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Salmon Holding Capacity in Southwestern New Brunswick

Department of Fisheries and Oceans
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m aquaculture
Aquaculture facilities
environmental impact

ABSTRACT

Department of Fisheries and Oceans. 2003. Salmon Holding Capacity in Southwestern New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2489: *iv* + 53 p.

A team of DFO Science staff was asked by the Directors of Science and Oceans Sectors, Maritimes Region, to provide an opinion on the status of salmon aquaculture-environment interactions in southwestern New Brunswick (Western Isles region) (SWNB). The document provides a scientific basis for determining sustainable holding capacity, offers advice regarding the environmental impacts of the industry as it is currently structured and measures that should be taken to ensure the sustainability of salmon aquaculture in the region.

RÉSUMÉ

Les directeurs des Sciences et des Océans dans la Région des Maritimes ont demandé à une équipe de scientifiques du MPO de leur donner une opinion sur l'état des interactions entre l'aquaculture du saumon et l'environnement dans le sud-ouest du Nouveau-Brunswick (S.-O. N.-B.) (région des îles de l'ouest de la baie de Fundy). Le présent document expose les arguments scientifiques servant à déterminer quelle est la capacité de charge viable; il présente aussi des avis au sujet des incidences environnementales de l'industrie dans sa structure actuelle ainsi que les mesures qu'il conviendrait de prendre pour faire en sorte que l'aquaculture du saumon soit viable dans la région.

INTRODUCTION

The southwestern New Brunswick (SWNB) salmon aquaculture industry has grown rapidly since its inception in the late 1970s. It now has a value roughly equal to that of harvest fisheries landings in New Brunswick. It is likely that the industry will continue to develop with the culture of other finfish species and perhaps bivalves. Fisheries and Oceans Canada (DFO) promotes the development and growth of sustainable mariculture and salmon aquaculture has become a major economic factor in the region. However, the long-term growth and sustainability of the industry, in SWNB as elsewhere, depends on a balanced approach that considers not only economic aspects, but also the needs for environmental protection and other users of coastal marine resources including harvest fisheries. Government, industry and other stakeholders agree that an integrated approach to coastal zone management is required.

Despite the many economic benefits, marine finfish aquaculture is known to cause changes in the environment and to displace other activities in the coastal zone. For example, those involved in traditional fisheries in coastal areas of SWNB believe that their harvests have been negatively impacted as a direct result of the rapid expansion of salmon aquaculture over the past 20 years. Environmental impacts have been observed that extend over a broad range of variable and spatial scales that extend beyond farm lease boundaries (Fisheries and Oceans 2003). Decreases in benthic macrofauna species abundance between 1989/91 and 1998/99 in SWNB are thought to reflect bay-wide changes due to the development of the salmon aquaculture industry (Lim and Gratto 1992, Pohle et al. 1994, 2001 and Pohle and Frost 1997).

Potential effects associated with continued expansion and sustainable operation of a finfish aquaculture industry in general have been recently summarized in a DFO review (Fisheries and Oceans 2003):

- Inlet-wide eutrophication (oxygen depletion, nutrient enrichment)
- Local sediment organic matter enrichment (increased sulfides in sediments)
- Potential toxic chemical effects (local and meso-scale, indigenous organisms)
- Inlet-wide changes in community structure (water column and benthic populations)
- Interference with traditional fisheries (physical, chemical and biological)
- Genetic interactions with wild stocks
- Transfers of diseases and parasites between cultured and wild stock

During 2001-2002 DFO created a Bay of Fundy Stakeholders Forum to address cross-sectoral issues around aquaculture development and other interests in the Bay of Fundy. The New Brunswick Department of Agriculture, Fisheries and Aquaculture (NBDAFA) indicated a willingness to consider such issues as environmental sustainability, cumulative capacity, and integrated management with respect to minimizing negative effects and promoting co-operation between stakeholders to allow expansion of the industry. Members of the salmon aquaculture industry desire continued growth in terms of locating some new sites and increased production on existing sites, the traditional fisheries industries are generally not supportive. They have expressed concern that expansion of the aquaculture industry could affect their livelihood through negative impacts on natural stocks of fish and invertebrates. Further research has been requested to address interactions between salmon aquaculture and traditional lobster, scallop, herring, urchin and clam fisheries.

Recent efforts by the salmon aquaculture industry in SWNB show a willingness to restructure to minimize environmental impacts, control the spread of disease and reduce negative interactions with other industries. Oceanographic circulation models and GIS-based information on resource and activity distribution are being used or are planned to be used for siting decisions within an integrated coastal zone management framework. Buffer zones between adjacent areas have been created by adjustments in licensing. New sites have not been approved where this would increase the number of farms in a restricted area. Technical issues of fish disease management are currently being addressed through joint Canada/US meetings on ISA management in New Brunswick and Maine with interactions between the New Brunswick Fish Health Unit Technical Committee and the equivalent in Maine. A National aquatic animal health program is also being developed in Canada and the US to exchange technical information.

A general aim of DFO Science Branch research throughout the period of development of the industry in SWNB has been to provide advice to help the industry grow while at the same time minimizing potentially negative environmental effects. However, in the past it has proven difficult to obtain information from the industry for modelling purposes. Data on stock size, feeding rates and food conversion efficiencies are needed to predict how environmental conditions may change with expansion of the industry. Environmental data on other anthropogenic and natural sources of organic enrichment are also required to assess total discharges. Similarly, information on rates of application of therapeutants are needed to apply research results on the fate and effects of specific chemicals used in aquaculture and to provide information on uptake and effects of potentially toxic organic and inorganic compounds in indigenous organisms. Although it is now available for some sites, in the past information on chemical usage patterns and application rates has not been readily available. As information for these critical variables becomes available, it will be possible to provide more accurate quantitative assessments of environmental interactions and sustainable stocking levels. Minimizing potentially negative environmental impacts and interactions with other fisheries will benefit both aquaculture and harvest fisheries industries.

PURPOSE

This paper presents calculations with data currently available to determine if a sustainable holding capacity of Atlantic salmon in SWNB with acceptable changes to the environment can be recommended. The question has been asked: "Is there a scientific basis for determining holding capacity (stocking density) that over the long-term would allow sustained production while at the same time minimizing negative environmental effects and impacts on traditional fisheries?" Historic and current stocking levels are examined to determine if it is possible to quantify potential effects of salmon aquaculture on some of the issues listed above. Although SWNB is the focus, data from Cobscook Bay, ME has been included to make calculations regionally complete. The document provides a scientific basis for determining holding capacity, offers advice regarding the environmental impacts of the industry as it is currently structured and recommends measures that should be taken to ensure sustainability of salmon aquaculture in the region.

CONTRIBUTING DFO STAFF

Les Burridge (MESD), Blythe Chang (AD), Michael Dowd (OSD), Barry Hargrave (MESD), Kats Haya (MESD), Peter Lawton (IFD), Tim Milligan (MESD), Fred Page (OSD), Shawn Robinson (AD), Rob Stephenson (MFD), Peter Strain (MESD), Dave Wildish (MESD), and Phil Yeats (MESD) contributed to the paper. John Sowles (State of Maine Department of Marine Resources)(DMR) provided data and information from Cobscook Bay, ME. Although none of the DFO Science staff involved in preparing this report are experts on fish health, input and comments on disease issues were provided by A. McVicar and J. Stewart who are recognized experts in this field. Aspects of fish health and disease management are central to a full description of environmental conditions affected by aquaculture. These issues are currently being discussed in bilateral (New Brunswick and Maine) Canada/US meetings. Paul Keizer, Alasdair McVicar, John Sowles and Jim Stewart commented on drafts of the manuscript.

HISTORY OF GROWTH IN SALMON AQUACULTURE IN SWNB

The first successful salmon farm in southwestern New Brunswick was an experimental project involving DFO, the Province of New Brunswick and private industry. This farm, located at Lords Cove, Deer Island, started in 1978 and produced its first harvest (6 t) in 1979. The second salmon farm was located at Dark Harbour, Grand Manan, but most of the expansion of the industry in the 1980s was in the Letang Inlet area of the mainland coast and around Deer and Campobello Islands. In the 1990s, more farms began operating in Passamaquoddy Bay and Grand Manan. More recently, new sites have been established in southern Grand Manan Island and in the Maces Bay area along the mainland coast. There are proposals for new sites further to the east toward Saint John. In addition to expansion to new sites, the industry has grown through increased production at the existing sites.

Growth of the industry has been quite rapid, despite problems such as outbreaks of sea lice (starting 1994) and infectious diseases such as Bacterial Kidney Disease (BKD), Furnunculosis, Vibiosis and Infectious Salmon Anemia (ISA) and a steady drop in prices since the late 1980s. It is interesting to note that a report prepared for DFO by Price Waterhouse (1990) predicted that by the year 2000, production from New Brunswick salmon farms could reach 8,000 to 12,000 tons. By 2002, there were 93 operating farms, with an estimated total of almost 20 million fish in sea cages (based on NBDAFA Approved Production Levels) (APLs)(Table 1). Estimated potential production and value in 2002 was 40,000 tons worth $230 million.

It is important to note that while there have been rapid increases in both production and numbers of approved sites over the past 20 years (Fig. 1), unlike numbers of farms, annual production site^{-1} has not increased continuously (Fig. 2A). The comparison is based on numbers of farms in any given year and reported harvest (production) the following year, reflecting the fact that smolts added to a new site are harvested the following year. Four periods of increasing productivity based on year-to-year changes in site specific production (1982-83, 1985-89, 1993-94, and 1997-98) have been followed by three or four years of decreased yield site^{-1} (Fig. 2B). The largest decrease occurred in 1997-98 as a result of

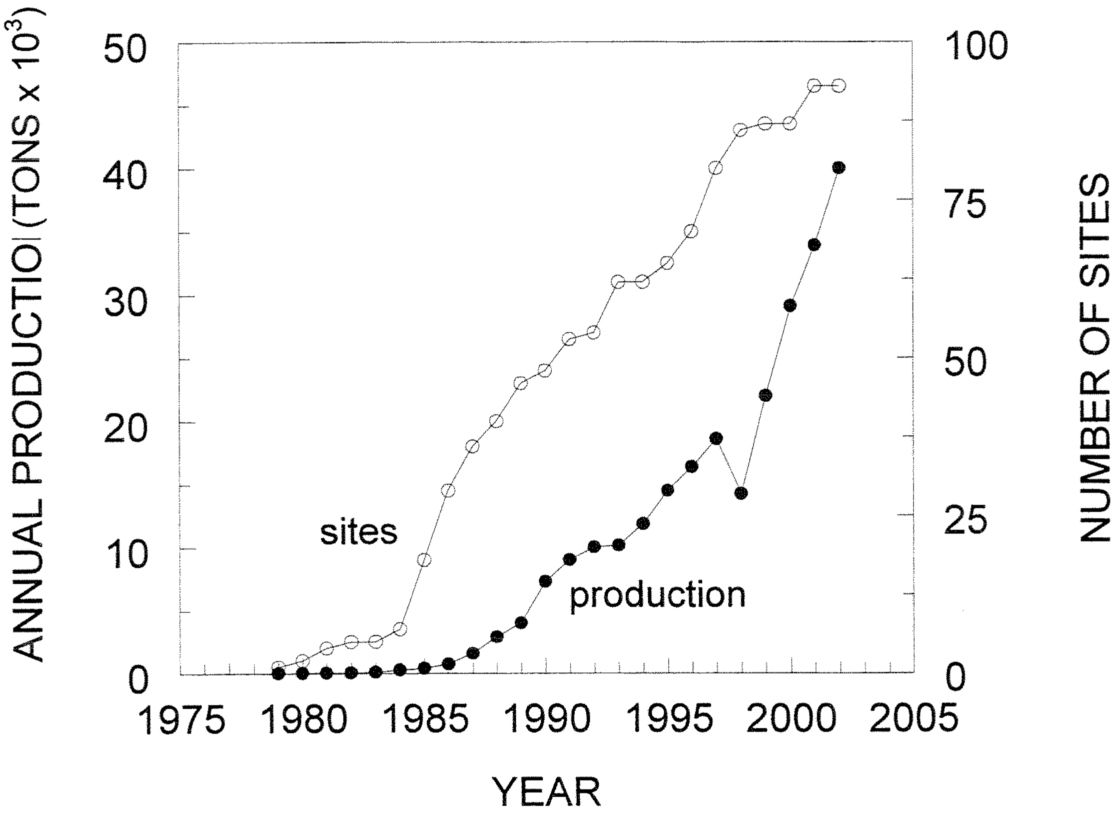

Fig.1. Growth of the salmon aquaculture industry in the Western Isles Region, southwestern New Brunswick, Bay of Fundy from its inception in 1979 to 2002 as annual production (thousands of tons) (solid circles) and numbers of sites (all approved operating and non-operating grow-out sites) (open circles). All values are for the years reported (number of approved sites in any given year is plotted with reported harvest biomass). Some sites are fallowed for all or part of a year. Newly approved sites in were not included until the year operations started. Historic production values are from the DFO Statistical Services Unit web page. The number of licensed sites is from data provided by the New Brunswick Department of Agriculture, Fisheries and Aquaculture. Data for production in 2002 represent 'potential production' from a NBDAFA fact sheet published in 2002. Data compiled by B. Chang based on NBDAFA information.

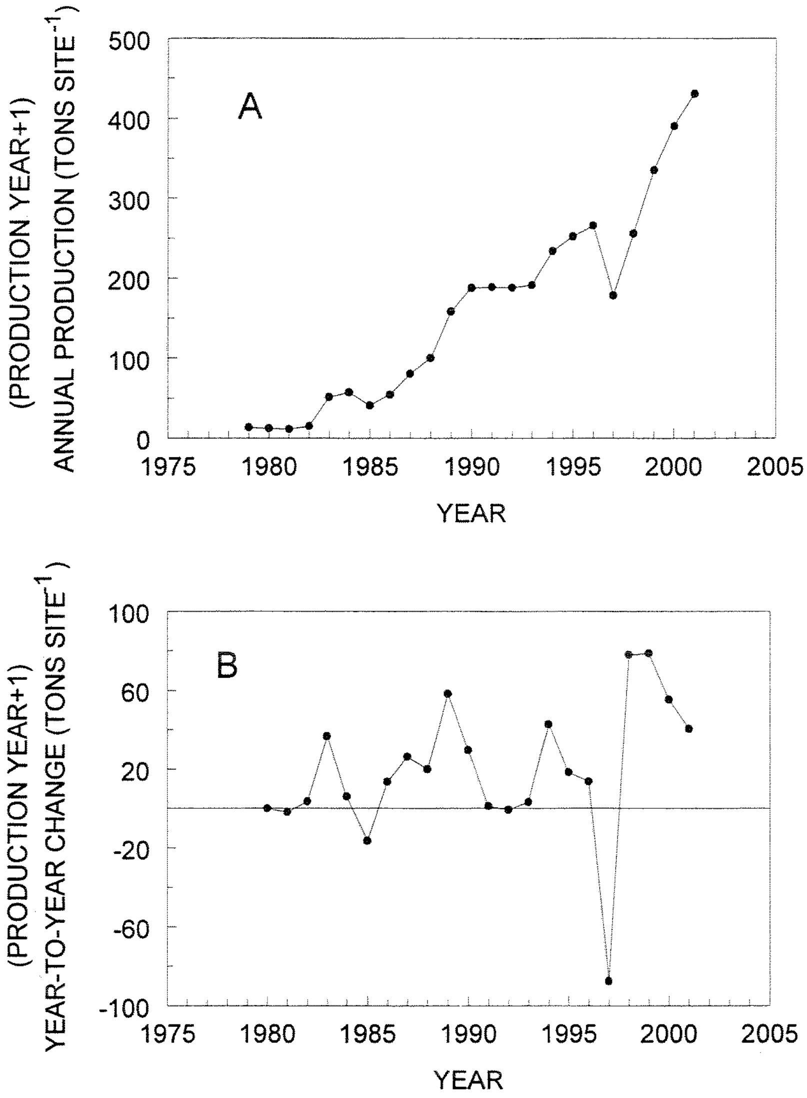

Fig. 2. (A) Annual production site^{-1} in the salmon aquaculture industry in the Western Isles Region, southwestern Bay of Fundy from 1979 to 2002 derived from data in Fig. 1. Production for each year was divided by the total number of farm sites in the previous year to calculate annual harvest as tons site^{-1}. (B) Data from panel (A) expressed as year-to-year change in site specific production.

effects of disease (primarily ISA). The decrease reflects government-imposed regulations that reduced stocking levels following ISA infections at some farms. Total production and site-specific production are currently at historic maxima reflecting continuous increases in APLs, however since 1999 year-to-year changes in production site^{-1} show a downward trend repeating the pattern seen in the mid-1980's and 1990's.

Changes in annual production expressed either as total and site specific harvest reflect many variables affecting growth of the industry. Recently, accessibility to new sites has been a major factor limiting expansion with only seven new sites added since 1998 (Fig. 1). The outbreak of ISA clearly resulted in decreased production in 1997 due to management action to reduce stocking density to limit the spread of the disease. However, between 1998 and 2002 annual production increased from 14 x 10^3 tons to 40 x 10^3 tons. The maximum stocking density recommended by NBDAFA for a site salmon aquaculture site is 18 kg m^{-3}. and we assume that the density of fish per cage does not exceed this maximum specified by the Provincial guideline Therefore recent increases in production must be achieved by increasing the number or sizes of stocked pens site^{-1}. The trend towards more fish on a site has been associated with an industry-wide move to use larger cages and the average total number of fish on licensed sites has increased through use of larger cage size. A small change in farm numbers has also occurred recently by deleting one site and merging it with another. Thus the total number of fish stocked was unchanged despite the deletion of one farm.

Expansion of production through increasing cage size and approved numbers of fish gives an apparent cost advantage due to the economics of scale. However, underlying the overall rapid growth in the industry during the past 20 years are periods when year-to-year changes show decreased production following a peak (Fig. 2B). Although the ISA virus was the major cause for reduced production in 1996-97, fish were also infected with BKD and Furunculosis (J. Stewart, personal communication). Outbreaks of BKD in New Brunswick in the last decade have been negligible and Furunculosis has been effectively controlled in salmon culture worldwide since the early 1990s by use of vaccines (A. McVicar, personal communication). Sea lice infestations have also occurred in SWNB in recent years. Although data is not available to assess the extent (number of farms affected) nor economic impacts, experience elsewhere (Norway, Scotland and Ireland) would indicate that parasites, like disease, affect fish growth and production negatively. Pathogenic effects associated with all infections affect fish performance and therefore production.

