within embayments, resulting in accelerated deposition of fine-grained sediment. Presently, there is no consensus on whether dense bivalve populations cause a net increase or decrease in sedimentation rates in coastal regions. However, if bivalve cultures influence the natural equilibrium among the major factors controlling sediment aggregation rate, sedimentary conditions within coastal regions may be altered.

INTEGRATION OF ECOSYSTEM EFFECTS

The available literature has shown that extensive bivalve culture has the potential, under certain conditions, to cause cascading effects through estuarine and coastal foodwebs, altering habitat structure, species composition at various trophic levels, energy flow and nutrient cycling. Simulation modelling has been one of the more focused approaches to assessing the net ecosystem impact of bivalve interactions with ecosystem components. Modelling can quantitatively and objectively integrate the potential negative ecosystem effects of the impact of mussel grazing on phytoplankton, zooplankton and the benthos, with the potentially positive effects of increased recycling of primary production and retention of nutrients in coastal systems (Fréchette and Bacher 1998). For example, such an integrative approach can help to assess whether or not the severity of ecosystem effects in different coastal areas are regulated by water motion and mixing. Numerical models can also be directed toward assessment of system productive capacity, fish/land-use interactions, farm management and ecosystem health. Past work has provided an excellent means of identifying gaps in knowledge.

A variety of methods has been applied to assessing the environmental interactions of bivalve aquaculture operations (Grant et al. 1993; Dowd 1997; Grant and Bacher 1998;

Smaal et al. 1998; Meeuwig 1999), but there is no standard assessment approach. Fully coupled biological-physical models may be envisioned (e.g. Prandle et al. 1996; Dowd 1997) that predict ecosystem changes in chlorophyll, nutrients and other variables of interest as a function of culture density and location. To do this, shellfish ecosystem models must be integrated with information on water circulation, mixing and exchange to account for transport and spatial redistribution of particulate and dissolved matter. Box models (Raillard and Menesguen 1994; Dowd 1997; Chapelle et al. 2000) offer a practical means to couple coastal ecosystem models with physical oceanographic processes. The bulk parameterizations of mixing required for these box models can be derived directly from complex hydrodynamic models (Dowd et al. 2002). Another promising avenue for improving ecosystem models is the use of inverse, or data assimilation, methods (Vallino 2000). These systematically integrate available observations and models, thereby combining empirical and simulation approaches, and improve predictive skill. Simulation models that focus on estimating mussel carrying capacity and related ecosystem impacts provide powerful tools for quantitative descriptions of how food is captured and utilized by mussels, as well as site-specific information on ecosystem variables and processes (Carver and Mallet 1990; Brylinsky and Sephton 1991; Grant 1996).

RESEARCH NEEDS

Few studies have assessed the potential environmental interactions of the bivalve aquaculture industry, and few quantitative measures presently exist to measure the ecosystem-level effects of this industry. Research on the ecosystem-level impacts of bivalve aquaculture is currently at a relatively early stage of development compared with finfish culture and for many other anthropogenic activities. As a result, ecologically relevant studies are needed on many topics, particularly the long-term responses of major ecosystem components (phytoplankton, zooplankton, fish, benthos, as well as the cultured bivalves) to bivalve-induced changes in system energy flow and nutrient cycling. The following general research areas have been identified to address gaps in knowledge:

- *Ecological role of bivalve filter-feeders*: accurately quantify the density-dependant role of bivalves in controlling phytoplankton and seston concentrations, including studies of hydrodynamics, bivalve ecophysiology, and phytoplankton community and productivity responses to grazing pressure.

- *Organic loading*: identify important processes controlling the severity of seabed organic enrichment impacts caused by bivalve biodeposits and determine the capacity of different coastal ecosystems to assimilate or recover from the effects of aquaculture-related organic loading.

- *Nutrient dynamics*: develop a predictive understanding of the potential effects of bivalve aquaculture on nutrient concentrations, elemental ratios and rate of cycling in coastal systems, and study the consequences of altered nutrient dynamics to phytoplankton communities and blooms, including harmful algal blooms.

