Assessing the environmental costs of Atlantic salmon cage culture in the Northeast Pacific in perspective with the costs associated with other forms of food production

Kenneth M. Brooks[1]
Aquatic Environmental Sciences, 644 Old Eaglemount Road, Port Townsend, Washington, United States of America

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ABSTRACT

There are environmental costs associated with every form of food production and none of these appear sustainable at the present time. The goal of a rational society should be to achieve sustainability of all food production and use of natural resources. That means understanding the environmental costs associated with all forms of agriculture, aquaculture and the harvesting of wild stocks. Those costs should then be prioritized and society should focus its energies on efficiently solving the most demanding problems. In a global sense, those most demanding problems likely involve topsoil losses and the availability of fresh water. It has been obvious for several decades that the oceans' food resources are being over-exploited and few jurisdictions have been successful in managing the harvest of fish and shellfish. Aquaculture holds a promise to supplement the ocean's bounty. Small scale aquaculture is an ancient practice, but industrial scale aquaculture is relatively new and because of its scale, it can potentially carry significant environmental costs which must be managed to insure that they do not become widespread or irreversible. Aquaculture's emergence as a major source of seafood has created social and economic tensions within some societies that are played out as environmental issues using keywords and terms such as sustainability. This paper describes the near-field environmental response to organic enrichment associated with salmon aquaculture in the Northeast Pacific. It is emphasized that the conclusions reached for this region cannot be applied to all salmon producing areas. Environment Risk Analysis (ERA) and Life Cycle Analysis (LCA) must be at least regionally specific and in most cases they must be specific to individual sites or groups of sites. A methodology for categorizing aquaculture

[1] brooks@olympus.net

hazards in an operative way is provided and definitions for terms such as *near-field* and *far-field* effects are suggested as is a method for prioritizing hazard assessments for salmon aquaculture. Primary production in the Northeast Pacific is generally light and not nutrient limited and salmon aquaculture has minimal potential to affect phytoplankton production in much of this region. The major environmental cost identified to date is benthic enrichment. Significant effects appear to be restricted to a few hectares within 200 m of netpens. Chemical remediation of sediments at reasonably well sited farms takes six months to a year. In the worst case studied, chemical remediation was nearly, but not totally, complete following five years in fallow. This site was predicted to be chemically remediated after seven years of fallow. Biological remediation, as defined herein, occurs within a year following completion of chemical remediation. This analysis suggests that the empirically measured reductions in the biomass of benthic invertebrates results in the loss of approximately 300 kg of wild fish during production of 2.5 million kg of Atlantic salmon. The yield of edible flesh from Atlantic salmon is 50 percent of live weight and it is 42 percent for beef cattle. In contrast to the small (1.6 ha average) and ephemeral (44 month long) effects created by salmon farming, the growing of an equivalent amount of beef is shown to require 6 982 ha of high quality pasture for 30 months plus as long as several hundred to a thousand years of remediation. Achieving sustainability requires prioritizing the costs of all forms of food production and focusing our energy on solving the most important and tractable issues first. For instance, by catch and lost fishing nets and pots waste a significant portion of the sea's bounty each year. From a sustainability point of view, these costs represent a far greater hazard to marine life than the lost production under a salmon farm.

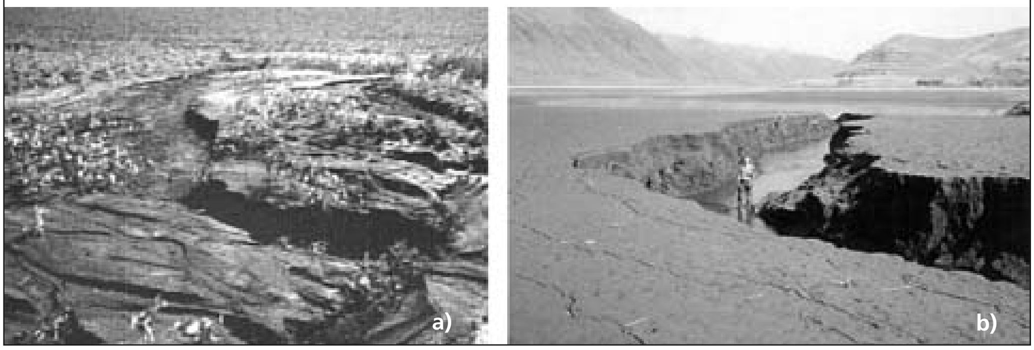
INTRODUCTION

As the expanding human population places additional stress on earth's resources, there is increasing interest in understanding and managing all of the costs of food production. Aquaculture is an ancient practice that holds a promise to supplement the ocean's supply of fish and shellfish in meeting the increasing demand for seafood. However, as with all human activity, the increasing intensity and scale of aquaculture has raised concerns that it may diminish natural productivity as it increases the human food supply.