BAY MANAGEMENT AREAS

The Province of New Brunswick (NBDAFA) and the industry have recognized that management of fish health issues such as sea lice, bacterial and viral pathogens requires co-ordination among adjacent farms. Beginning in 1998, the salmon aquaculture industry and NBDAFA began considering a spatial re-organization of farm sites to improve disease management, increase production efficiencies, and reduce negative interactions with traditional fisheries. Recent changes in structure within the industry involved moving from Multi- to Single Year Class rearing in specific areas to minimize the spread of disease and ensure a period of fallowing. The concept of Bay Management Areas (BMAs), originally developed in Europe, was introduced in SWNB during the late 1990s as a management strategy to allow expansion while reducing the likelihood of disease transmission between sites and improve economic efficiency to remain competitive in the market place. This has become part of the Province's "Bay of Fundy Marine Aquaculture Site Allocation Policy" released in October 2000. In nearby Maine, single year-class policy was adopted in 2002 with Cobscook Bay divided into two BMAs.

Twenty-one BMAs were initially defined by NBDAFA, encompassing all marine grow-out sites approved in SWNB in 2001 (Fig. 3). The number increased to 22 in 2002. Farm leases are designated as either 'odd' or 'even' year classes. Smolts are usually introduced in the spring in odd years at odd year class sites, but in some cases stocking occurs in the fall. Fall-stocked smolts show minimal growth during their first winter and they are usually included with the year-class placed in the following spring. This distinction has not been made in calculations reported below where APLs in odd years are used to calculate biomass in September of the following even year (the second year of growth) and vise versa for odd years.

The separation of year classes is intended to minimize disease transmission when multi-year classes are held together within the same growing area or hydrographic mixing unit (Stewart 1998). However, the application of Single Year Class rearing on an odd/even year basis in SWNB has created a management regime of small BMAs where fish of mixed year classes are held in close proximity within some hydrographic areas. This is opposite of recommendations by Stewart (1998). BMAs should be sufficiently large to ensure separation of year classes and to avoid placing smolts near market-year fish to minimize disease transmission between year classes. Thus, as far as possible, all farms within a hydrographic region should be on the same year class schedule.

The aquaculture industry's willingness for restructuring is reflected in the adoption of a Single Year Class approach proposed by DFO (Stewart 1998). However, this change has been applied to the small area BMAs shown in Fig. 3 in such as way as to lead to an imbalance in APLs in odd and even years. This has exacerbated already significant environmental impacts of oxygen stress, nutrient and organic matter loading in some areas as discussed below. While sites with smolts in any one BMA are not located next to those with market-year fish, the odd/even imbalance across BMAs, when they are aggregated into larger hydrographic regions, maximizes the potential for disease and parasite transmission due to the much greater biomass present in alternate years. The implications of the imbalance for negative impacts on environmental variables are discussed in Appendices A and B.

Boundaries of existing BMAs are currently under review by NBDAFA and ISA management plans have recommended that the total number of farms in some areas be reduced. There is also a planned review of the "exclusion areas" and "controlled growth areas" established in the NBDAFA policy document of 2000. There is recognition within the industry that over-production in some bays may have been a factor in the spread of disease. As a result, in 1998 following the ISA outbreak, two farms were removed from Lime Kiln Bay when the owners were granted new sites elsewhere. Also, as mentioned above, salmon

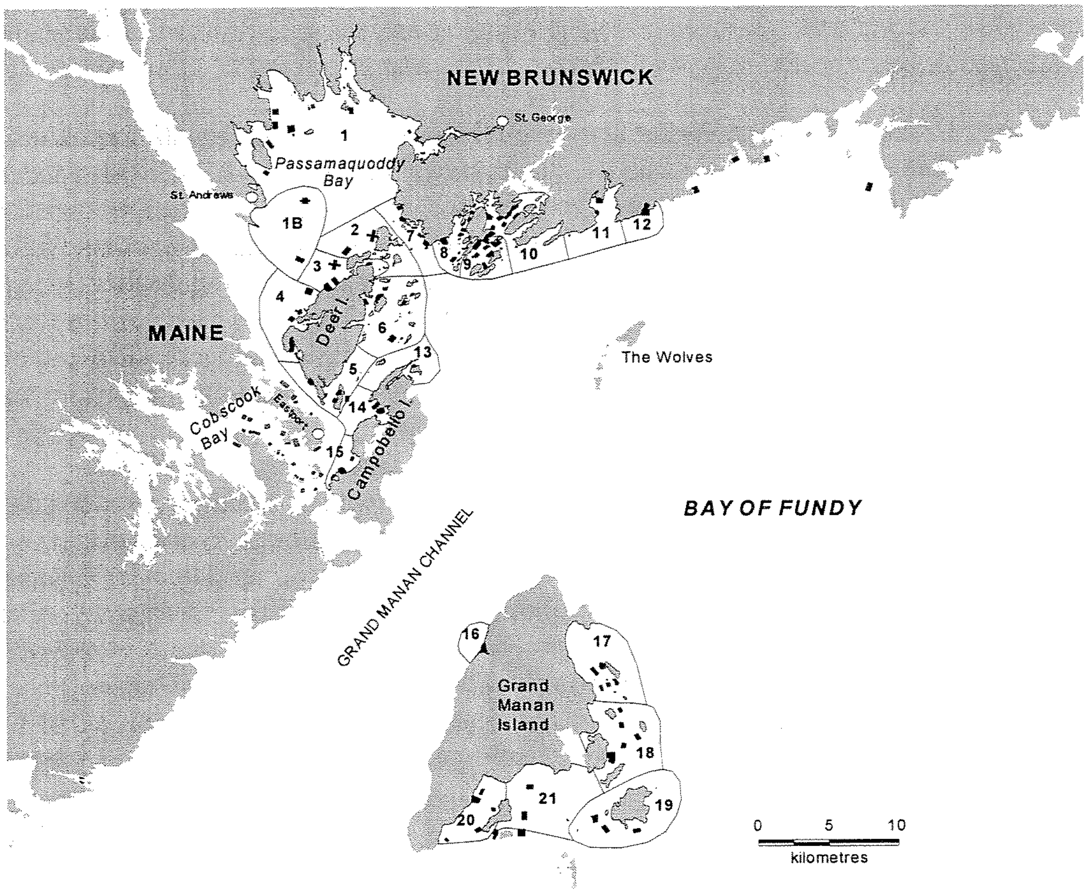

Fig. 3. Twenty two Bay Management Areas in 2002 (redrawn from New Brunswick DAFA map). There were 21 BMAs in 2001. A new subdivision (1B) was created in southern Passamaquoddy Bay in 2002.

have been permanently removed from two farm sites in northern Deer Island (BMA 2, Fig. 3) in an attempt to create a buffer zone between The Letang area and Deer Island.

Disease issues, particularly ISA, have prompted the restructuring and the desire by the industry to move to fewer BMAs with effective buffer zones. The provincial government is also attempting to accommodate traditional fishery concerns as part of the spatial re-distribution. Re-organization to fewer, but larger, farms with increasing distances between sites are intended to improve efficiencies, husbandry, bio-security, and reduce vessel traffic. There is also the assumption that negative environmental impacts and interactions with traditional fisheries can be reduced through re-arrangement of BMAs. However, one consequence of the trend to larger farm sites with more cages and more fish, is that no matter what the distribution pattern among BMAs, when disease or parasitic infections occur, the risk of mass mortalities is increased.

As discussed in the Appendices, areas where one-day tidal excursions are of limited extent are most vulnerable to potential problems associated with oxygen depletion and hyper-nutrification. Farms, particularly large ones, should not be located in areas with poor circulation. Also, the use of BMAs or other management strategies that does not reduce the overall number of fish in areas of restricted tidal exchange offers no protection against the widespread distribution of waste products, reduced oxygen levels or transfer of infectious agents. High levels of biomass held in a tidally restricted area may lead to oxygen depletion and increased accumulation of wastes. If this results in increased stress fish may be more vulnerable to disease and parasitic infections. Potential interactions between salmon aquaculture and traditional fisheries may also become more contentious when salmon farms are numerous in a small area. Coastal fisheries for species such as lobster and crab are often located in specific areas with well-define boundaries. Conflicts may arise when new salmon aquaculture sites remove access to an area traditionally used for these harvest fisheries.

Circulation models and water mass physical characteristics in SWNB suggest that there are regions where the probability of mixing within a region is greater than between adjacent areas (Fig. 4). Following the DFO Ocean Management Branch terminology, these can be considered as units within a Coastal Management Area. We use the term **Coastal Management Regions** (CMRs) to identify these hydrographic sub-regions. Similar areas were recommended as functional BMAs by DFO when advice on these issues was requested by NBDAFA in 1998.

The CMRs are much larger in area than the BMAs specified by NBDAFA (Fig. 3). Average water residence time can be estimated within each CMR designated as Grand Manan (1, 2), Campobello and Deer Islands (3, 4, 5), Passamaquoddy Bay (6), Letang/Letete Passage (7 subdivided by inlet), and Other Areas (Beaver Harbour, Foleys Cove and Maces Bay to Seeleys Cove) and Cobscook Bay ME (Fig. 4). Farms were grouped to calculate total Approved Production Limits (APLs) for odd and even years in each CMR (Table 1). The Letang/Letete area (CMR 7) was divided by inlet into sub-regions due to the high density of farms in a small area. No attempt was made to make calculations for sub-areas within Cobscook Bay which was considered as one region. Areas and volumes for Cobscook Bay were taken from Brooks et al. (1999) and Larsen et al. (2003).

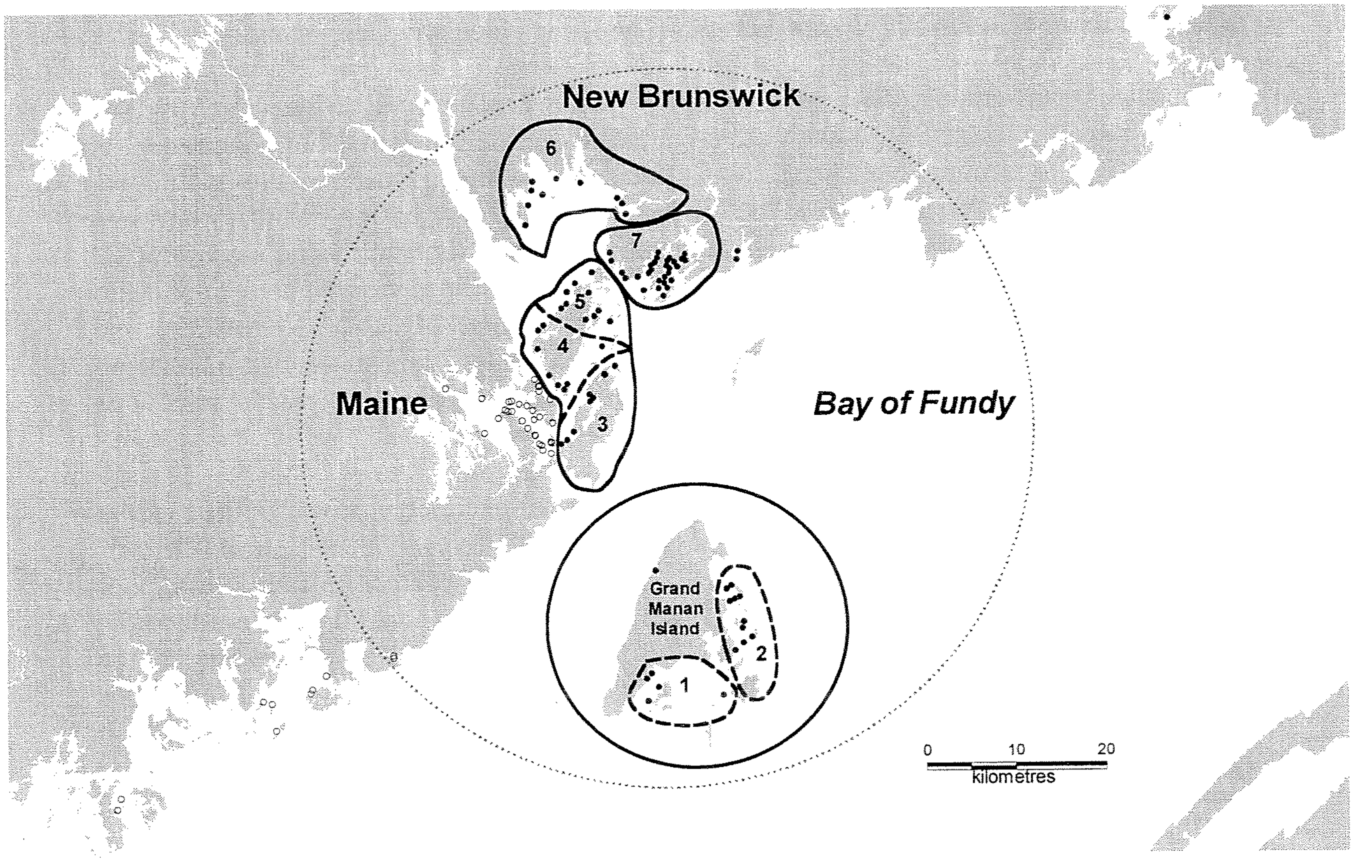

Fig. 4. Oceanographic/hydrographic areas (Coastal Management Regions) (CMRs) based on water mass mixing and residence time characteristics in the Western Isles area, Bay of Fundy. A similar map was proposed in 1998 by DFO Science Branch to assist the provincial government and aquaculture industry in identifying Bay Management Areas (BMAs). A tidal current model and estimates for mean water mass residence time were used to identify numbered areas where mixing within a region is greater than between regions. Solid heavy lines indicate that the water mass is somewhat isolated, heavy dotted lines indicate that there is a potential for limited exchange and the light dotted lines indicate the overall mixing area. The CMRs regions incorporate 22 smaller BMAs currently used by NBDAFA for management purposes (Fig. 3). Solid dots indicate salmon farms licensed in 1998 in New Brunswick. Open circles are all historic licensed salmon farm sites in Cobscook Bay. Only 7 in the Outer Bay area were stocked in 2002.

Table 1. Number of licensed farms and Approved Production Limits (APL) (total numbers of fish) for odd and even year classes for salmon aquaculture sites in southwestern Bay of Fundy in 2002. APL data for 22 designated NBDAFA Bay Management Areas (Fig. 3) was grouped by numbered CMRs (oceanographic regions and sub-regions) shown in Fig. 4. Percent of total APL in each region was calculated for combined APL values for odd and even year classes. Data compiled by B. Chang based on NBDAFA information.

Region (sub-region) CMR	**Number of Sites (2002)**	**APL ($x10^6$)**		**Percent of Total**[1]
		odd	**even**	
Grand Manan				
1 (south)	11	3.19	0.22	17.2
2 (north)	11	-	2.55	12.9
Campobello/Deer Island				
3 (Campobello Island)	9	0.23	1.33	7.8
4 (Deer Island north)	10	-	2.80[2]	14.2
5 (Deer Island south)	11	0.64	1.34	10.0
N. Passamaquoddy Bay				
6	8	1.08	0.27	6.8
Letang/Letete				
7 (Lime Kiln Bay/Letang)	8	1.08	-	5.4
(Bliss Harbour)	7	1.42	-	7.2
(Back Bay)	8	1.32	-	6.7
(Letete Passage)[3]	4	0.30	0.34	3.2
Other Areas				
8 (Beaver Harbour, Maces Bay, Foleys Cove)	6	0.30	1.39	8.5
Cobscook Bay (Maine)[4]	26	1.50	1.50	NA
TOTAL (New Brunswick)	93	9.54	10.23	

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[1] Total APL for 22 BMAs designated in SWNB in 2002 by NBDAFA (19.77 x 10^6); [2] Does not include one haddock/cod site on Deer Island; [3] Includes areas within Letete Passage and Letang Harbour not encompassed by Lime Kiln Bay, Bliss Harbour and Back Bay; [4] Cobscook Bay figures reflect total leases issued. Thirteen are contained in each of two BMAs. Not all leases are active in any one year. In 2002, 4 leases were actively farmed and 7 were stocked in 2003. The APL is based on anticipated values for 2004 forward.

DISTRIBUTION OF SALMON STOCKING DENSITY IN DIFFERENT CMRs

Currently APLs for odd and even years in all areas in SWNB are approximately equal (9.54 and 10.23 x 10^6 smolts, respectively) but there is a discrepancy between years in some CMRs (Table 1). CMR 7 (sub-areas identified within Lime Kiln Bay/Letete Passage), for example, contains 22.5% of the total APL (combined odd and even years) but stocking in Lime Kiln Bay, Bliss Harbour and Back Bay only occurs in odd years. Similarly in CMRs 3, 4 and 5 (Campobello/Deer Island) with 32% of the total, the number stocked in even years is approximately 6.3 times higher than in odd years. Thus, overall production for CMRs representing approximately half of the total APLs in the SWNB region is not balanced with large odd/even year differences in biomass. The result of how Single Year Class stocking has been applied has led to smolts being located next to second year fish in adjacent CMRs 1 and 2 (Grand Manan Island) and 5 and 7 (northern Deer Island and Letang/Letete) (Fig. 4).

Information on current (2002) salmon stocking densities in odd and even years in Cobscook Bay, ME was provided by John Sowles. Salmon aquaculture has been restricted from the inner part of the bay since the late 1980's due to concerns over nutrient carrying capacity. Of the total number of leases located in Outer and Middle Cobscook Bay, only 14 have ever been stocked and the number of active sites was severely reduced as a result of ISA during the late 1990's. During 2001, four farm sites were populated with smolts and in 2002 the number was increased to 7. All active farms (3 stocked in odd years, 4 stocked in even years) are located in Outer Cobscook Bay. Current stocking density is approximately 60 to 75% of historic levels.