- *Ecosystem structure*: investigate the effects of bivalve culture on ecosystem structure resulting from direct competition between bivalves, zooplankton and epibionts for trophic resources, and the transfer of energy and nutrients to benthic food webs.

- *Numerical modelling*: integrate knowledge obtained on the consequences of bivalve culture on ecosystem structure and function through the use of ecosystem modelling to assess the net impact of aquaculture activities on major system components and to address issues of aquaculture productive capacity and sustainability.

- *Ecosystem status*: develop a scheme for classifying and assessing the state of ecosystem functioning for regions supporting bivalve aquaculture. Integrate multiple ecosystem stressors from anthropogenic land- and marine-use in ecosystem studies of culture systems.

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CHEMICAL USE IN MARINE FINFISH AQUACULTURE IN CANADA: A REVIEW OF CURRENT PRACTICES AND POSSIBLE ENVIRONMENTAL EFFECTS

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EXECUTIVE SUMMARY

There has been a great deal of scientific debate regarding the environmental consequences of chemical usage in aquaculture. The debate has also moved into the public domain: where views of the opposing sides are typified by several highly publicized anti-aquaculture articles and, most recently, television documentaries (Ellis 1996; Goldburg and Triplett 1997; Milewski et al. 1997), and the responses to these articles from the finfish aquaculture industry (e.g. Canadian Aquaculture Industry Alliance 2001a,b).

Scientific reviews of the subject have been prepared by Zitko (1994) and GESAMP (1997). Issues raised and recommendations made by these authors have yet to be addressed in a significant manner. In addition, the authors of recent reviews of environmental impacts of aquaculture have identified chemical inputs from aquaculture activity as an area requiring further research (Nash 2001; Anonymous 2002). Several projects recently funded by Fisheries and Oceans Canada's (DFO) Environmental Science Strategic Research Fund (ESSRF) have allowed scientists to begin to address some of these topics. However, these projects are still in the early stages of identifying sources of contamination and potential effects on the environment, particularly to non-target species.

This review is a summary of potential sources of chemical contamination, chemicals that may be involved and knowledge about the potential effects of these compounds. Each identified class of chemical contaminants could be the subject of its own comprehensive review. Pesticides, drugs, persistent organic pollutants and metals are discussed in the context of the Canadian aquaculture industry.

Two classes of compounds will not require further research. Food additives include antioxidants (preservatives) and carotenoid pigments (flesh coloring) and are unlikely to cause any effects in the environment. MS-222 (tricaine methanesulfonate) is used in the New Brunswick aquaculture industry, and no adverse environmental effects are foreseen with its use (Zitko 1994).

Chemicals used in the Canadian aquaculture industry are identified in Table 1. The table summarizes recent scientific information regarding their use, persistence and potential effects in the environment. There are relatively few publications in the primary literature regarding the environmental fate and effects of chemicals used in aquaculture in Canada.

It is clear that a number of gaps in knowledge exist for each compound or class of compound. A more thorough review of each compound would identify further specific gaps related to that chemical.

For antibiotics, there appears to be no published data collected around Canadian aquaculture sites regarding the following: presence of antibiotics in sediments and aquatic biota; presence and prevalence of antibiotic-resistant organisms in sediments and indigenous species; or antibiotic residues in fish and non-target aquatic organisms. Accumulation of antibiotics in sediments may interfere with bacterial communities and affect mineralization of organic wastes (Stewart 1994), but no studies have been published in Canada.

Most work on pesticides to date has been conducted in the laboratory and has focused on determining the acute responses of aquatic organisms (non-target species) to exposure(s) to anti-sea lice chemicals. Limited field trials have focused on lethality of single treatments. Short-term responses to pesticide applications and long-term studies to establish the natural variability in local populations and measures of change in biodiversity need evaluation. Currently, commercially important non-target species have attracted much of the attention regarding effects of chemicals. There are apparently no data regarding the effects of these chemicals on microorganisms and planktonic species that form the foundation of the marine food chain in the near-shore environment. The chemical formulations of pesticide and disinfectant products have not been determined, and many of the 'inert' ingredients may be toxic to aquatic biota (Zitko 1994).