There are environmental costs associated with all forms of food production. This was brought to light by a young environmental activist several years ago when she stated that her environmental footprint was small because her diet focused on bread and vegetables. Indeed there are environmental costs associated with a loaf of bread. Figure 1a describes soil erosion in Eastern Washington and Figure 1b describes the accumulation of eroded topsoil behind one of several dams on the Columbia River in Washington State where significant quantities of wheat are produced. The annual soil loss from cropland in the United States is four tonnes/acre-year. Depending on the global region, topsoil is being lost 16 to 300 times faster than it is being replenished and forty percent of earth's cropland is degraded (NRCS, 1999). During mediation of a major pesticide issue in Washington State, a farmer lamented that the pesticides he used to grow wheat were not tolerated by peas in their rotation. His solution was to flush the pesticides off his 6 000 acres of cropland with 15 cm of irrigation water. Both of these are examples of the environmental costs associated with a loaf of bread and discussions of the environmental costs of terrestrial agriculture are incomplete unless they include these and similar costs.

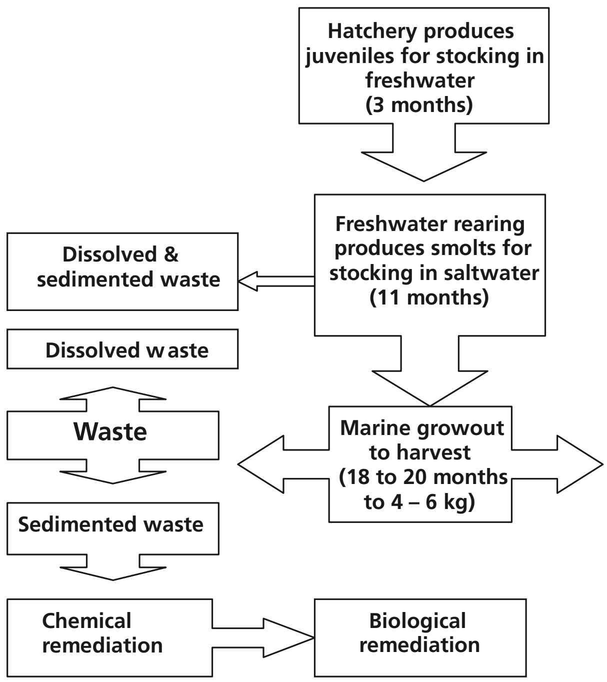
Aquaculture creates environmental costs as well. The purpose of this paper is to assess the nearfield effects associated with organic enrichment from salmon aquaculture in the Northeast Pacific and to attempt to put them into perspective with some of the costs associated with producing an equivalent amount of beef. Figure 2 describes a typical salmon production cycle lasting 32 to 34 months. Definitions for terms used in this paper are provided below.

FIGURE 1
a) Local soil erosion in Eastern Washington. b) Accumulation of eroded topsoil behind one of the dams on the Columbia River in Washington State



Nearfield effects are those that can be measured during point in time surveys. They include organic enrichment of sediments measured through sulfide, redox potential, nutrients (N and P) and organic matter measured as Total Volatile Solids (TVS) or Total Organic Carbon (TOC). Macrobenthic community surveys provide sensitive indications of environmental effects in homogeneous substrates. However, they are expensive and time consuming and they are problematic in heterogeneous environments. Near-field benthic effects have been observed to distances of 205 m downcurrent from Northeast Pacific salmon farms (Brooks, 2001). Water column effects can often be measured within netpens and to several metres downcurrent. However, they have not been detectable 30 m downcurrent at salmon farms in the Northeast Pacific (Brooks and Mahnken, 2003a). Nearfield effects have typically been monitored by producers in compliance with government mandated programs.

FIGURE 2
Phases in the production of Atlantic salmon and associated waste streams. A more inclusive list of potential hazards and environmental costs is provided in Appendix 1



Far-field effects are those that cannot be measured by point in time surveys. These effects include ecosystem eutrophication resulting in increased primary production; reduced oxygen tension due to cumulative effects of all organic inputs, including salmon farms, and the biological oxygen demand associated with sedimented waste and the senescence of increased system-wide primary production. Assessment of far-field effects requires long-term and widespread monitoring to include collection of baseline data. Many coastal waters receive significant nutrient inputs from terrestrial activities including urbanization and agriculture. Therefore, determining cause and effect relationships between observed far-field effects and specific sources is difficult. Mass balance models are useful in this regard, but require inventories of (for instance) all nutrient inputs, which can be difficult and expensive in large and/or complex landscapes. There is increasing interest in waterbody specific computer models that track the dispersion of nutrients and other contaminants and their uptake by macroalgae and/or phytoplankton. Few waterbodies have been modeled in this regard, but the models allow government management by partitioning the total maximum daily load (TMDL) among contributors. Monitoring and managing of waterbodies and the multitude of contributors of any stressor is usually undertaken by government. However, there are few examples of the application of this approach to aquaculture.