SALMON BIOMASS DISTRIBUTION

Mass balance calculations presented in Appendix A were used to assess impacts of salmon aquaculture on dissolved oxygen, nutrients, and organic carbon in SWNB in relation to current (2002) numbers of fish in odd/even years. If potentially negative environmental effects are related to numbers of fish, then the relative magnitude of impacts might be determined by expressing biomass area^{-1} and volume^{-1} in each CMR. Although other factors such as water residence time affect the interpretation, the likelihood of negative environmental effects might be expected to be reduced in regions with a large area and volume but with a small fish biomass. Although numbers used are inherently approximate due to lack of information on actual stocking densities and assumptions and uncertainties in estimates for material fluxes, the relative magnitude for values in different areas is illustrated by the calculations. Waste discharges are assumed to be uniformly distributed into the total area and volume of each CMR. To the extent that this is not true, local impacts will be greater than predicted.

Salmon biomass scaled by area and volume in different CMRs varies widely with large odd/even year differences (Table 2). Highest area- and volume-specific values occur in the Letang/Letete CMR where the greatest between-year differences are also found. Area-specific biomass in even years in Lime Kiln Bay, Bliss Harbour and Back Bay is an order-of-magnitude higher than in odd years. The same pattern occurs in Grand Manan, Campobello/Deer Islands, Passamaquoddy Bay and Other Area CMRs, but the odd/even year differences are less dramatic (e.g. a six-fold difference the Campobello/Deer Island CMR). This is the same magnitude of between-year differences as in the Letang sub-areas, but the absolute biomass level is lower in the Campobello/Deer Islands CMR and hence would be expected to reduce odd/even year differences in environmental effects. Because Cobscook Bay was depopulated in 2002, present standing stock is a small fraction of what it was pre-2001. Annual stocking biomass for Cobscook Bay (Table 2) are projected estimates based on an even distribution of leases across two BMAs.

The extremely high salmon biomass levels on a whole-inlet basis in Lime Kiln Bay, Bliss Harbour and Back Bay (>1 kg m^{-2} in even years, an order-of-magnitude less in odd years) can be given ecological context by comparison with the sizes of wild fish stocks and natural benthic communities in SWNB. This does not mean that currently high salmon biomass is displacing natural stocks, it simply allows the magnitude of cultured biomass to be considered in relation to natural populations of fish and invertebrates.

Historic catches by weir and seine fisheries in Bliss Harbour, for example, show that prior to salmon aquaculture, schools of herring commonly moved through the area between July and October (R. Stephenson , pers. comm.). Wildish et al. (1990) estimated that herring schools in the Letang/Letete region could have an average size of 557 MT (1 MT = 1000 kg). Two year old herring weigh approximately 50 g (R. Stephenson, pers. comm.) and thus an average sized school would weigh 10^7 g. If a school this size entered Bliss Harbour (4.06 km^2, 35.6 x 10^6 m^3) the biomass would be equivalent to 2.5 g m^{-2} and 0.3 g m^{-3} on a whole-inlet basis The values are two orders of-magnitude less than the biomass of salmon in Bliss Harbour in even years (Table 2). Applying the same calculation to the entire Letang/Letete CMR (37.2 km^2) reduces relative values of herring to salmon biomass for the larger region by ten fold. It must also be emphasized that, unlike farmed salmon, migratory herring are not permanent, hence the impact of their biomass on other ecosystem components is transitory.

Benthic macrofauna biomass distribution has been measured in various inshore and offshore locations throughout SWNB and the Bay of Fundy over the past 25 years (Wildish et al. 1977, Wildish 1983, Wildish and Peer 1983, Lim and Gratto 1992, Pohle et al 1994, 2001, Pohle and Frost 1997, Wildish et al. 2002). Macrofauna biomass is highly variable (5 to 1500 g wet weight m^{-2}) and determined by sediment type and location. In general, for similar benthic habitats, values of benthic infauna dominated by polychaetes are higher inshore than offshore with biomass usually <100 g m^{-2}. Higher biomass of suspension feeding molluscs (*Modiolus modiolus*) (> 1 kg m^{-2}) occurs in dense reefs of in central regions of the lower Bay of Fundy, but these areas are restricted in size. Salmon biomass in most CMRs is of a similar magnitude to that observed for benthic infauna in soft sediments (range 8 to 375 g m^{-2}). Salmon biomass in the three Letang sub-regions in even years is comparable to maximum values in offshore mussel reefs (Table 2).

CHEMICALS IN AQUACULTURE

A summary of compounds and potential environmental impacts of chemicals used in the Canadian Aquaculture industry was provided in Cantox (2001), Haya et al. (2001) and Fisheries and Oceans Canada (2003). In general access to information on chemicals used in the industry is restricted and dependent on the type of compound. For example, data on

Table 2. Comparison of salmon biomass in SWNB in odd and even years based on APLs (derived from numbers of smolts indicated in Table 1) calculated for the total area^{-1} and

volume^{-1} in different CMRs (shown by number in Fig. 4). Odd year APLs were used to calculate biomass in even years and vise versa. Biomass was calculated for mid-September assuming that fish weigh 800 g in their first year and 4.9 kg in the second year of growth (from Appendix A).

Area (CMR)[1]	Biomass/Area (g m^{-2})		Biomass/Volume (g m^{-3})	
	Odd	Even	Odd	Even
Grand Manan Isl. (1,2)	78.9	90.9	3.6	4.2
Campobello/Deer Isl. (3,4,5)	155.8	24.8	7.2	1.1
N. Passamaquoddy Bay (6)	7.7	30.7	0.4	1.4
Letang/Letete (7)	44.8	542.7	4.1	49.8
Lime Kiln Bay	440.8	2700.0	78.3	479.3
Bliss Harbour	279.8	1713.8	31.9	195.6
Back Bay	224.7	1376.2	49.7	304.7
Letete Passage	62.9	55.5	4.9	4.4
Other Areas (8)	184.1	39.7	16.8	3.6
Cobscook Bay ME	64.5	64.5	13.6	13.6

[1] Biomass per area and volume for each CMR and sub-region is calculated on the basis of total surface area and water volume at mid-tide

antibiotic prescriptions is not routinely released.

The potential for inlet-wide dispersion of chemical contaminants may be greatest for soluble compounds since particle-bound substances are more likely to settle and accumulate in sediments if currents are low. Soluble compounds are also generally more bioavailable and hence of greater concern than chemicals that bind to particulate matter. While the mass balance models discussed in Appendices may be used to estimate potential negative environmental impacts of excessive salmon biomass in some areas, we are not as yet in a position to estimate how chemical contaminants in feed or used as therapeutants affect indigenous organisms. It is difficult to establish links between the presence of compounds and aquaculture activity or to establish cause-effect relationships.

Soluble compounds (such as Azamethiphos) used for control of parasites have potential for widespread dispersion. Other chemicals such as antibiotics (oxytetracycline, Tribrissen and Florfenicol) and zinc, present in feed, are more likely to be deposited under and close to farm sites. Although the general use of antibiotics in salmon aquaculture was greatly reduced during the 1990s from previous levels, oxytetracycline (OTC) continues to be prescribed in SWNB (Cantox 2001). Although actual values are difficult to obtain, an estimated 42 g of OTC 1000^{-1} fish was used for salmon production in Atlantic Canada in 1999. In Maine, only OTC and emamectin benzoate are used to treat bacterial infections and parasites, respectively, and usage data is available on request (State of Maine, DMR). Similar information is not publically available in Canada.

Zinc is a dietary supplement and most farms use copper-based antifoulants. As discussed in Appendix D, anomalous zinc and copper concentrations (above those expected based on background levels in non-impacted areas) in sediments have been used to indicate the horizontal extent to which particulate matter released from salmon farms sites can be detected in SWNB (Yeats et al. 2002). Organic compounds such as PCBs, PAHs, and chlorinated pesticides (e.g. DDE) may be present in lipid-rich feed, and these compounds have also been measured in sediments in SWNB. Observations in 1998 (Haya et al. 2002) indicated that concentrations of PCBs were higher under cages than 25 m away, however total concentrations of PAHs increased with distance from a farm site. A different composition of the PAH mixture in sediments vs. that in fish oil and feed indicated a non-aquaculture source for these compounds. It must be emphasized that concentrations of all of these chemicals were within acceptable ranges specified as Canadian guidelines (CCME 1999).

Cumulative effects of these chemical pollutants have not been detected on an inlet-wide scale in SWNB. A scaling exercise with a water-borne pesticide (Salmosan®, Azamethiphos) coupled with lethality data from laboratory experiments with lobsters indicated that single anti sea-louse (bath) treatments are unlikely to result in death of lobsters (Burridge et al. 1999, Haya et al. 2002). The work did not take into account the probability of cumulative effects or the risk of sublethal responses occurring in indigenous species. To date work on the presence, fate and effects of chemicals of aquaculture origin is limited to a few targeted studies. Data are available regarding the presence of trace metals, a limited number of organic compounds and the presence and distribution of antibiotic residues in sediments. Although studies have been conducted over limited spatial scales, metal composition (iron, zinc and copper) and other elements (manganese and calcium) were elevated in sea urchins at least 75 m away from a cage site (Chou et al. 2003). Since inorganic and organic compounds such as trace metals, and chlorinated and aromatic hydrocarbons can have multiple sources (for example, from municipal sewage and long range atmospheric input) it is often difficult to attribute concentrations measured at a given location to one source, such as aquaculture.

SEDIMENT VARIABLES

Data summarized in Appendix D show that differences in concentrations of some metals (copper, zinc) in sediment can be identified between aquaculture and reference sites. As discussed in the Appendix flocculation and increased sedimentation rates of particulate matter provide a rapid transport method for removing particles from the water column to the sediments. Aggregation is increased when organic matter concentrations are high as occurs in the vicinity of salmon farms. The organic coatings on particles also serve to bind surface-active compounds such as trace metals. As mentioned above, although enhanced concentrations of zinc and copper have been measured in subtidal and intertidal sediments where salmon farms are most concentrated (Appendix D, Figs. D.3 and D.4), levels are below the probable effects concentrations for toxicity established as Canadian guidelines.

RECOMMENDATIONS

Data in Table 2 show that levels of salmon biomass expressed on an inlet-wide basis in some sub-areas within CMR 7 are very high relative to values in other regions. Stocking densities within Lime Kiln Bay, Bliss Harbour and Back Bay are large enough that measurable changes in dissolved oxygen, nutrients, and particulate carbon deposition have been predicted to occur (Appendix A). Seasonal oxygen depletion occurs naturally throughout SWNB (Appendix C, Fig. C.1) and increased BOD due to aquaculture is additive. In some areas of SWNB during mid- to late summer there is an on-going need to provide aeration at sites where oxygen supply is insufficient to meet the demands of salmon and to maintain concentrations at optimal levels (>6 mg L^{-1}) as discussed in Appendix C. APLs in The Letang area, where maximum biomass per area and volume occurs, would have to be reduced by ~90% to be comparable to stocking densities in other CMRs.

Previous studies of oxygen, nitrogen and carbon budgets in Lime Kiln Bay and the Letang region have reached similar conclusions with respect to environmental effects of over-stocking. Wildish et al. (1990) used data derived from published literature to calculate that over 10 h at night during summer with the APL at the time (320,000 market-size fish) salmon respiration would exceed the sum of water column and sediment oxygen consumption for the whole of Lime Kiln Bay by 12%. The same calculations two years later (Hargrave et al. 1992) estimated that oxygen consumed by salmon and their particulate wastes could range from 39 to 50% of total inlet oxygen uptake, similar to values in Table B.3 (24 to 47%). Calculations using APLs in different areas of the Letang system in 2000, assuming an equal mix of one and two year old stock, showed that respiration due to salmon (excluding BOD due to waste released as unconsumed feed and faeces) varied from 9 to 23% of total demand (Phillips and Hargrave 2002). Ammonia release in Lime Kiln Bay in 1992 was estimated to be >60% of total nitrogen regeneration and particulate carbon 15 to 22% of production in the inlet systems. Values estimated for 2002 are comparable (nitrogen - 54 to 79%; carbon - 33 to 59%) (Table B.3).

The mass balance calculations reported in Strain et al. (1995) and summarized with updated data in Table B.1 show how BOD, nitrogen and carbon release attributable to salmon has increased over the past decade. Today inputs to the Letang system due to salmon with maximum biomass in even years based on annual averages exceed all other sources by 2 to 3 times for BOD and nitrogen and 1.2 times for carbon. Maximum discharges in September are approximately 2.3 times higher than the annual average values (Appendix A).

Strain et al. (1995) pointed out that box model calculations are a useful way for assessing potential negative effects of eutrophication due to aquaculture when uncertainties make direct measurements difficult or impossible. It must be emphasized that prediction of worst-case input estimates, as used here for September when water temperatures and biomass levels are high, provide a precautionary approach for calculating an upper limit of stocking levels above which negative impacts may occur. Despite the fact that estimates of flushing time, biomass, feeding levels and harvested production are poorly known, the data in Table 2 clearly indicates that three sub-areas within The Letang region have very high salmon biomass relative to other CMRs. These are also inlets where mass balance calculations show that cultured salmon in even years are responsible for a substantial (>20%) fraction of total oxygen consumption, and nutrient and organic carbon releases from anthropogenic and natural sources (Appendix B).

Reductions in salmon biomass in the Letang CMR may be possible by re-location of some existing licenses to new areas. Although sites to allow expansion of the industry have been difficult to find, new farms have recently been established in southern Grand Manan Island, Seeleys Cove and Maces Bay. There are also plans to convene a joint industry-government meeting within the next few months to consider the potential for offshore cage culture. Moving farms from embayments with restricted circulation and long residence times to well flushed areas (open embayments or offshore) could benefit the industry by providing a healthier growth environment for fish if adequate conditions of temperature and current speed can be met. This would also reduce further environmental deterioration that is certain to occur if high biomass levels in the three most adversely affected inlets are not lowered.

Until specific data on stocking levels, farm production and performance become available through co-operation between industry, provincial and federal agencies involved with the licensing and management of aquaculture in Canada, the precision of model calculations presented above and in Appendices will be limited. While the conclusions could be refined with more comprehensive and accurate data, values for areas and volumes and current APLs in various CMRs determine the distribution of biomass on an inlet-wide basis shown in Table 2. The overall conclusion is therefore considered to be relatively robust in predicting that negative environmental impacts on water column and sediment variables will continue to be observed in those areas with highest biomass. The potential for the spread of infectious diseases and parasites is also likely to be greatest in these areas. It must be re-emphasized that calculations in Appendix A and B are based on areal averages. Complete homogeneous mixing of waste products does not occur, and so localized impacts on both water column and sediment variables could be much greater. This is most likely to be in areas with maximum salmon biomass (Lime Kiln Bay, Bliss Harbour and Back Bay).

REFERENCES

Brooks, D.A., M.W. Baca and Y.-T. Lo. 1999. Tidal circulation and residence time in a macrotidal estuary: Cobscook Bay Maine. Est. Coastal and Sehlf Sci. 49: 647-665.

Burridge, L.E., K. Haya, V. Zitko and S.L. Waddy. 1999. The lethality of Salmosan (azamethiphos) to American lobster (*Homarus americanus*) larvae, postlarvae and adults. Ecotoxicol. Environ. Safety 43: 165-169.

CCME. 1999. Canadian environmental quality guidelines. Canadian Council of Ministers of the Environment, Winnipeg, Manitoba.

Cantox Environmental Inc. 2001. Scoring and ranking of chemicals used in regional aquaculture operations in Atlantic Canada based on ecological risk potential. Environment Canada, Environmental Protection Agency, Dartmouth, NS, 39 pp + appendices.

Chou, C.L., K. Haya, L. A. Paon and J. D. Moffatt. 2003. Metals in green sea urchin (*Strongylocentrotus droebrachiensis*) as an indicator of the near-field effects of chemical wastes from salmon aquaculture sites in New Brunswick, Canada. Bull. Environ. Contam. Toxicol, 70: 948-956.

Fisheries and Oceans Canada. 2003. A scientific review of the potential environmental effects of aquaculture in aquatic ecosystems. Vol. 1. Can. Tech. Rep. Fish. Aquat. Sci. 2450: ix + 131 p.

Hargrave, B.T., W.L. Silvert and P.D. Keizer. 1992. Partial budgets for ammonia, oxygen and particulate organic carbon in Letang Inlet: implications of salmonid aquaculture. DFO Workshop: The Assimilative Capacity of the Letang Inlet for salmonid aquaculture wastes, January 23, 1992, Bedford Institute of Oceanography, 4 p.

Haya, K., L. E. Burridge and B. D. Chang. 2001. Environmental impact of chemical wastes produced by the salmon aquaculture industry. ICES J. Mar. Sci. 58: 492-496.

Haya, K, L. Burridge, J. Hellou, C. Chou, S. Waddy, M. Ikonomou and G. Pohle. 2002. Environmental impacts of chemical wastes produced by the salmon aquaculture industry, p. 58-60. In B.T. Hargrave (Ed.), Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report. Can. Tech. Rep. Fish. Aquat. Sci. 2411: v+117 p.

Larsen, P.F., C.B. Erickson, S. Barker, J. Wright, R. Smith and R. Keyes. 2003. Use of cost effective remote sensing to map and measure marine intertidal habitats in support of ecosystem modelling efforts: Cobscook Bay, Maine. Manuscript in preparation.

Lim, S.S.L. and G.W. Gratto. 1992. The effects of organic enrichment from Atlantic salmon aquaculture sites on the benthic macrofaunal communities in the lower Bay of Fundy. Atlantic Reference Centre, Huntsman Marine Science Centre, St. Andrews, NB. 168 p.

Phillips, G.A. and B.T. Hargrave. 2002. Modelling ecosystem assimilative capacity: comparison of pelagic/benthic/salmon respiration in Letang Inlet (SWNB), p. 75-78. In B.T. Hargrave (Ed.), Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report. Can. Tech. Rep. Fish. Aquat. Sci. 2411: v + 117 p.

Pohle, G. and B. Frost. 1997. Establishment of standard benthic monitoring sites to assess long-term ecological modification and provide predictive sequence of benthic community succession in the inner Bay of Fundy, New Brunswick. Atlantic Reference Centre, Huntsman Marine Science Centre, St. Andrews, NB. 119 p.