Little is known about the relationship between aquaculture and environmental contaminants, such as persistent organic pollutants (POPs) and metals. Feeds may be a source of contaminants to farmed fish. Knowledge of the constituents of each formulation is required for an accurate assessment of potential risk. Metals may be deposited near aquaculture sites from at least two other sources: leaching from metal cage structures and antifoulant paints. Chlorinated compounds (Hellou et al. 2000) and metal concentrations (Chou et al. 2002) were found to be higher when the total organic carbon content was high in sediments. Wooden cages with styrofoam floats may be a source of plastic contaminants (Zitko 1994). However, little known is known about the effects of plastics on aquatic organisms.

In addition, generic gaps can be identified in relation to the scientific approach and methodology:

- Chemical-related research is needed in all areas where marine finfish aquaculture is practiced in Canada. Research needs to be continued in New Brunswick, where scientists have a considerable database upon which to build and have the best opportunity to monitor long-term trends. In addition, work needs to be expanded in Newfoundland, Nova Scotia and British Columbia, where little such work has been conducted.

- Toxicity data are limited to lethality tests conducted over short time frames (e.g. 24, 48 and 96 h). More work is required to determine chronic lethal and sublethal effects and the effects of realistic exposures of these compounds on indigenous species.

- While there are laboratory-derived data on many compounds, there is almost no information regarding effects of chemicals of aquaculture origin in the field. Field surveys and experiments that investigate short-term responses to chemical application as well as long-term studies to establish natural variability in local populations and measure changes in biodiversity (and other indicators of environmental health) are needed.

- Toxicity testing relies on single species and single compound testing in the laboratory. There is a serious lack of data regarding the cumulative effect of exposure to chemicals and the concentration and fate of chemicals of aquaculture origin. The cumulative impact of chemicals and impact of multiple exposures to non-target organisms need to be determined.

Table 1. A Summary of Chemical Compounds Used in the Canadian Aquaculture Industry**

Chemical	Use	Persistence in Sediment	Bioaccumulation	Potential Effects
Oxytetracycline	Antibiotic	Persistent for long periods depending on environmental factors (Björklund et al. 1990; Samuelsen 1994; Hektoen et al. 1995; Capone et al. 1996); Half-life 419 days under stagnant, anoxic conditions (Björklund et al. 1990)	Uptake by oysters and crabs either in the laboratory or in close proximity to salmon cage sites (DFO 1997); Concentration in tissues of rock crabs over US FDA limit (Capone et al. 1996)	Resistance to oxytetracycline may occur in fish, non-target organisms and bacterial community near aquaculture sites (Björklund et al 1991; Hansen et al. 1993; Hirvelä-Koski et al. 1994)
Tribrissen	Antibiotic	Estimated half-life of 90 days at 6-7 cm deep (Hektoen et al. 1995)		
Romet 30	Antibiotic		Uptake by oysters (Jones 1990; LeBris et al. 1995; Capone et al. 1996; Cross unpublished data)	
Florfenicol	Antibiotic	Estimated half-life of 4.5 days (Hektoen et al. 1995)		
Teflubenzuron	Drug; In-feed sea lice control	Solubility 19 $\mu g \cdot L^{-1}$ with a log K_{ow}[a] of 4.3, indicating a potential to persist (Tomlin 1997); Persistence >6 months in area <100 m from treated cage (SEPA 1999b)		Chitin formation inhibitor; Juvenile lobster mortalities reported (SEPA 1999b); Mitigation possible by depuration prior to molting (McHenery 1997; SEPA 1999b)
Emamectin benzoate	Drug; In-feed sea lice control	Solubility 5.5 $mg \cdot L^{-1}$ with log K_{ow} of 5, indicating potential to persist (SEPA 1999b)	Withdrawal period of 25 days prior to marketing salmon	Chloride ion movement disruptor (Roy et al. 2000); Lethal to lobsters at 735 $\mu g \cdot kg^{-1}$ of food (Burridge et al. 2002); Induces molting in lobsters (Waddy et al. 2000c)
Ivermectin	Drug; In-feed 'off-label' treatment for sea lice control	Solubility of 4 $mg \cdot L^{-1}$ (Tomlin 1997); Could persist for 28 days (Wislocki et al. 1989; Roth et al. 1993)	Withdrawal period of 180 days prior to marketing; Accumulated in lobster tissue over 10 days (Burridge, Haya and Zitko unpublished data)	Chloride ion movement disruptor (Roy et al. 2000); Cumulative 80% Atlantic salmon mortality to 0.2 $mg \cdot kg^{-1}$ for 27 days (Johnson et al. 1993); 96h LC50 at 8.5 $mg \cdot kg^{-1}$ food for shrimp; NOEC[b] was 2.6 $mg \cdot kg^{-1}$ food (Burridge and Haya 1993)
Azamethiphos	Pesticide; Bath treatment for sea lice control	Solubility 1.1 $\mu g \cdot L^{-1}$ with a log K_{ow} of 1.05, not expected to persist (Tomlin 1997)	Unlikely to accumulate in tissues (Roth et al. 1993, 1996)	Neurotoxin, acetylcholinesterase (AChE) inhibitor, but not cumulative (Roth et al. 1993, 1996); Mutagenic *in vitro* (Committee for Veterinary Medicinal Products 1999; Zitko 2001); 1-h bath at 1 $mg \cdot L^{-1}$: lethal to 15% salmon after 24 h (Sievers et al. 1995); Larval/adult lobster 48-h LC50 at 3.57-1.39 $\mu g \cdot L^{-1}$ /NOEC 120 min at 1 $\mu g \cdot L^{-1}$ (Burridge et al. 1999a, 2000a); Behavioral responses at >10 $\mu g \cdot L^{-1}$ (Burridge et al. 2000a,b)