Ecosystem. As used herein, is defined as the body of coastal water that encompasses an area forming a relatively discrete hydrologic and biological entity. Ecosystems may be an embayment adjacent to a channel; an entire estuary; a series of interconnected estuaries or a coastal region that is hydrologically contiguous. In other words, the term ecosystem is defined as that area over which the hazard(s) associated with aquaculture can reasonably be expected to affect other resources. The extent of an ecosystem in this context is related to the effect being considered and it will increase as the scale of aquaculture expands within a region.

Economic costs *refer* to the value of goods and services necessary for the production of aquaculture products. They include energy, feeds, infrastructure, salaries, government fees, etc.

Environmental cost as used in this paper is defined as an imposed change that reduces the environment's natural productivity including the abundance and diversity of plants and animals within the affected area. Environmental costs are multidimensional in that they may create effects over some three dimensional space. They also have a temporal dimension. Ephemeral costs may last a few weeks to a few years. Longer term costs may reduce natural productivity for decades, and irreversible costs create changes that affect an environment's productivity for a century or longer. Lastly, environmental costs differ in the degree of their effects. The loss of natural productivity may be barely distinguishable or it can be dramatic resulting in near defaunation of an area. The "environmental cost" associated with an activity depends on all of these dimensions and as stated in the precautionary approach, the costs of greatest concern are those that are "significant, widespread and irreversible."

Hazard is an input or action that results in the imposition of an environmental cost. Hazards include the release of toxins, disease vectors, eutrophication, mechanical effects, etc.

CATEGORIZING THE ENVIRONMENTAL COSTS ASSOCIATED WITH SALMON AQUACULTURE

The environmental costs and hazards associated with each phase of salmon culture are described in Appendix 1. Depending on the desired level of detail, the list could be expanded.

Cost and hazard analyses are site specific

Subtle environmental differences between and within regions require individual analyses. As will be seen, upwelling delivers large quantities of nutrients to near-shore areas in the Northeast Pacific with the result that primary production is generally light limited and is seldom nutrient limited. In this region, sedimented organic waste is the primary hazard observed during the marine growout phase of salmon production. Within the Northeast Pacific Region, there is tremendous variation in the extent and consequences of organic loading. Five to 10 percent of historic farms have created significant negative effects that have proven long lasting with chemical remediation taking as long as seven to ten years (Brooks, Stierns and Backman, 2004). At very well flushed sites with current speeds up to 125 cm/sec, the abundance and diversity of the macrobenthos has been significantly enhanced in response to salmon production (Brooks, 1995c). Varying degrees of adverse effects have been documented within 60 to 200 ms of netpens at perhaps 75 to 85 percent of Northeast Pacific sites. Sediments at several of these sites have been shown to chemically remediate in six months to a year (Brooks 1993c, 1999; Brooks *et al.*, 2003). Thus, while it is possible to discuss regional environmental costs in general, quantitative assessments of near-field effects must be conducted on a site specific basis.

Categorizing environmental costs

The environmental costs associated with any activity are, in large part, dependent on how the activity is managed and assessing environmental costs must be accomplished within the range of management options available. For instance, siting of intensive netpen operations is a management issue that has proven to be the most important factor in determining the benthic response to netpen aquaculture. Other facets of management have a direct and substantial influence on environmental effects. Definitions and typical management approaches for the following four types of hazards are provided below.

Category I hazards are common to many activities in coastal environments. These costs associated with these hazards can be minimized or avoided through known strategies such as proper engineering, worker training, inspection of infrastructure, and etc. Examples of Category 1 hazards include collision of boats with aquaculture structures, which can be mitigated by proper lighting and other programs administered by government agencies such as the Coast Guard; avoidance of fuel spills; collection and disposal of trash, including feed bags; requirements for properly engineered anchoring systems; periodic inspection of infrastructure including containment nets; noise abatement; and etc. Category 1 hazards do require some level of risk assessments because the environmental exposure to them can vary significantly from site to site. Management of Category 1 hazards is typically accomplished through imposition of *Conditions* on permits, use of *Best Management Practices, Codes of Conduct,* and government regulatory programs applicable to a broad range of coastal users.