Pohle, G., B. Frost and R. Findlay. 2001. Assessment of regional benthic impact of salmon mariculture within the Letang Inlet, Bay of Fundy. ICES J. Mar. Sci. 58: 417-426.

Pohle, G.W., S.S.L. Lim and B.R. Frost. 1994. Benthic monitoring of salmon aquaculture sites by the Huntsman Marine Science Centre: effects of organic enrichment on benthic macrofaunal communities in the lower Bay of Fundy, p. 92-100. In B.M. MacKinnon and M.D.B. Burt [eds.]. Proceedings of the Workshop on Ecological Monitoring and Research in the Coastal Environment of the Atlantic Maritime Ecozone. Environment Canada, Atlantic Region Occ. Rep. 4.

Price Waterhouse. 1990. Department of Fisheries and Oceans. Econ. Commer. Anal. Rep. 67.

Stewart, J.E. 1998. Sharing the waters: an evaluation of site fallowing, year class separation and distances between sites for fish health purposes on Atlantic salmon farms. Can. Tech. Rep. Fish. Aquat. Sci. 2218: vii + 56 p.

Strain, P.M., D.J. Wildish, and P.A. Yeats. 1995. The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet. Mar. Poll. Bull. 30: 253 - 261.

Wildish, D.J. 1983. Sublittoral sedimentary substrates, p. 140-155. In. M.L.H. Thomas (Ed.) Marine and Coastal Systems of the Quoddy region, New Brunswick. Can. Spec. Publ. Fish. Aquat. Sci. 64.

Wildish, D.J., H.M. Akagi and A. Martin. 2002. Seasonal patterns of biological and physical variables in sediments of Lime Kiln Bay during 2000-2001. Can. Tech. Rep. Fish. Aquat. Sci. 2447: iii + 46 p.

Wildish, D.J., J.L. Martin, R.W. Trites and A.M. Saulnier. 1990. A proposal for environmental research and monitoring of organic pollution caused by salmonid mariculture in the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 1724: iii + 24 p.

Wildish, D.J., and D.L. Peer. 1983. Tidal current speed and production of benthic macrofauna in the lower Bay of Fundy. Can. J. Fish. Aquat. Sci. 40: 309-321.

Wildish D.J., N.J. Poole and D.D. Kristmanson. 1977. Temporal changes in sublittoral macrofauna in L'Etang Inlet caused by sulfite pulp mill pollution. Fish. Mar. Ser. Tech. Rep. 718: 13 p.

Yeats, P.A. 2002. Trace metal tracers of fish farm wastes, p. 80-83. In B.T. Hargrave (Ed.), Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report. Can. Tech. Rep. Fish. Aquat. Sci. 2411: v + 117 p.

Appendix A: Oxygen demand and nutrient loads from finfish aquaculture in southwestern New Brunswick (P. Strain)

Introduction

Sea-cage salmon aquaculture discharges a number of waste types into the marine environment. Included in these wastes are nutrients (nitrogen and phosphorus) and organic matter. The organic wastes include waste feed and salmon faeces that are partially decomposed by bacteria. This decomposition process consumes oxygen, adds additional nutrients and lowers the oxygen content in both the water column and surface sediments. The respiration of the farmed fish further reduces the oxygen levels. In areas of intensive aquaculture, these waste streams can have significant impacts on the ecosystem: organic wastes may smother or otherwise alter benthic habitat, nutrients can stimulate growth of phytoplankton and/or attached algae, and reduced levels of dissolved oxygen can stress native organisms as well as the farmed fish. The buildup of nutrients, the reduction of dissolved oxygen levels and the stimulation of algal growth are all aspects of a process known as eutrophication.

A number of different approaches may be used to calculate the size of oxygen demand and nutrient discharges due to finfish aquaculture. One straightforward approach is to compare the inputs to the farms (salmon smolts, feed) with the outputs (mortalities, harvested fish). Unfortunately, this approach is not possible in Southwestern New Brunswick (SWNB) because the appropriate data on feed use and fish production is not available from the industry. It is worth noting that providing monthly reports of feed usage, mortalities and fish harvested to regulators is a statutory condition of licence for growers in some other jurisdictions (e.g. Maine: Sowles and Churchill, 2003). Another approach is to model the growth of the fish, calculating the nutrient production and oxygen use from fish respiration, waste feed and fish faeces, as the fish grow from smolt to harvest size. Silvert (1994) produced such a model for salmon aquaculture in SWNB that was used to estimate nutrient release and oxygen demand from salmon farms in the Letang Inlet in SWNB for 1992 (Strain et al., 1995).

A fish growth model is used here to estimate the oxygen demand and nutrient discharges from the salmon aquaculture industry in SWNB that reflect farming practices and the total licensed capacity of the industry in 2002. These estimates are then used to assess the potential for these discharges to influence natural conditions in large areas of the region (i.e. to have ‘far-field’ effects). The results show that aquaculture discharges into the Letete Passage/Back Bay/Bliss Harbour/Lime Kiln Bay/Letang area have the potential to change oxygen and nutrient concentrations and nutrient inputs in the whole inlet. Whether or not such concentration changes are measurable in a specific location depends on tidal mixing, water residence time and the ability of the biota to buffer such changes. The model calculations show that aquaculture activity in these areas may have already exceeded the carrying capacity of the receiving environment. Changes in other large areas of SWNB, including northern Passamaquoddy Bay, Deer/Campobello Islands, Grand Manan and the mainland from Beaver Harbour to Maces Bay, are minor. However, the results of this kind of impact analysis are very sensitive to the scale to which the analysis is applied. Even in a region which on average is affected only to a minor extent severe impacts may occur locally in places that are less well flushed and/or more intensively farmed than the region as a whole.

Methods

The estimates for nutrient inputs and oxygen demand presented here are based on an updated version of the Silvert (1994) model that reflects changes in farming practices, improved information on conditions at NB salmon farms, and improved values for some of the physiological parameters necessary to run the model:

- A modern feed conversion ratio (= weight of feed use / weight of fish produced) of 1.1 (B. Glebe, personal communication) is used in the model. This may be a somewhat optimistic representation of current feeding practices in the industry (F. Page, pers. comm.).
- Feed composition has been updated to reflect modern feeds.
- The model uses the average size of smolts placed in cages (90 g), the average grow-out period (21.25 months), and predicts the average harvest weight (4.9 kg) that match data from a 1995-97 survey of 20 SWNB salmon farms (Peterson et al., 2001).
- The values for a number of the physiological parameters, including the partitioning of nitrogen between growth and faeces, the proximate composition of whole salmon, the relative energy and protein demands of growth and respiration, have been updated based on new studies published since the previous calculations were done (Shearer et al., 1994; Einen et al., 1995; Storebakken at al., 1998; Thodesen et al., 1999).

The model is capable of predicting the carbon, nitrogen and phosphorus stored in fish tissue, and produced as waste in fish faeces, urine and waste feed. It also predicts the oxygen used in respiration, and in the decomposition of faeces and waste feed. Calculating the impacts of nutrients released and the oxygen consumed by the decomposition of waste feed and faeces requires an estimate of the fraction of these wastes that decompose in short periods. Oxygen consumption in the model is based on 50 % of these wastes being easily decomposed. This value is derived from a comparison between 5-day BOD (biological oxygen demand) and COD (chemical oxygen demand) data for similar wastes, and is consistent with direct measurements of oxygen uptake both by particles settling under fish cages and by sediments beneath fish cages (B. Hargrave, personal communication).

It is difficult to assess the precision of the estimates produced by the model. More detailed data on feed use, fish harvest weights, harvest times, etc. from the industry would make more systematic validation of these models much simpler. In addition, a number of factors have not been included in the model. Waste loads may be overestimated by as much as 10 % because fish losses through mortality and escapes are not considered in the model; on the other hand, waste loads may be underestimated by a similar amount because anecdotal reports suggest that only the most efficient farms are achieving FCR's as low as 1.1 (personal communications, F. Page). However, the results are consistent with calculations based on other approaches for similar areas (eg Cobscook Bay, Maine: Sowles and Churchill, 2003), and probably predict the waste loads to within 30 %.

Results and Discussion

Table A.1 summarizes the outputs of the fish growth model, listing total O_2 consumed, and the total discharges of carbon, nitrogen and phosphorus to the water column and sediments. These waste discharges are listed as totals for the entire grow-out period, per ton of fish produced and as maximum daily discharges per 1000 fish for first, second or third year farm sites. 'Third' year sites are those with mature fish still on site in January of the second calendar year following introduction of smolts. Water temperatures and fish metabolism combine to produce these maximum daily discharges in September for first and second year sites. Average daily discharges (averaged over the entire calendar year) for first, second and third year sites may be determined by dividing the values in Table A.1 by 2.7, 2.3 and 14.9 respectively; total discharges (over a calendar year) can then be determined by multiplying the average daily discharges by 365. Since all of the results in Table A.1 depend on the seasonal temperature cycle and farming practices (feed use, type of feed, grow-out period), they are specific to SWNB. Since farming practices change relatively slowly, it should be possible to use these values to estimate discharges from actual or proposed farms in SWNB for some time to come. However, the numbers of Table A.1 do not depend on the current distribution of farm sites in SWNB.

Fig A.1 shows how the consumption of oxygen varies through the entire grow-out period. Curves showing all the other waste discharges have the same shape as the one for oxygen consumption. Peak discharges occur in September / October of each year: there is a lag of a few weeks between the maximum water temperatures and maximum discharges because the biomass of the fish is increasing fast enough at this time of year to more than compensate for the slight decline in water temperature. Maximum rates of discharge are about three times higher in the second year of growth than in the first and are a consequence of the greater biomass on site in the second year. The timing of these maximum discharges is close to the time at which the receiving environment is most subject to eutrophication effects. Relatively high water temperatures produce the lowest dissolved oxygen levels, macroalgal biomass is high and starting to die and decompose, and natural nutrient concentrations are near the low point of their seasonal cycle.

It is possible to assess the wider area impacts of the discharges of nutrients and oxygen demand from aquaculture activities by examining the total waste loads for larger areas. 'Bay Management Areas' proposed by DAFA (Fig. 3) are too small to be considered as hydrographically separate regions. On the other hand, the CMRs shown in Fig. 4 represent oceanographic areas that may be sufficiently distinct for purposes of this calculation. These areas were proposed by DFO several years ago for management of salmon aquaculture in SWNB. They are used here to examine the significance of discharges from salmon aquaculture by combining the estimates of the wastes from the fish growth model with the approved production limits (APLs) for odd and even year classes (APLs data for 2002 from Table 1) for each of these areas.

Table A.2 lists the APLs and calculated waste discharges into each of the CMRs in a number of different ways. The CMR called 'Other' includes newer leases between Beaver Harbour and Maces Bay that do not fall in the four original CMRs defined. These estimates are based on the distribution of farm sites in SWNB in 2002. Note that the APLs in Table

A.2 are the number of smolts that growers may put on their sites in odd or even years. On the other hand, the discharges in the table are the total discharges due to the odd and even year class fish in an CMR in an odd or even year. For example, in an even year, Northern Passamaquoddy Bay would be expected to have a total 0.27 million year fish from year class 1, 1.08 x 10^6 fish from year class 2 and 0.27 x 10^6 fish from year class 3.

The total discharge information for the Letete Passage/Back Bay/Bliss Harbour/Lime Kiln Bay (subsequently referred to as the 'Letang' CMR) can be compared to the aquaculture discharges presented in Fig. 2 of Strain et al. (1995), which included farms in the whole Letang 'Inlet' (i.e. Back Bay, Bliss Harbour, Lime Kiln Bay and Letang Harbour), but not Letete Passage. Discharges predicted for this CMR for odd years are similar to those predicted for the Letang Inlet in 1992 prior to introduction of single-year class management in the area. However, discharges predicted for even years are approximately 2.5 times higher than they were in 1992. The move to a Single Year Class management system has been accompanied by a marked increase in APLs in recent years. The increase has exacerbated potential environmental impacts in those areas with the highest stocking density. This is because smolts are only introduced to these three inlets in odd years (Table A.2). Hence 2-yr fish occur at all sites during the second year (leading to increased biomass as all fish mature in even years). In 1992, the aquaculture industry was clearly the largest anthropogenic contributor of oxygen demand and nutrients to the Letang Inlet (other human sources included two fish processing plants, a pulp mill, and a sewage treatment plant). This situation has continued through the past decade such that now in even years BOD, nitrogen and carbon inputs from salmon aquaculture are estimated to be 1.6 to 3.4 times greater than the second largest anthropogenic source (Table B.1, Appendix B).

Table A.2 also lists the predicted maximum daily discharges for each waste into each CMR. Once again, the maximum daily discharges occur in September when water temperatures and fish biomass are high. These maximum daily discharges are 2.3 times higher than the corresponding daily discharges averaged over the entire calendar year. Note that there are some substantial differences for some CMRs between the total APLs for odd and even year sites, with corresponding differences in the discharges.

Table A.2 also includes estimates for the change in ambient oxygen and nutrient concentrations that would be caused by the fish farm wastes for three of the five CMRs. These are worst-case estimates because they are based on the maximum daily waste discharges and the year of the odd/even cycle with the higher discharges. These calculations assume no biological alteration of the farm wastes: their purpose is to compare the magnitude of the impacts of fish farm wastes with natural processes. The other inputs to the calculations are the volumes of water in the CMRs (from Gregory et al., 1993, or estimated from the hydrographic chart) and estimates of the residence times for the CMRs (Thompson et al. 2002).

Data to do the same calculations for the remaining two CMRs (Grand Manan, 'Other') are not readily available, but residence times are likely shorter, and volumes equal or greater than, the ones in these calculations. If so, the expected changes in ambient concentration for these two CMRs would be less than values in Table A.2. It must be emphasized that the scale on which these calculations are done is very important. Severe localized impacts may occur within a larger CMR for which predicted changes in ambient levels are relatively small.

The predicted changes in ambient oxygen and nutrient concentrations for the Northern Passamaquoddy Bay and Deer/Campobello Island CMRs are very small. A decrease of 1.6 μM for dissolved oxygen is less than 0.5 % of oxygen saturation (275 μM) at the ambient temperature (12 °C) and salinity (33.5). Changes of 0.2 μM in nitrogen and 0.012 μM in phosphorus are much smaller than the concentrations of these nutrients in offshore waters in the Bay of Fundy (e.g. see Martin et al. 2001). But the predicted changes for the Letang CMR are very significant. A 48 μM decrease in oxygen is equivalent to a drop of 17 % in oxygen saturation or a decrease of 1.5 mg l^{-1}. An increase in dissolved inorganic nitrogen of 6.2 μM is comparable to or greater than expected background levels.

There is some field data that confirms the very high concentrations of nitrogen in these waters. Bugden et al. (2001) reported nitrate + ammonia concentrations as high as 9.7 μM in Back Bay in September 1999. The increased availability of inorganic nitrogen could be promoting increased biomass of intertidal algae or other undesirable growth. Macroalgae have a large capacity for nutrient uptake and may form extensive beds in response to nutrient enrichment (Chopin et al. 2000). While increased macroalgal production of commercial species such as *Ascophyllum* has an economic advantage, other species such as the green algal *Enteromorpha* may cause adverse ecological effects on soft-shell clams in intertidal areas (Auffrey et al. 2002). The increase in phosphorus is not as great as that for nitrogen (since excess phosphorus is generally present in these waters), but is still within the range expected in background levels. All of these changes are predicted for an area much larger than that of the farm sites themselves. Changes in dissolved oxygen and nutrients close to the farm sites will undoubtedly be higher. It is likely that the aquaculture activity in the Letang CMR has already exceeded the carrying capacity of the receiving environment.

References

Auffrey, L.M, S.M.C. Robinson and M.A. Barbeau. 2002. Green algae and clams: What's the story? p. 84-91. In B.T. Hargrave (Ed.), Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report. Cans. Tech. Rep. 2411: v + 117 p.

Bugden, J.B.C., B.T. Hargrave, P.M. Strain and A.R.J. Stewart. 2001. Spatial patterns of some physical and chemical variables in Passamaquoddy Bay and Letang Inlet, southwestern Bay of Fundy, September 1999. Can. Tech. Rep. Fish. Aquat. Sci. 2356: iv + 96 p.

Chopin, T. D., D. Welles and E. Belyea. 2000. Seaweeds, nutrients and aquaculture in coastal waters ... let's put things in perspective, p. 39. In. R.W. Rangely and J. Davies (Eds.). Gulf of Maine rockweed: management in the face of scientific uncertainty. Huntsman Mar. Sci. Center Occ. Rep. 00/1, St. Andrews, N.B.

Einen, O., I. Holmefjord, T. Asgard and C. Talbot. 1995. Auditing nutrient discharges from fish farms: theoretical and practical considerations. Aquaculture Res. 26: 701-713.

Gregory, D., B. Petrie, F. Jordan and P. Langille. 1993. Oceanographic, geographic and hydrological parameters of Scotia-Fundy and southern Gulf of St. Lawrence inlets. Can. Tech. Rep. Hydrog. Ocean Sci. 143: viii + 248 pp.

Martin, J.L, M.M. LeGresley and P.M. Strain. 2001. Phytoplankton monitoring in the Western Isles region of the Bay of Fundy during 1997-98. Can. Tech. Rep. Fish. Aquat. Sci. 2349: iv + 85 p.

Peterson, R.H., F. Page, G.D. Steeves, D.J. Wildish, P. Harmon and R. Losier. 2001. A survey of 20 Atlantic salmon farms in the Bay of Fundy: influence of environmental and husbandry variables on performance. Can Tech. Rep. Fish. Aquat. Sci. 2337: v + 117 p.

Shearer, K.D, T. Asgard, G. Andorsdottir and G.H. Aas. 1994. Whole body elemental and proximate composition of Atlantic salmon (*Salmo salar*) during the life cycle. J. Fish Biol. 44: 785-797.

Silvert, W. 1994. Simulation models of finfish farms. J. Appl. Icthyol. 10: 349-352.

Sowles, J. and L. Churchill. 2003. Exposure and potential effects from nutrient enrichment by salmon aquaculture in Cobscook Bay. Manuscript in preparation.