Table 1 (continued). A Summary of Chemical Compounds Used in the Canadian Aquaculture Industry**

Chemical	Use	Persistence in Sediment	Bioaccumulation	Potential Effects
Copper-based antifouling paints	Antifoulant; Reduce fouling biota on nets	Elevated copper (Cu) reported in sediments (Burridge et al. 1999a)	May accumulate in aquatic biota	100-150 mg(Cu)·kg^{-1} in sediment may affect benthic fauna diversity (Debourg et al. 1993); Most sample locations > ISQG[c] of 18.7 mg·kg^{-1} , lethal to amphipods and echinoids (Burridge et al. 1999a)
Iodophors	Disinfecting equipment	Not expected (Zitko 1994)		Formulations may contain compounds harmful or toxic to aquatic biota (Zitko 1994; Madsen et al. 1997; Ashfield et al. 1998)
Chlorine/Hypo-chlorite	Disinfectant; Net cleaning			Toxic to aquatic organisms (Zitko 1994)
PCBs, PAHs,p,p"-DDE	Found in fish feed (Zitko 1994)	PCBs not detectable at 0.05-0.10 μg·g^{-1} dry wt (Burridge et al. 1999a); p,p'-DDE detected at DL=1 ng·g^{-1}, dry wt (Hellou et al. 2000)	Changing lipid profiles in wild fish (Zitko 1994)	
Cadmium, Lead, Copper, Zinc, Mercury	From cage structures; Fish feed	Copper >2, zinc 1-2 times higher in sediments below cages than in fish feed (Chou et al. 2002); Cadmium exceeded 0.7 μg·g^{-1} (Burridge et al. 1999a)	May be toxic or accumulate in aquatic biota	
Polystyrene beads	Styrofoam floats	Source of low molecular weight contaminants (Zitko 1994)		Benthic fauna altered by altering pore water gas exchange, by ingestion or by providing habitat for opportunistic organisms (Goldberg 1997)

** The table includes only compounds known to be used (presently or historically) in Canada. Other classes of compounds are used routinely in other jurisdictions and may be introduced to Canada in the future.

a – log K_{ow} = logarithm of the octanol-water partition coefficient. It is internationally accepted that log K_{ow} >= 3 indicates a potential to bioaccumulate. The *Canadian Environmental Protection Act* (CEPA) recognizes log K_{ow} >= 5 as indicative of potential to persist and/or bioaccumulate (Beek et al. 2000).

b – NOEC = No Observed Effect Concentration

c – ISQG = Interim Sediment Quality Guidelines

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