Storebakken, T., K.D. Shearer and A.J. Roen. 1998. Availability of protein, phosphorus and other elements in fish meal, soy-protein concentrate and phytase-treated soy-protein-concentrate-based diets to Atlantic salmon, *Salmo salar*. Aquaculture 161: 465-479.

Strain, P.M., D.J. Wildish, and P.A. Yeats. 1995. The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet. Mar. Poll. Bull. 30: 253 - 261.

Thodesen, J.B. Grisdale-Helland, S.J. Helland and B. Gjerde. 1999 Feed intake, growth and feed utilization of offspring from wild and selected Atlantic salmon (*Salmo salar*). Aquaculture 180: 237-246.

Thompson, K.R., M. Dowd, Y. Shen and D. Greenberg. 2002. Probabilistic characterization of tidal mixing in a coastal embayment: a Markov chain approach. Cont. Shelf. Res. 22: 1603-1614.

Table A.1. Wastes from Salmon Aquaculture Operations in Southwest New Brunswick

Substance	**kg Waste / Ton of Fish Produced**	**Maximum Rate of Discharge: Year 1 Kg d^{-1} (1,000 fish)$^{-1}$**	**Maximum Rate of Discharge: Year 2 kg d^{-1} (1,000 fish)$^{-1}$**	**Maximum Rate of Discharge: Year 3 kg d^{-1} (1,000 fish)$^{-1}$**
Water column impacts				
O_2 Consumed (respiration + decay of faeces and waste feed)	580	4.5	13	4.2
Carbon respired	140	1.0	3.1	0.99
Nitrogen discharges	32	0.25	0.74	0.23
Phosphorus discharges	4.3	0.033	0.099	0.031
Sediment impacts				
Carbon buried	82	0.63	1.9	0.60
Nitrogen buried	15	0.11	0.34	0.11
Phosphorus buried	3.0	0.023	0.068	0.021
Notes	1	2	3	4

Notes:

[1] Amount of waste produced during the entire grow-out cycle, per metric ton of fish produced; [2] Maximum rate of discharge found during the first calendar year of growth, for each 1000 fish. This occurs on Sept 30. Average daily discharges (averaged over the entire calendar year) are 2.7 times less than the values in this column; [3] Maximum rate of discharge found during the second calendar year of growth, for each 1000 fish. This occurs on Sept 18. Average daily discharges (averaged over the entire calendar year) are 2.3 times less than the values in this column; [4] Maximum rate of discharge found during the third calendar year of growth, for each 1000 fish. This occurs on Jan 1. Average daily discharges (averaged over the entire calendar year) are 14.9 times less than the values in this column.

Table A.2. Impacts of fish farm wastes on proposed Ocean Management Regions in SWNB. The Approved Production Limits are the number of smolt that may be started in each CMR in odd and even years as of 2002. However, discharges are the total discharges due to all odd and even year class fish in each CMR during odd and even years.

Substance	**Pass. odd / even**[7]	**Letang odd / even**	**Deer Isl. odd / even**	**Grand Manan odd / even**	**Other odd / even**
Approved Production Limits (2002 APLx10^6)	1.08 / 0.27	4.11 / 0.335	0.865 / 5.465	3.189 / 2.71	0.30 / 1.39
Total annual discharges (metric tons (calendar year)$^{-1}$)					
O_2 consumed	1350 / 2500	3600 / 9000	12,300 / 5700	8000 / 8700	3200 / 1630
Carbon (waste feed + faeces)	380 / 700	1030 / 2500	3500 / 1620	2300 / 2500	900 / 460
Nitrogen (total)	108 / 200	290 / 720	990 / 460	650 / 700	260 / 131
Phosphorus (total)	16.8 / 31	46 / 112	153 / 72	100 / 109	40 / 20
Water column impacts, maximum daily discharges[6] **(metric tons d^{-1})**					
O_2 Consumed (respiration + decay of faeces and waste feed)	8.4 / 15.7	22 / 56	77 / 36	50 / 55	20 / 10.2
Carbon respired	1.96 / 3.7	5.3 / 13.3	18.0 / 8.4	11.8 / 12.8	4.7 / 2.4
Nitrogen discharge	0.47 / 0.87	1.26 / 3.14	4.3 / 1.98	2.8 / 3.0	1.11 / 0.56
Phosphorus discharges	0.062 / 0.116	0.168 / 0.42	0.57 / 0.26	0.37 / 0.41	0.148 / 0.075
Sediment impacts, maximum daily discharges[6] **(metric tons d^{-1})**					
Carbon buried	1.19 / 2.22	3.2 / 8.0	10.9 / 5.1	7.1/ 7.7	2.8 / 1.44
Nitrogen buried	0.21 / 0.40	0.57 / 1.43	1.95 / 0.90	1.27 / 1.38	0.50 / 0.26
Phosphorus buried	0.043 / 0.080	0.116 / 0.29	0.39 / 0.182	0.28 / 0.28	0.102 / 0.052
Worst-case changes in ambient water column concentrations (μM)					
Dissolved O_2	-1.6	-48	-1.6	-	-
Nitrogen	0.2	6.2	0.2	-	-
Phosphorus	0.012	0.38	0.012	-	-
Notes	1	2	3	4	5

Notes:
[1]Northern Passamaquoddy Bay, [2]Letete Passage, Back Bay, Bliss Harbour, Lime Kiln Bay, [3] Deer and Campobello Islands, [4]Grand Manan Island, [5]farms outside of the four CMRs, [6]maximum inputs occur from Sept 19 - Sept 28, [7]'odd / even' refers to whether the year is an odd or even number (different numbers of smolts are introduced into these CMRs in odd and even years)

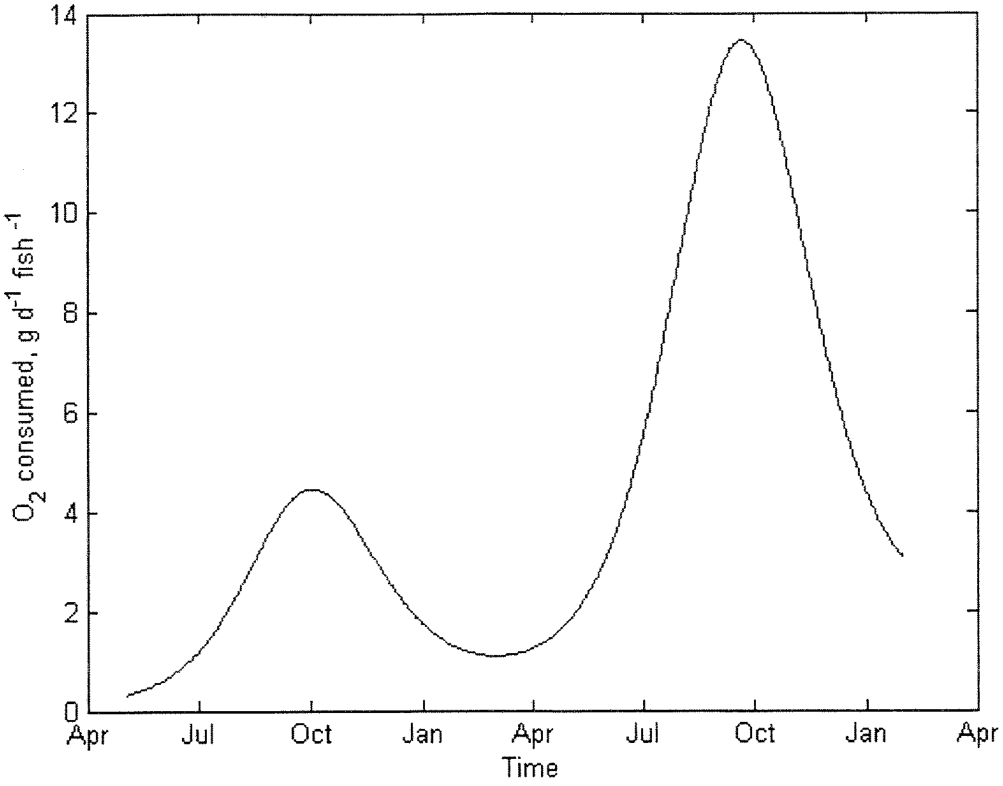

Fig A.1. Total oxygen consumption (ie oxygen used by fish respiration and by the decomposition of waste feed and faeces) during the entire grow-out period of a single salmon.

Appendix B. Evaluating the potential magnitude of eutrophication effects of salmon aquaculture in SWNB (B.T. Hargrave)

Introduction

The magnitude of soluble and particulate wastes released by salmon aquaculture can be assessed if estimated rates of input are considered in relation to natural and anthropogenic sources that add and remove dissolved and particulate matter in coastal ecosystems (Strain et al. 1995). Production, respiration, remineralization and sediment burial are natural processes acting on fluxes of oxygen, nitrogen, and organic carbon in all coastal waters. Respiration by fish (including oxygen consumed by fecal and food wastes), dissolved nitrogen release, and carbon loss through respiration, faeces and waste food based on current allowable production limits (APLs) were calculated in Appendix A. Maximum fluxes in September in odd and even years were compared to other processes that consume oxygen and release nitrogen and carbon (primary production, microbial respiration, and nitrogen remineralization) in pelagic and benthic ecosystem components.

The purpose of this Appendix is to compare the relative magnitude of oxygen, nitrogen and carbon fluxes due to salmon in various CMRs with fluxes due to natural and anthropogenic sources and sinks for these elements. If BOD loadings and nutrient discharges from salmon aquaculture are within the range of natural variability when all natural and anthropogenic inputs are considered, then it might be concluded that an ecological capacity exists in an area to assimilate increased inputs of nutrients and organic matter. On the other hand, if calculated releases of waste products by salmon are a significant fraction of total fluxes from all anthropogenic and natural sources, potential environmental changes might be predicted due to increased nutrient and organic matter discharges.

Methods

Hydrographic and salmon biomass variables

Calculations were based on mid-tide surface area and volumes for various CMRs used in Appendix A to estimate the area and dilution volume into which wastes were assumed to be homogeneously distributed. No attempt was made to account for advection and tidal mixing since the size of the CMRs was assumed to encompass tidal excursions within each CMR. Sub-areas of the Letang CMR used for computations are shown in Wildish et al. (1990). Values for other areas were derived from geographic and oceanographic data for inlets in the SWNB region reported in Gregory et al. (1993) as described in Appendix A. Stocking densities for 2002 were based on allowable production limit (APLs) as numbers of fish in odd and even years (Table 1) calculated on the basis of CMR regions.

Separate calculations were made for Cobscook Bay, Maine (current APLs provided by John Sowles, personal communication) since this region is adjacent to the Campobello/Deer Island CMR (Fig. 4). The Letang/Letete CMR was subdivided into Lime Kiln Bay, Bliss Harbour, Back Bay and Letete Passage and other areas in inner Letang Harbour since calculations in Appendix A showed that this region is potentially more seriously impacted with increased rates of oxygen demand and release of nutrients and particulate matter than other CMRs.

Releases of waste products by any organism are allometrically scaled to body size so that with maturity feeding, growth, respiration and excretion increase rapidly. Metabolic rates also increase with temperature. The combined effects of increasing body size and temperature lead to maxima in all of these metabolic processes during the second year of culture in mid- to late September (Fig. A.1, Appendix A). To provide worst-case estimates for maximum waste release, all calculations were based on mature fish (4.9 kg body weight; Peterson et al. 2001) during September. The exception was in the Letang/Letete CMR where sites are stocked only in odd years (Table 2). Growth by September of the first year was assumed to produce salmon with an individual weight of 800 g. Estimates of primary and macroalgal production, pelagic and benthic respiration, nitrogen, oxygen and carbon fluxes were made for September when seasonally high temperatures lead to maximum rates (Hargrave et al. 1993). Carbon loss by salmon was calculated as the sum of CO_2 respired, released as waste food and faeces and buried in sediments (Table A.2, Appendix A). All rates were calculated as MT (1 MT = 1000 kg) on a daily basis for the total area/volume at mean tide in each CMR.

Anthropogenic sources

No recent (updated) estimates of oxygen consumption, nitrogen release or organic carbon fluxes from anthropogenic sources to regions within SWNB are available. The pulp and paper mill (upper Letang Inlet), fish processing plant in Black's Harbour, and municipal sewage assessed by Strain et al. (1995) continue to discharge into The Letang area with additional sources from St. Andrews entering Passamaquoddy Bay and from Eastport ME to Cobscook Bay. The sardine cannery in Back Bay is no longer operating. Strain et al. (1995) estimated biological oxygen demand (BOD), nitrogen and carbon input from these anthropogenic sources for Letang Inlet in 1991-92. The earlier values were increased by 25% to calculate current values that might be expected due to population and industrial growth over the past decade. Some of these effluents are now treated before release and industrial improvements in fish processing have probably restricted, and may have reduced nutrient concentrations and BOD in plant effluents. Although human population size in the surrounding areas has grown, the increase has been relatively slow in comparison with the expansion of the aquaculture industry. Since the focus of the calculations is to compare non-anthropogenic (natural) sources with updated anthropogenic sources and estimated releases from salmon aquaculture, the 25% increase in values used previously should be sufficiently conservative to reflect all of these changes.

Primary and macrophyte production and nitrogen regeneration

Phytoplankton production has been measured at several locations in SWNB and offshore areas in the lower Bay of Fundy (Prouse et al. 1984, Emerson et al. 1986, Harrison and Perry 2001, Kepkay et al. 2002). The range of daily phytoplankton growth during late summer and fall months (0.6 to 1.7 mg C m^{-2} d^{-1}) is typical of coastal waters in Atlantic Canada. In many areas, particularly nearshore, the depth of light penetration is relatively shallow (5 to 15 m) due to high suspended particle concentrations and dissolved/colloidal coloured substances (Logan et al. 1984; Harrison and Perry 2001). The production system alternates between net autotrophic during summer (production-driven) to net heterotrophic during winter when respiration increases markedly (Kepkay et al. 2002). Phytoplankton may be light limited during summer periods of highest growth. The photic zone was assumed to have a maximum depth of 15 m with an estimate of average phytoplankton production of 1 g C m^{-2} d^{-1}.

Studies of macrophyte distribution in intertidal and sub-littoral zones throughout SWNB provide estimates of biomass and production (Neish 1971, Logan et al. 1984; Sharp and Semple 1992; Sharp et al. 1999). An average biomass of the predominant commercial species (rockweed, *Ascophyllum nodosum*) in intertidal areas in SWNB in 1991 varied from 4.6 to 10.4 kg m^{-2} Annual production:biomass ratios are 0.4 to 0.5 depending on the method of calculation (Sharp et al. 1999) so values for annual production would range from 1.8 to 5.2 kg dry weight (equivalent to 2.5 and 7.1 g C m^{-2} y^{-1} assuming 50% of dry weight as organic carbon). Intertidal areas represent from 15 to 40% of the total area in various CMRs, so representative values for macrophyte production on an inlet-wide basis would vary from 0.4 to 2.8 g C m^{-2} y^{-1}. Since this range is the same as that observed for phytoplankton production, for the purposes of the calculations the daily rate of phytoplankton production was doubled to estimate total autotrophic carbon supply from marine primary production. A C:N ratio of 6 was used to calculate nitrogen requirements of phytoplankton/macroalgae. 50% could be reasonably supplied by ammonia regeneration in the water column. A mean value for benthic ammonia release was derived from measurements using sediment cores collected in central areas of Lime Kiln Bay and Bliss Harbour (Hargrave et al. 1993).

Respiration

Pelagic and benthic oxygen consumption was estimated from data presented in Kepkay et al. (2002) assuming no depth variation and applied uniformly in all CMRs. Measurements of oxygen uptake by particulate matter suspended in flood tide water in Cumberland and Minas Basins at the head of the Bay of Fundy (Hargrave et al. 1983) fall within the range of values measured in Lime Kiln Bay, Bliss Harbour and at the offshore Wolves station by Kepkay et al. (2002) during late summer/fall months. Subtidal sediment oxygen uptake was calculated using the mean rate measured in September in central Bliss Harbour (Hargrave et al. 1993) and applied equally across the total mid-tide area in each CMR.

Results and Discussion

Comparison of new estimates of BOD, nitrogen and carbon released into the Letang Inlet system from salmon in 2002 with data from 1991-92 shows that aquaculture remains the single largest source of BOD and nutrient input (Table B.1). All values expressed as daily averages were derived from annual inputs (from Table A.1), and thus effects of maximum salmon biomass on fluxes in September during the second year of growth are not represented. A decade ago fish plant effluent entering Black's Harbour was estimated to be a source of BOD and nutrients approximately equivalent to that derived from aquaculture. Increased salmon biomass since 1991-92 has dramatically increased these inputs. In even years, when salmon biomass is maximum, aquaculture inputs of BOD, carbon and nitrogen now exceed fish plant inputs by 1.4 to 3.4 times. Although data is not currently available for calculations for other CMRs, it is likely that the pattern would be similar throughout SWNB since salmon biomass has increased in all areas in the past decade.

Water column respiration, largely due to microbial oxygen consumption (Kepkay et al. 2002) accounts for the largest sink in the oxygen budget for SWNB (Table B.2a). As mentioned above, suspended particulate matter concentrations are relatively high and turbid conditions limit light penetration (Harrison and Perry 2001). A net heterotrophic condition, where respiration equals or exceeds autotrophic primary production (Kepkay et al. 2002), would be consistent with high rates of water column oxygen utilization. The magnitude of oxygen consumption in different CMRs is directly proportional to water volume since a constant rate was assumed for all areas. Similarly, sediment oxygen demand, one to two orders of magnitude less than water column consumption, is scaled by area.

The range of oxygen uptake due to salmon respiration in September in odd/even years (4 to 77 MT region^{-1}) is similar to that for sediment oxygen uptake (1 to 66 MT region^{-1}). What is more striking, however, is that daily oxygen demand by salmon calculated for Lime Kiln Bay, Bliss Harbour and Back Bay at this time of year (5 to 19 MT) amounts to a significant fraction of estimated water column respiration in these sub-areas (51 to 164 MT). The proportion is greatest in even years in Lime Kiln Bay (27%) with smaller values in Back Bay (18%), and Bliss Harbour (11%). Salmon respiration in Cobscook Bay is <1% of estimated water column oxygen consumption, similar to other CMRs outside of the three Letang sub-areas.

When oxygen depletion is expressed as a percent of total (pelagic + benthic + fish) respiration, the disproportionate consumption by salmon for even years in Lime Kiln Bay, Bliss Harbour, and Back Bay (14 to 28 %) contrasts lower values (<5%) in all other areas (Table B.3). The calculations clearly show why conditions of sub-optimal dissolved oxygen concentrations requiring re-aeration in late summer months have occurred in some areas with restricted circulation and relatively long water residence times in the Letang region.

The general patterns observed for oxygen fluxes in absolute and relative magnitudes in different CMRs between odd and even years also appear in the calculations for nitrogen and carbon fluxes (Tables B.2b, B.2c and B.3). In Lime Kiln Bay, carbon flux (respiration + loss in faeces and waste feed + burial) attributable to salmon in even years is 40% higher than carbon fixed by autotrophic primary production (the comparable increment for nitrogen is 30%). This means that more of these elements are transferred through salmon than are cycled in the water column and sediments. Cultured fish are now a major biogeochemical pathway of carbon and nitrogen flux in these inlets.

Values in bold in Table B.3 represent CMRs and years where fluxes of elements through salmon are >20% of the total. This threshold is exceeded in even years in Lime Kiln Bay, Bliss Harbour and Back Bay with the greatest discrepancy in Lime Kiln Bay. The pattern is consistent across CMRs and odd/even years - fluxes through salmon as a percent of the total for all elements are maximum where the highest area and volume-specific biomass of fish occurs. Oxygen, nitrogen and carbon fluxes due to salmon in all other CMRs are <20% of total fluxes.

The 20% threshold for oxygen depletion, nutrient or carbon enrichment to determine if fluxes due to cultured fish are large with respect to other fluxes is arbitrary. It is used here only to indicate areas where precaution should be exercised for management purposes. It is possible that in some areas, where other sources of increased BOD and nutrient loading occur, a lower threshold might apply. In the Letang area, and perhaps elsewhere in SWNB, it may be that water column respiration was high prior to aquaculture development and all sources of additional BOD should be minimized to maintain as high levels of dissolved oxygen as possible. However, the predicted increment in oxygen demand and nutrient supply from salmon has been so large in some areas that changes in water column concentrations of dissolved oxygen and nutrients are now measurable (Appendix A). An optimum holding capacity might be defined as one that leads to fluxes of oxygen, nitrogen and carbon through salmon that are within the natural ranges of variability and do not add significantly (for example <10%) to natural fluxes.

Summary

Additional studies of oxygen consumption, nutrient and organic matter fluxes due to salmon, other industrial sources and natural processes will improve the accuracy of the mass balance estimates presented here. However, the relative magnitudes of numbers in the calculations reflects areas and volumes assigned to each CMR into which waste products are assumed to be uniformly distributed. These calculations are conservative since homogeneous mixing does not occur. Waste products will be mixed into smaller volumes than those estimated for CMRs increasing the likelihood of adverse environmental effects in some areas.

If it is accepted as a precautionary threshold that fluxes of oxygen, nitrogen and carbon due to salmon aquaculture in an area should not exceed 20% of total fluxes, reductions of up to 90% are required in Lime Kiln Bay, Bliss Harbour and Back Bay (Table B.3). These three inlets contain approximately 23% of the total APL in the entire SWNB industry (Table 1). The relatively small area with a high concentration of licensed farm sites result in levels of biomass in these areas that are 10 to 100 times greater than in other CMRs (Table 2).

If APLs remain at current levels, it seems almost certain that increased eutrophication will lead to higher nutrient levels with more frequent and widespread oxygen depletion and organic enrichment. There will also be increased likelihood of disease and parasitic infections. Using the suggested threshold, current APLs in Lime Kiln Bay, Bliss Harbour and Back Bay result in stocking levels that exceed a sustainable holding capacity in these inlet systems. Decreases in APLs in these areas would prevent further negative environmental changes and associated losses in aquaculture production.

References

Emerson, C.W., J.C. Roff and D.J. Wildish. 1986. Pelagic-benthic energy coupling at the mouth of the Bay of Fundy. Ophelia 26: 165-180.

Gregory, D., B. Petrie, F. Jordan and P. Langille. 1993. Oceanographic, geographic, and hydrological parameters of Scotia-Fundy and Southern Gulf of St, Lawrence inlets. Can. Tech. Rep. Hydrogr. Ocean Sci. 143: viii +248 p.

Hargrave, B.T., D.E. Duplisea, E. Pfeiffer and D.J. Wildish. 1993. Seasonal changes in benthic fluxes of dissolved oxygen and ammonium associated with marine cultured Atlantic salmon. Mar. Ecol. Prog. Ser. 96: 249-257.

Hargrave, B.T., N.J. Prouse, G.A. Philips and P.A. Neame. 1983. Primary production and respiration in pelagic and benthic communities at two intertidal sites in the upper Bay of Fundy. Can. J. Fish. Aquat, Sci. 40 (Suppl. 1): 229-243.

Harrison, G. and T. Perry. 2001. Water column productivity, Letang Inlet and the Wolves, NB, p. 6-11. In B.T. Hargrave and G.A. Phillips (Eds.), Environmental Studies for Sustainable Aquaculture (ESSA): 2001 workshop report. Can. Tech. Rep. Fish. Aquat. Sci. 2352; viii + 73 p.

Kepkay, P., G. Harrison, J. Bugden and T. Perry. 2002. Carbon loading and carbon dynamics in the Quoddy Region, p. 51-54. In B.T. Hargrave and G.A. Phillips (Eds.), Environmental Studies for Sustainable Aquaculture (ESSA): 2001 workshop report. Can. Tech. Rep. Fish. Aquat. Sci. 2352; viii + 73 p.

Logan, A., F.H. Page and M.L.H. Thomas. 1984. Depth zonation of epibenthos on sublittoral hard substrates off Deer Island, Bay of Fundy, Canada. Est. Coastal and Shelf Sci. 18: 571-592.

Neish, 1. 1971. The distribution and abundance of rockweed on the Bay of Fundy shore of New Brunswick. Rept. To New Brunswick Dept. of Fisheries, Atlantic Mariculture, Ltd.

Peterson, R.H., F. Page, G.D. Steeves, D.J. Wildish, P. Harmon and R. Losier. 2001. A survey of 20 Atlantic salmon farms in the Bay of Fundy: influence of environmental and husbandry variables on performance. Can. Tech. Rep. Fish. Aquat. Sci. 2337: v + 117 p.

Prouse, N.J., D.C. Gordon, Jr., B.T. Hargrave, C.J. Bird, J. McLachlan, J.S.S. Lakshminarayan, J. Sita Devi and M.L.H. Thomas. 1984. Primary production: organic matter supply to ecosystems in the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 1256.

Sharp, G. and R. Semple. 1992. Data base for management strategies *Ascophyllum nodosum* (rockweed) resources Southwestern New Brunswick. CAFSAC Working Paper 92/218.

Sharp, G., R. Ugarte, T. MacEachron, R. Semple and G. Black. 1999. Structure of the *Ascophyllum nodosum* (rockweed) habitat and the effects of harvesting perturbation in southwestern New Brunswick. RAP Working Paper 99/29, 18 pp.

Strain, P.M., D.J. Wildish, and P.A. Yeats. 1995. The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet. Mar. Poll. Bull. 30: 253-261.

Wildish, D.J., J.L. Martin, R.W. Trites and A.M. Saulnier. 1990. A proposal for environmental research and monitoring of organic pollution caused by salmonid mariculture in the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 1724: iii + 24 p.

Table B.1. Inputs (MT d^{-1}) of biological oxygen demand (BOD), dissolved and particulate nitrogen and carbon by salmon in Letang Inlet region in SWNB. Data for anthropogenic sources for 1991-92 from Strain et al. (1995) with values as daily discharge rates (annual totals ÷365) for sewage, pulp mill and fish plant inputs increased by 25% to reflect industrial and population growth since 1992. Fish processing plant wastes enter Black's Harbour and pulp mill effluents enter the head of Letang Harbour with river discharge. Inputs from salmon aquaculture were calculated for Lime Kiln Bay, Black's Harbour, Bliss Harbour, and Back Bay. Daily inputs from salmon aquaculture were derived from total annual discharges ÷365 for 2002 for odd and even years in the Letang/Letete CMR (from Table A.1 , Appendix A).

Source	BOD	Nitrogen	Carbon
runoff	0.35	0.03	0.82
precipitation	-	0.05	-
sewage treatment	0.24	0.013	0.14
pulp mill	0.65	0.011	0.38
fish plant production	7.2	0.75	4.18
salmon aquaculture			
(1991-1992)	12.0	0.79	2.33
(2002 odd)	9.9	0.79	2.82
(2002 even)	24.7	1.97	6.85

Table B.2a. Comparison of oxygen flux (MT $region^{-1}$ d^{-1}) due to water column respiration (including macrophytes), sediment oxygen consumption and salmon respiration + waste products. Data sources for estimates of water + subtidal sediment oxygen uptake are described in the text. Data for water column impacts from salmon respiration + waste oxygen consumption are from Table A.2 (Appendix A) for odd and even years.

Area (CMR) Year	Water (pelagic)	Sediment (subtidal)	Salmon (+waste) odd	 even
Grand Manan (1,2)	17146	66	50.0	55.0
Campobello/Deer Isl. (3,4,5)	17146	66	77.0	36.0
N. Passamaquoddy (6)	17146	66	8.4	15.7
Letang/Letete (7)	1866	15	21.6	55.7
Lime Kiln Bay	51	1	4.9	14.0
Bliss Harbour	164	2	6.4	18.5
Back Bay	98	2	5.9	17.2
Letete Passage	1866	10	4.4	6.0
Other Areas (8)	2488	14	20.0	10.2
Cobscook Bay ME	1740	44	19.5	19.5

Table B.2b. Comparison of nitrogen flux (MT $\text{region}^{-1}\ \text{d}^{-1}$) due to water column ammonia regeneration (phytoplankton + macrophytes), sediment ammonia remineralization and total nitrogen release due to salmon excretion + faecal and food waste + burial. Data sources to calculate nitrogen fluxes in water and from sediments are described in the text. Data for maximum daily salmon discharges (water column and sediment impacts) are from Table A.2 (Appendix A) in odd and even years.

Area (CMR) Year	Water (pelagic)	Sediment (subtidal)	Salmon odd	Salmon even
Grand Manan (1,2)	29	2	4.1	4.4
Campobello/Deer Isl. (3,4,5)	29	2	6.3	2.9
N. Passamaquoddy (6)	29	2	0.7	1.3
Letang/Letete (7)	6.2	0.32	1.8	4.7
Lime Kiln Bay	0.3	0.02	0.4	1.3
Bliss Harbour	0.7	0.03	0.5	1.6
Back Bay	0.8	0.04	0.5	1.5
Letete Passage	4.4	0.23	0.4	0.3
Other Areas (8)	6	0.30	1.6	0.8
Cobscook Bay ME	19	1.00	1.6	1.6

Table B.2c. Comparison of carbon flux (MT region^{-1} d^{-1}) due to primary production (phytoplankton/macrophytes) and carbon release by salmon due to carbon respired, released as faeces and waste food and buried. Data sources to estimate phytoplankton and macrophyte production are described in the text. Data for carbon released by salmon are from Table A.2 (Appendix A) in odd and even years.

Area (CMR)	Primary Production	Salmon	
Year		odd	even
Grand Manan (1,2)	344	18.9	20.5
Campobello/Deer Isl. (3,4,5)	344	28.9	13.5
N. Passamaquoddy Bay (6)	344	3.2	5.9
Letang/Letete (7)	74	8.4	21.3
Lime Kiln Bay	4	1.9	5.6
Bliss Harbour	8	2.4	7.3
Back Bay	9	2.3	6.8
Letete Passage	53	1.8	1.6
Other Areas (8)	74	7.5	3.8
Cobscook Bay ME	228	7.5	7.5

Table B.3. Comparison of oxygen, nitrogen and carbon fluxes through Atlantic salmon and pelagic and benthic ecosystem components in various CMRs in SWNB. Oxygen consumption includes respiration of fish + faeces and waste food. Total nitrogen loss includes soluble excretion and burial in sediments. Carbon release includes respiration and burial in sediment. Maximum daily discharges (MT d^{-1}) in September of year 2 from Table A.1 (Appendix A). Percent of total (including salmon) oxygen, nitrogen and carbon fluxes in pelagic + benthic ecosystem components calculated from data in Tables B.2a, B.2b, and B.2c in odd and even years for various CMRs. Bold numbers indicate fluxes through salmon >20% of the total.

	Percent of total flux due to salmon					
Area (CMR)	Oxygen		Nitrogen		Carbon	
Year	odd	even	odd	even	odd	even
Grand Manan(1,2)	0.3	0.3	11.9	12.7	5.2	5.6
Campobello/Deer Islands (3,4,5)	0.4	0.2	17.2	8.7	7.8	3.8
N. Passamaquoddy Bay (6)	<0.1	0.1	2.2	4.0	0.9	1.7
Letang/Letete (7)	1.1	2.8	**21.9**	**41.2**	10.3	**22.3**
Lime Kiln Bay	8.6	**21.4**	**54.4**	**78.5**	**32.6**	**58.8**
Bliss Harbour	3.7	10.0	**41.8**	**68.7**	**22.8**	**47.3**
Back Bay	5.6	14.7	**38.3**	**63.8**	19.7	**42.0**
Letete Passage	0.3	0.2	8.1	6.3	3.3	2.9
Other Areas (8)	1.1	0.5	19.8	11.2	9.2	4.9
Cobscook Bay ME	0.8	0.8	7.5	7.5	3.2	3.2

Appendix C. Fish-farm induced dissolved oxygen depletion (F.H. Page)

Introduction

Calculations in Appendix A assume that farm-derived wastes are mixed homogeneously. Thus predictions of changes in dissolved oxygen (DO) assume that consumption is evenly distributed throughout an CMR. However, larger changes in ambient DO levels impacts may occur on a local scale within and near pens that are not predicted by box model calculations. Although DO is not routinely monitored, observations at some fish farms in SWNB have shown that concentrations within the cages are reduced to below 6 mg l^{-1} and sometimes below 4-5 mg l^{-1}. These events often occur for short periods of time (hours) within each tidal cycle and usually in areas where water currents are <2-5cm s^{-1} for about one hour or more. Back Bay Narrows, Bocabec Bay, Fairhaven, Pendelton Passage and regions of the Bliss Harbour area among others have experienced low oxygen levels in the past. Low oxygen concentrations can result in losses in fish production through reduced growth and increased susceptibility to disease. These negative effects in turn result in significant economic losses.

Modelling the Influence of Caged Salmon on Dissolved Oxygen in Seal Cove

A simple model is described here for estimating the impact of the existing Approved Production Limit (APL) and Estimated Site Potential (ESP) on the dissolved oxygen (DO) levels within Seal Cove, Grand Manan Island. The approach requires information on the ambient concentration of DO, a specified threshold that indicates the desired lower limit of DO, the rate of oxygen utilization by caged salmon and the flushing rate of the Cove. The calculations could be formulated to estimate the number of salmon needed to achieve a specified 'target' DO.

Ambient DO Concentrations

The impact of the localized reductions on dissolved oxygen on the ecosystem depends in part on the degree of spatial and temporal persistence of the reduced dissolved oxygen zone as well as the magnitude of the depletion. Back-of-the-envelope calculations suggest that the spatial scale of influence may be on the order of 100 to 1000 m but this will typically not be evenly distributed. It will exist as narrow plumes or streaks of water with low DO and the degree of depletion should decrease with distance from a farm.

Data collected by DFO from Seal Cove during the summer and fall of 2002 suggested that concentrations away from fish farms and fish plant effluents were similar to and within the range of previously observed offshore values (Fig. C.1). Historic data suggest ambient offshore DO values during late summer and fall between 7 and 9 mg l^{-1}. The ambient concentration of DO in Seal Cove during the late summer and early fall was approximately 9 mg l^{-1}. Industry reports suggest that lower DO concentrations were experienced in some areas of Seal Cove a few years ago and concentrations in the past may have fallen below 6 mg l^{-1} for short periods of time in some localized areas. A more extensive monitoring of DO concentrations within Seal Cove and in nearby offshore waters is required to clarify the ambient status and its variability.

Threshold Dissolved Oxygen Concentration

In order to estimate the carrying capacity of an area in terms of oxygen utilization, a threshold concentration of DO must be adopted based on the minimum desirable concentration. A threshold of 6 mg l^{-1} was adopted for the purposes of this analysis. Although a lower value could be selected, published literature indicates that salmonids begin to show behavioral modifications at DO less than about 6.75 mg l^{-1}. Previous studies also suggest that the health status of fish deteriorates when DO levels fall below about 6 mg l^{-1}. From a practical perspective a threshold of 7 mg l^{-1} would perhaps be too high a target if DO concentrations within Seal Cove are in fact similar to those experienced in offshore areas. DO may approach 7 mg l^{-1} seasonally in some years and caged salmon could then reduce concentrations further below this value. A minimum threshold value of 6 mg l^{-1} seems to be a reasonable compromise. This gives a reasonable level of environmental protection while enabling the aquaculture industry areas to establish farms where DO levels will not fall below the threshold. In Seal Cove, adoption of a 6 mg l^{-1} threshold would provide the salmon and other industries with a 3 mg l^{-1} buffer when the ambient DO level is 9 mg l^{-1} and a 1 mg l^{-1} buffer when the ambient concentration is 7 mg l^{-1}.

Rate of Water and DO Exchange

Seal Cove, a semi-enclosed tidal embayment on Grand Manan Island in the mouth of the Bay of Fundy, is approximately 4.8 kilometers long and 2.1 kilometers wide. Average depth at low tide and tidal range are ~15 m and 4 m, respectively. The volume of water at low tide is therefore approximately $1.5 \cdot 10^8$ m^3. The volume brought into the bay each tide is $4 \cdot 10^7$ m^3 and the volume at high tide is $2 \cdot 10^8$ m^3.

The residence time (RT) for water in Seal Cove estimated by the tidal prism method is 4.25 tidal cycles which equals 53 hours (2.2 d). This time scale is usually interpreted as the time needed to exchange about 63% of the water in the bay. The time for 95% flushing is 3·RT (6.6 d). This assumes that the water entering the bay is instantaneously mixed with the water already present. Also inflowing water is assumed not to have been in the bay before and that none of the water leaving the bay returns. None of these assumptions are completely correct and they usually result in an underestimate of RT – i.e. the actual RT is longer and more time is required to flush the bay than estimated by the tidal prism method. The underestimation may be a factor of ~2 or more. If RT was underestimated by a factor of 2, the flushing rate for Seal Cove would be approximately 10 d.

More accurate RT estimates can be obtained using circulation and drogue tracking models. Particle tracks generated by our tidally-driven model for southern Grand Manan indicate that many of the model drogues remained in the Cove after 5 tidal cycles and that the assumption of no return of water into Seal Cove on each tide is not valid (Fig. C.2). This supports the conclusion that flushing time is underestimated by the tidal prism method.

Rate of DO utilization

As of the winter of 2002-2003, the combined APL for the five salmon farms within Seal Cove (BMA 20) is 1,269,000 fish and the estimated site potential (ESP) is 1,744,000 (personal communication, Barry Hill). The oxygen consumption rate for salmon is approximately 100 mg DO kg^{-1} fish h^{-1} assuming that each fish has a wet weight of 4 kg, water temperature is approximately 12°C and the fish are swimming at ~ 1 body length s^{-1}. The DO consumption rate for a 4 kg fish is therefore 400 mg DO $fish^{-1}$ h^{-1} and the rate for 1,269,000 fish is approximately $5x10^8$ mg DO h^{-1} (Table C.1). These rates are perhaps most applicable during the later summer and early fall of a pre-market salmon production cycle.

Assuming the water within the bay is instantaneously mixed throughout the bay, calculations based on the above values indicate it would take between approximately 44 to <15 d for salmon to consume all the DO buffer in Seal Cove if there was no tidal exchange. It would take about 45 days if the buffer was 3 mg l^{-1}, 30 days for a 2 mg l^{-1} buffer and 15 days for a 1 mg l^{-1} buffer. These times would be reduced if the DO utilization rate was increased by other factors such as an increased respiration due to feeding, biomass of fish in the bay above the APL, and additional BOD from sediments, fish plant effluents, fish faeces and waste feed. The fish growth model described in Appendix A predicts DO consumed by the decomposition of fish faeces and waste feed to be ~ 60% of that used by salmon respiration. The respiration rate $unit^{-1}$ time could easily double based on increased feeding activity alone. This would reduce time scales by 50% if respiration was elevated continuously. Published data show that basal metabolism can increase 4-fold after feeding. If respiration rates were assumed to be permanently increased by a factor of 2 due to feeding, associated time scales for utilization of DO with buffer levels of 3 to 1 mg l^{-1} would be 23 to 7.5 days.

The ratio of time for fish to utilize the DO buffer (Tbuf) to the flushing time (Tfl) gives an indication of the relative likelihood that caged salmon can influence DO concentrations within the bay. If salmon respiration requires a long time to use the DO buffer relative to the time needed to flush the bay (Tbuf/Tfl >> 1) then the risk of using up the buffer is small. On the other hand, when Tbuf/Tfl <<1, DO is being utilized faster than it is being replaced by tidal flushing and salmon are likely to consume the buffer resulting in DO levels within areas of the Cove below the desired threshold. When the ratio is ~1, the utilization rate is similar to the flushing rate and localized depletions of DO below the desired threshold may occur. A ratio close to 1 also indicates that significant increases in DO utilization will lower the ratio to <1 where more extensive DO depletion is likely to occur.

If regulators and farmers want to avoid problems associated with DO depletion, a ratio close to 1 indicates that a site is close to or at its maximum carrying capacity with respect to maintaining DO at non-critical levels. Increases in the total number of fish within the APL reduce the ratio by about 0.1 for every 100,000 fish added. A similar reduction occurs if the water temperature increases by a few degrees and if the fish grow faster and reach a larger size (5 kg). Therefore the addition of ~100,000 fish will not substantially change the ratios reported in Table C.1. Since it would be prudent to ensure as large a buffer against the likelihood of DO depletions as possible, efforts should be made to increase the ratio above 1. If this is not an attractive option, more extensive information and detailed calculations could be made for a site to determine more precisely the risk of depleting the DO to undesirable levels.

Values of Tbuf/Tfl for Seal Cove, based on the cumulative APL and ESP described above, are between 6.7 and 0.4 (Table C.1). For the situation with high ambient DO concentration

(9 mg l^{-1}) and the corresponding DO buffer of 3 mg l^{-1}, the APL-based ratio varies between 6.7 and 1.6 and the ESP based ratio varies between 4.8 and 1.2. This suggests there is some room to increase the APL toward the ESP. The risk here is associated with the uncertainty of ambient DO concentrations being consistently as high as 9 mg l^{-1}. It may be more prudent to assume a lower ambient DO concentration of 7 mg l^{-1} and a corresponding buffer of 1 mg l^{-1}. In this case the APL-based ratio varies between 2.2 and 0.6 and the ESP-based ratio is between 1.6 and 0.4. This suggests the ESP for Seal Cove is too high resulting in ratios <1. It also suggests that there is little room to increase the APL toward the ESP in this location.

Whether or not this scenario is the most appropriate for Seal Cove depends on the probability that ambient DO concentrations will be ~7 mg l^{-1} and the assumption that other sources of oxygen utilization are unimportant relative to salmon respiration. It must also be emphasized that concerns about DO depletion and a small buffer are greatest between August and October when water temperatures are highest, ambient DO concentrations are lowest (Fig. C.1) and when fish reach pre-market size with maximum respiration rates. The scenarios described above are based on these worst-case conditions that only occur in some areas during a limited time of the year. Although more data are needed to clarify effects of seasonality on ratio calculations, wide spread DO problems reported throughout SWNB during 1999 indicate the potential magnitude of the problem. Serious DO depletion occurred in areas such as the Back Bay Narrows where the range of Tbuf/Tfl was similar to that calculated for Seal Cove.

Several questions must be answered and more detailed information obtained if the risks implied by this analysis are to be quantified and useful to the industry and regulators. For example, is 6 mg l^{-1} the correct threshold to maintain healthy conditions for fish growth and environmental protection? What is the natural variability in ambient DO concentrations? What methods can be used to provide a better estimate of flushing time? What other sources of oxygen demand occur in addition to fish respiration and what is their magnitude? Can the time-dependant concentration of DO within the bay be predicted to a satisfactory level to permit timely management decisions that avoid risk to both fish and the environment caused by oxygen depletion?

Summary Points

1. Data from offshore areas within southwestern New Brunswick (e.g. the Wolves and East Quoddy Head) indicate that DO concentrations undergo a natural seasonal cycle with a seasonal minimum occurring in the late summer and fall as low as 7 mg l^{-1}. Data collected in the summer and fall of 2002 showed that ambient DO concentrations near the middle of Seal Cove were typical of those in the offshore waters of southwestern New Brunswick.

2. A minimum threshold for DO concentrations of approximately 6 mg l^{-1} might be proposed as a target to maintain water quality around fish farms and for coastal areas receiving other sources of effluents. This would benefit both growers and the environment. Some growers already use this concentration as a rule-of-thumb to indicate deteriorating conditions when remedial action is required. However, a broad discussion is required to determine if this threshold is useful as a regulatory guide.

3. Box model calculations suggest the Approved Production Limit (APL) and to a greater extent the Estimated Site Potential (ESP) for salmon farms within Seal Cove have the potential to reduce the average ambient DO concentrations within the Cove by 1-2 mg l^{-1} during the time needed for tidal exchange of water. This does not necessarily mean that local areas of low concentration will consistently be present. It does, however, suggest that when regional ambient concentrations of DO are within the lower limits of the natural range of variation (7-8 mg l^{-1}), localized depressions to 6 mg l^{-1} or less may occasionally occur.

4. Both observations and simple model outputs confirm that concentrations of dissolved oxygen at some farms in the past have been reduced below the suggested critical threshold of 6 mg^{-1}. An earlier advection-diffusion water quality model of the Letang Inlet area also predicted the presence of localised reductions in the concentration of DO in the vicinity of some fish farms. These models could be significantly improved and refined by combining fish farm, benthic and pelagic DO demands and measures of water circulation.

5. From the perspectives of ecosystem protection and optimum production and health of caged salmon it is commonly suggested that concentrations of DO <6 mg l^{-1} should be avoided.

6. These considerations are based on a calculated DO utilization rate for mature fish during late summer and fall when water temperatures are maximum and concentrations are at a seasonal low level– i.e. the likely worst-case time of year. The calculations also only included salmon oxygen consumption based on current APL and ESP numbers for Seal Cove. Oxygen demand by other processes, such as microbial respiration in the water and sediments, the degradation of the salmon faeces and waste feed, and effluent from the local fish plant have not been considered. Inclusion of these additional sinks for DO would further lower the DO buffer and reduce the ratio. Processes that add DO such as wind mixing and photosynthesis were also not included. It was assumed the net result of all processes that add and remove DO are reflected in the observed ambient DO level.

7. Given the caution indicated by these simple calculations, it may be prudent to gather additional information to refine and test the robustness of the calculations. DO depletion is hard to detect with traditional point sampling. Towed sensors along transects could be used to show the spatial extent and duration of depletion events. Although these observations have not been made in SWNB, equipment and expertise exist within DFO for such research. The observations would provide empirical evidence for the scale of DO depletion. Results could be used for ground-truthing models that would be applicable for farm management purposes.

8. Further development of respiration-advection models in conjunction with observations of DO distribution around fish farms cannot be accomplished without focused research. Funding sources must be identified for this purpose if effects of reduced oxygen concentrations on fish growth and susceptibility to disease are to be assessed.

Table C.1. Summary of physical characteristics, flushing time, oxygen utilization time and utilization/flushing ratio estimates for Seal Cove, Grand Manan in the southwest New Brunswick area of the Bay of Fundy.

Seal Cove Grand Manan	**Primary Scenario - low temp. - average size of fish**
Physical Characteristics	
Length (m)	5000
Width (m)	2100
Depth at low tide (m)	15
Tide Height (m)	4
Low Tide Volume (m^3)	$1.6x10^8$
Tidal Volume (m^3)	$4.2x10^7$
High Tide Volume (m^3)	$2x10^8$
Water temperature (°C)	12
e-folding flushing times (tidal cycles, hrs, days)	4.25 tides, 53h, 2.2d
95% flushing times (tidal cycles, hrs, days)	12.8 tides, 158h, 6.6d
Dissolved Oxygen Characteristics	
Ambient DO (mg l^{-1})	7-9
DO Threshold (mg l^{-1})	6-7
Threshold DO Deficits (mg l^{-1})	0-3
Salmon Farm Characteristics	
Size of fish (kg)	4
Fish Swimming speed (body length s^{-1})	1
Basic Resp. Rate/kg (mg DO kg^{-1} h^{-1}) at above temp.	99
Basic Resp. Rate/fish (mg DO $fish^{-1}$ h^{-1})	398
Approved Production Limit (APL #fish)	1,269,000
Respiration Rate for APL (mg DO h^{-1})	$5x10^8$
Time (d) for APL to utilize DO deficit of 1mg l^{-1}	14.7
Estimated Site Potential (ESP #fish)	1,744,000
Respiration Rate for ESP (mg DO h^{-1})	$6.9x10^8$
Time (d) for ESP to utilize DO deficit of 1mg l^{-1}	10.7
Ratio of Utilization Time/95% Flushing Time*	
0 mg l^{-1}deficit assuming APL and ESP	0
1 mg l^{-1}deficit assuming APL and ESP – basic resp.- feeding respiration = 2 x basic resp.	2.2 (*1.1*); 1.6 (*0.8*) 1.1 (*0.6*); 0.8 (*0.4*)
2 mg l^{-1} deficit assuming APL and ESP – basic resp. - feeding respiration = 2 x basic resp.	4.4 (*2.2*); 3.2 (*1.6*) 2.2 (*1.1*); 1.6 (*0.8*)
3 mg l^{-1} deficit assuming APL and ESP – basic resp. feeding respiration = 2 x basic resp.	6.7 (3.3); 4.8 (2.4) 3.3 (*1.6*); 2.4 (*1.2*)

Note: * ratio values are based on APL and 95% flushing (APL and 2*95% flushing); ESP and 95% flushing (ESP and 2*95% flushing) i.e. bracketed values are based on the assumption of the flushing rate being under-estimated by a factor of 2.

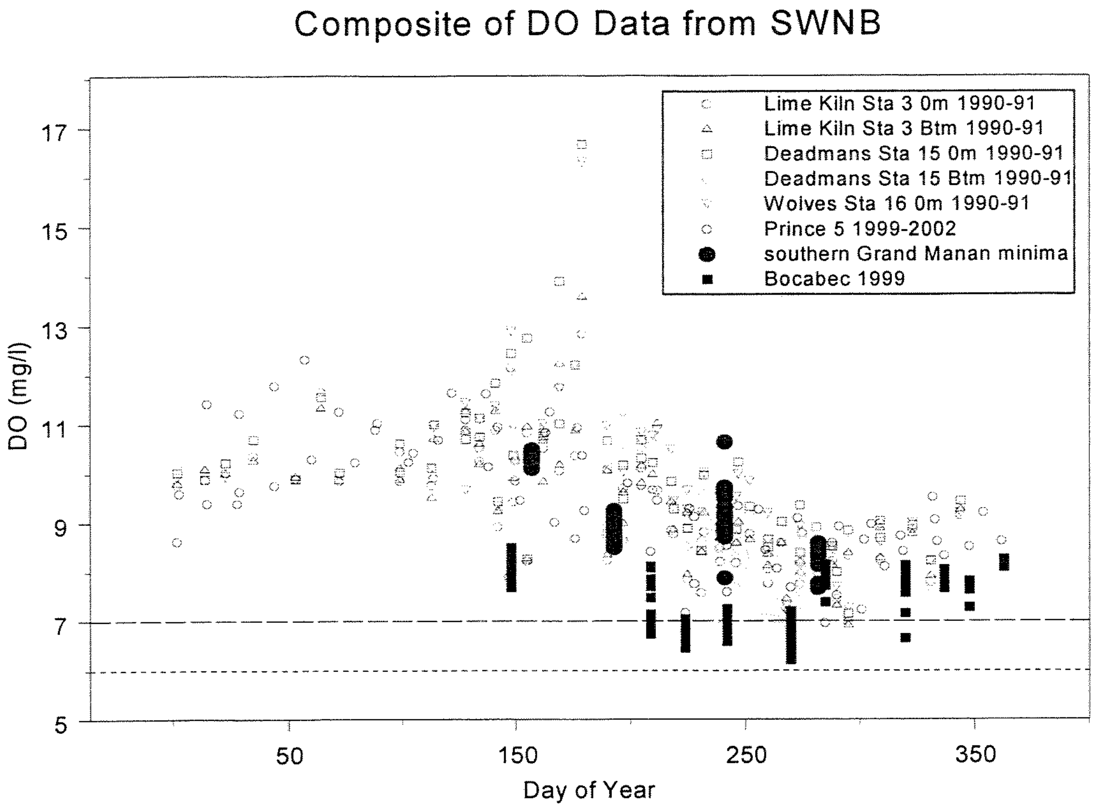

Fig. C.1. Measurements of the concentration of dissolved oxygen (DO) obtained from several locations within the southwestern New Brunswick area of the Bay of Fundy. Data obtained from Seal Cove in the year 2002 are shown as solid dots. The data from Bocabec Bay (solid squares) are shown for comparison. None of the measurements were taken immediately adjacent to fish farms.

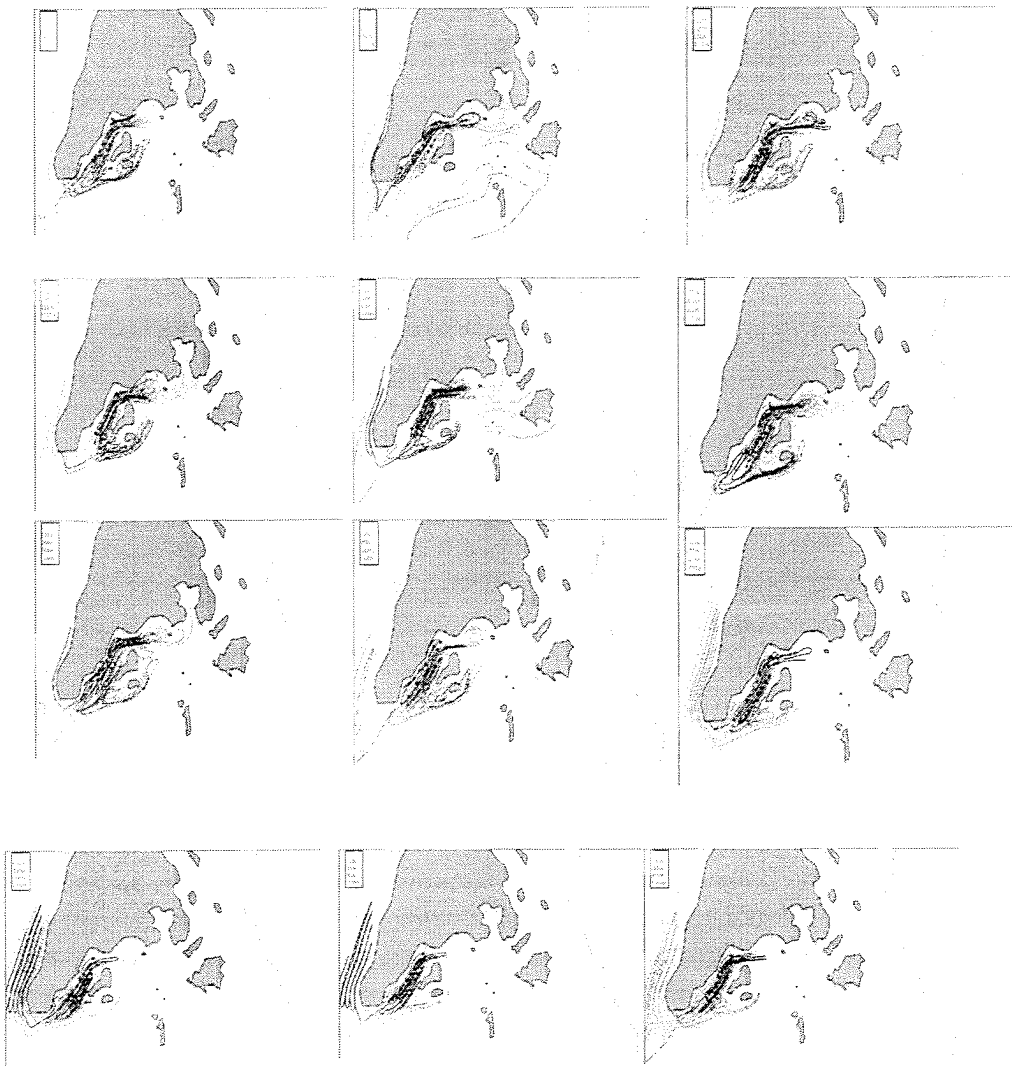

Fig. C.2. Tracks of particles released near the surface at a series of locations distributed throughout the central region of Seal Cove. Particles were released at 1 hour intervals and tracked for approximately 5 tidal cycles. The panels show the tracking results for release hours 1 to 12 with releases progressing from left to right and the 1 hour release in the upper left column.

Appendix D. Particle aggregation and tracers for particulate matter dispersion from finfish aquaculture in southwestern New Brunswick (T. Milligan, S. Robinson and P. Yeats)

Introduction

The aggregation dynamics of the particulate material and the hydrodynamics within a body of water will control the fate of surface-active contaminants. The formation and deposition of large, fast sinking aggregates by flocculation, which occurs in all saltwater and most freshwater environments, governs the distribution of fine particulate material deposited within the coastal zone (Milligan and Loring 1997, Kranck 1993).

Aggregation models such as those of Jackson (1995) and Hill (1996) contain three major terms to describe the development of a flocculated suspension: 1) particle number or concentration, 2) particle adhesion efficiency or stickiness and 3) particle break-up, most often due to an applied shear. The equilibrium size distribution of a flocculated suspension can be considered a balance between particle aggregation and disaggregation, hence changes to turbulence, composition or concentration can affect the distribution of fine particulate material and contaminants (Milligan and Loring 1997, Milligan and Hill 1998). Bacterial degradation has also been shown to increase floc formation (Muschenheim et al. 1989).

Changes in flocculation due to organic enrichment from aquaculture

Milligan and Loring (1997) hypothesized that the introduction of waste feed and faecal material from aquaculture operations, and their resulting degradation products, could increase both particle concentration and particle stickiness resulting in an increase in aggregation rate, floc strength and settling velocity. Intense aquaculture could also be expected to decrease turbulence due to altered circulation patterns as a result of pen structures. As a result, the natural flocculation and depositional equilibrium could become unbalanced towards increased deposition of fine particulate material and the sequestering of contaminants within surficial sediments. Parameterization of the disaggregated inorganic grain size (DIGS) of bottom sediments has been used to determine the amount of fine-grained sediment deposited in a flocculated form (Kranck and Milligan 1985, Kranck et al. 1996). Floc limit, the diameter at which the amount of floc settled material equals the amount of single grain settled material, describes the relative amount of floc settled material within a sediment, with larger values resulting from greater floc settling.

Evidence of increased floc settling has been found in both Back Bay and Lime Kiln Bay, areas of intense aquaculture in SWNB. The DIGS profile and floc limit for a core collected in Back Bay shows increasing concentration of floc settled material above 9-cm in the core (Fig. D.1). While no dates are available for sediments at various depths in this core, the time scale for the altered sedimentation pattern can be estimated by comparing floc limit values for stations in Letang Inlet sampled in 1990 and 1999 (Fig. D.2). In the depositional areas of Lime Kiln Bay, floc limit doubled over the 9-year period. Samples from more erosional sites showed no variation between sampling periods. These data suggest that fine grained sediment deposition has been altered over a time period that coincides with the development of aquaculture in the area.

Sediment trace metal enrichment

As a consequence of the alteration to the aggregation dynamics of suspended matter in Lime Kiln Bay, elevated concentrations of surface-active contaminants could be expected. Results from trace metal analysis in samples collected during 1999 showed levels of zinc and copper that exceeded predicted levels based on a lithium normalization technique (Figs. D.3 and D.4). Even the most elevated samples had copper and zinc concentrations that were much lower than probable effects level guidelines for contaminants in marine sediments (CCME 1999). Enrichment was greatest at the stations in Lime Kiln Bay where increased floc limit was found. Copper and zinc are two trace metals that have been suggested as tracers for release of dissolved and particulate matter from finfish aquaculture sites (Fisheries and Oceans 2003). Elevated levels of other metals were not found in the samples.

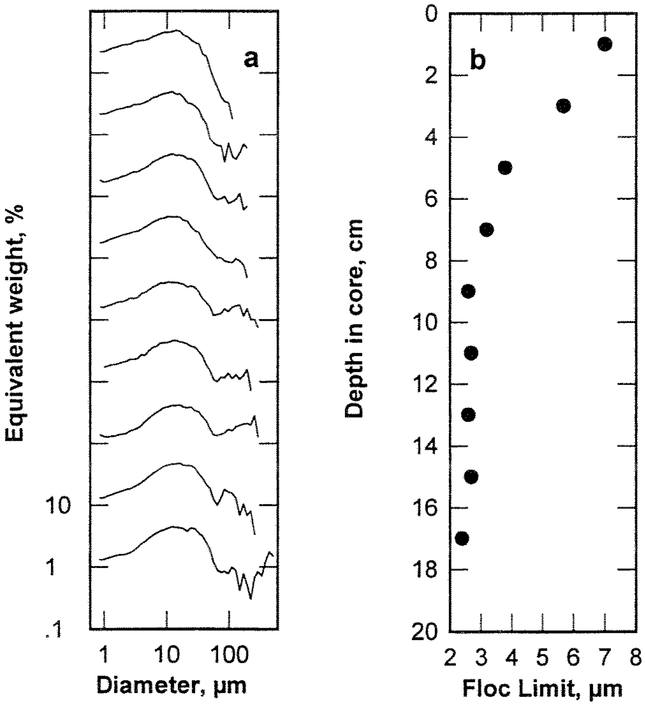

Fig. D.1. Disaggregated inorganic grain size distributions showing change in relative amount of floc settled material towards the top of a core collected in Back Bay NB (a) and the floc limit value determined from the size spectra (b).

A study using copper and zinc as tracers of particulate matter transport to two beaches in the Quoddy region that were near salmon growing operations indicated that the levels of particulate deposition on the clam flat were related to the depositional characteristics of the beach. Although one site on Deer Island was adjacent (100 m) to a salmon site, it had lower relative levels of copper and zinc than another beach (Hinds Bay) in Letang that was over a

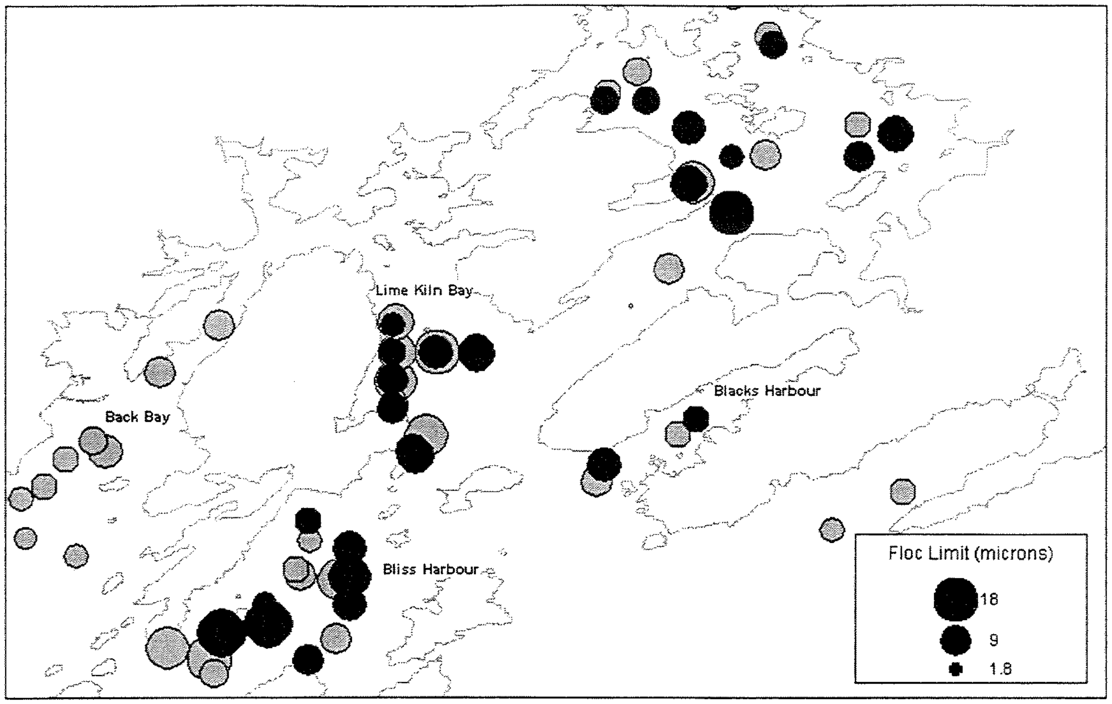

Fig. D.2. Floc limit for surficial sediments in Letang Inlet area for 1990 (black) and 1999 (grey). Floc limit has doubled in the depositional areas in Lime Kiln Bay.

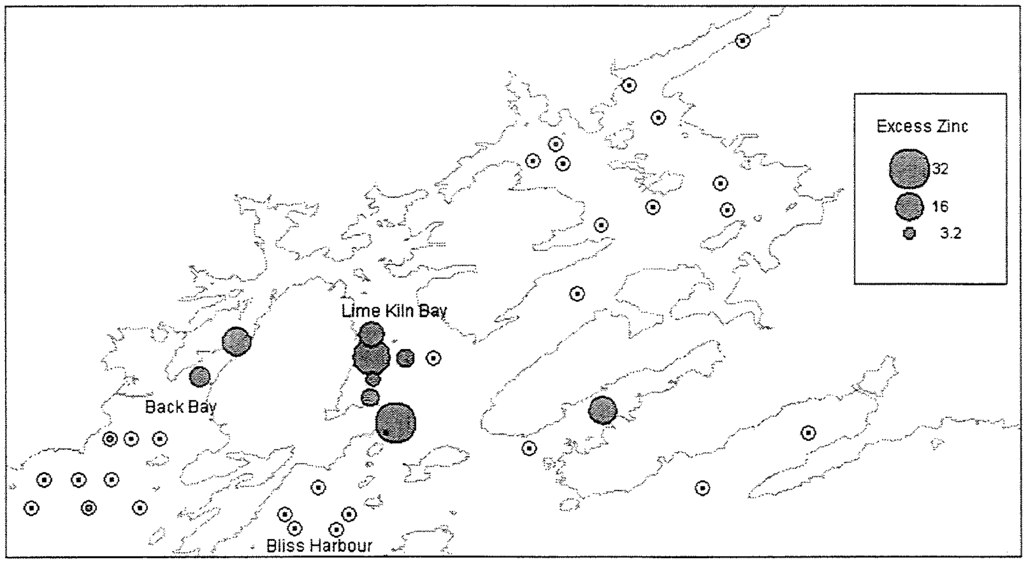

Fig. D.3. Excess zinc (ppm) in surficial sediments in Letang Inlet area in September 1999 calculated using lithium normalization. Excess zinc has increased an order of magnitude in Lime Kiln Bay and Back Bay.

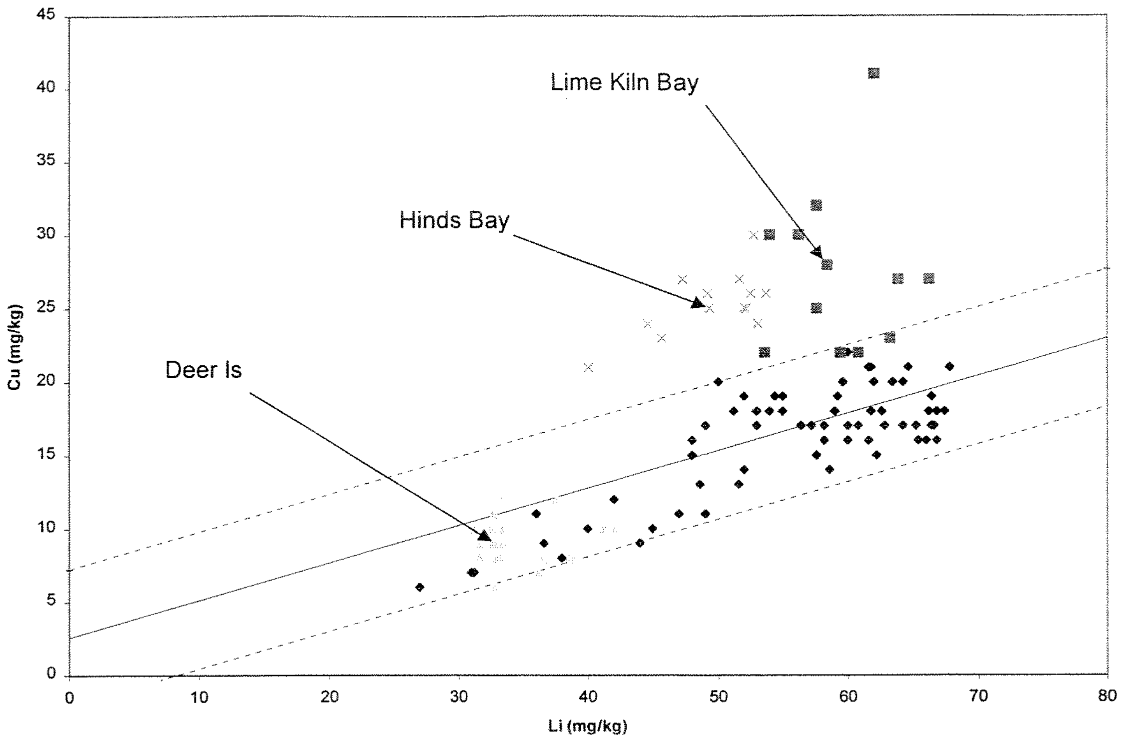

Fig. D.4. Copper vs lithium relationship for sediments from the Passamaquoddy area. The Deer Island and Hinds Bay samples are intertidal beach samples and the Lime Kiln Bay samples from bay bottom samples away from farm sites. The remaining samples (black diamonds) define the background relationship between copper and lithium in the Passamaquoddy area.

kilometer from the nearest salmon site (Fig. D.4). The main differences between the two sites were related to sediment grain size and the degree of exposure. One conclusion of this study is that particulate material deposited in an intertidal region adjacent to an aquaculture site may not stay there, depending on the erosional characteristics of the beach. This also implies that if suspended solids make it to the beaches, then dissolved nutrients from the sites will also be washing over the intertidal area.

Water that is rich in dissolved nitrogen may be beneficial to the growth of marine algae in the intertidal and subtidal zones. In the intertidal zone, one of these species is *Enteromorpha intestinalis*. This green alga can form felt-like mats on the surface of the beaches that cover large areas of the surface. Local studies have shown that these algal mats reduce clam densities (*Mya arenaria*) in the area, decrease clam burial depth and reproductive output (Auffrey and Robinson 2001; Auffrey et al. 2002; Robinson unpublished data).

References

Auffrey, L. and S. Robinson. 2001. Effects of green macroalgal mats on the population dynamics of soft-shell clams (*Mya arenaria*) in southwestern New Brunswick.pp.35-37. In: Hargrave, B.T. and G.A. Phillips (Eds.) Environmental Studies for Sustainable Aquaculture (ESSA):2001 Workshop Report. Can. Tech. Rep. Fish. Aquat. Sci. 2352: vii + 73 pp.

Auffrey, L., S.M.C. Robinson and M.A. Barbeau. 2002. Green algae and clams: What's the story? pp.84-91. In: Hargrave, B.T. (Ed.) Environmental Studies for Sustainable Aquaculture (ESSA):2002 Workshop Report. Can. Tech. Rep. Fish. Aquat. Sci. 2411: v + 117 pp.

CCME. 1999. Canadian environmental quality guidelines. Canadian Council of Ministers of the Environment, Winnipeg, Manitoba.

Hill, P.S. 1996. Comparison of two models of aggregation in continental shelf bottom boundary layers. Deep-Sea Res. 43: 679-702.

Jackson, G.A. 1995. Comparing observed changes in particle size spectra with those predicted using coagulation theory. Deep-Sea Res. 42: 159-184.

Kranck, K. and T.G. Milligan. 1985. The origin of grain size spectra of suspension deposited sediment. Geomar. Lett. 5: 61-66.

Kranck, K., P.C. Smith and T.G. Milligan. 1996. Grain size characteristics of fine-grained unflocculated sediments I: 'One-round' distributions. Sedimentology 43: 589-596.

Kranck, K. 1993. Flocculation and sediment particle size. Arch. Hydrobiol./Suppl. 75: 299-309.

Milligan, T.G. 1994. Suspended and bottom sediment grain size distributions in Letang Inlet, N.B., October 1990, Can. Tech. Rep. Hydrogr. Ocean Sci. 156: iv + 51pp.

Milligan, T.G. and P.S. Hill. 1998. A laboratory assessment of the relative importance of turbulence, particle composition, and concentration in limiting maximal floc size and settling behaviour. J. Sea Res. 39: 227-241.

Milligan, T.G. and D.H. Loring. 1997. The effect of flocculation on the size distributions of bottom sediment in coastal inlets: implications for contaminant transport. Water, Air, Soil Poll. 99: 33-42.

Muschenheim, D.K., P.E. Kepkay, and K. Kranck. 1989. Microbial growth in turbulent suspension and its relation to marine aggregate formation. Neth. J. Sea Res. 23: 283-292.