Category II environmental hazards are inherent to the intensive cultivation of all plants and animals. They include organic enrichment from fed aquaculture (shrimp and piscivorous fish) and organic depletion associated with extractive aquaculture (bivalves, carp, etc). In the first case it is the local area's *assimilative capacity* that is challenged and in the second case it is the *carrying capacity* of the system that must be considered. These hazards can result in either positive or negative effects. In some cases enrichment may result in increased abundance and diversity of wildlife. As the degree of enrichment increases beyond the environment's assimilative capacity, negative responses associated with eutrophication including reduced sediment redox potential may occur. Similarly, extractive aquaculture may be critical to controlling eutrophication in some estuaries that are naturally or anthropogenically enriched. Chesapeake Bay in the United States is an excellent example of an estuary suffering from the lack of the extraction of phytoplankton by bivalves (Newell, 1988). However, the Bay of Marennes-Oleron is an example of an estuary in which overstocking of bivalves (oysters) resulted in exceeding the estuary's carrying capacity, causing reduced growth of the cultured species and likely reduced productivity of the entire food web (Raillard and Menesguen, 1994). In either case, Category II hazards are the inevitable result of the intensive cultivation of animals. While these hazards cannot be avoided in open culture, it can be managed to enhance environmental health in some cases and to control the temporal and spatial extent of adverse effects in others. Management typically begins with careful siting and restraints on allowable production levels at both the local and ecosystem levels. Computer models provide promise of assessing the environment's assimilative or carrying capacity on increasing spatial scales. However, these models have not yet achieved a level of sophistication providing reliable predictions of environmental (chemical or biological) responses. In many cases, the environmental effects associated with Category II hazards are managed through implementation of *Performance Standards.* Monitoring and enforcement is then required to insure compliance.

Category III hazards are associated with potential, but not necessarily inevitable, release of contaminants. These hazards include sediment accumulations of trace metals originating in feed and antifouling compounds; therapeutants including antibiotics and pesticides; organic inputs associated with net cleaning, disposal of mortalities; and etc. Category 3 hazards are managed through proper siting and efforts to minimize or eliminate their effects. These hazards are frequently amenable to quantitative or semi-quantitative risk assessment.

Category IV hazards are those that are unexpected or that can possibly occur, but for which there is limited knowledge upon which to base quantitative or semi-quantitative assessments. They involve disease transfer in both directions; ecological interactions (competition for habitat and food) associated with cultured shellfish and escaped finfish; and genetic interactions between cultured and wild species. Some of these interactions have been better studied than others for example mussel genetics; transfer of disease from wild stocks to cultured stocks; disease transfer to both wild and cultured stocks of bivalves associated with poorly controlled movement of flat oysters (*Ostrea edulis*) resulting in *Bonamia* infections; or the spread of *Perkinsus marinus* and MSX in cultured and wild stocks of American oysters (*Crassostrea virginica*). Other Category IV hazards have not been well documented or remain controversial such as the contribution of sea lice from Atlantic salmon cultured in the Northeast Pacific to wild stocks of pink salmon (*Oncorhynchus gorbuscha*) as discussed by Brooks (2005b; 2006) or the potential for Mediterranean mussels (*Mytilus galloprovincialis*) to displace the more common Baltic mussel (*Mytilus trossulus*) in the northeastern Pacific (Brooks, 2005a). These types of hazards are difficult to assess quantitatively or semi-quantitatively and they are frequently studied only in an effort to develop management strategies when a need is observed. While Category IV hazards are not well documented, they can potentially impose high environmental costs if not adequately understood and managed.

PRIORITIZING THE HAZARD ASSESSMENT PROCESS ASSOCIATED WITH SALMON AQUACULTURE IN THE NORTHEAST PACIFIC

Given the broad range of possible and/or asserted environmental costs requiring risk analysis, a first step is to prioritize hazard assessments based on the likelihood of obtaining useful information. Table 1 provides a comparison of the potential for achieving useful information associated salmon aquaculture hazard assessments. The values in Table 1 were derived using the following metrics:

Availability of empirical evidence
Availability of empirical evidence supporting a hazard assessment is evaluated on a scale of 1 to 5. A low score is assigned if little empirical evidence describing an effect is available. A high score is assigned hazards for which there is substantial empirical evidence. Some costs, such as eutrophication or the potential for genetic interaction of Atlantic salmon with Pacific salmon are well documented. These receive scores of 3 to 5. There is little empirical evidence supporting some of the other costs, such as the potential for antibiotic transfer to humans associated with consumption of wild fish and shellfish harvested in the vicinity of salmon farms. These costs would likely receive scores of 1 or 2. The metric is considered important because it is difficult or impossible to assess the costs of an asserted hazard in the absence of empirical evidence describing those costs.

Probability that the hazard will result in a demonstrable environmental cost
Such probability is measured on a scale of 1 to 5. This score is proportional to the probability that the consequences of the hazard will be realized. The probability of nutrient release to the environment in the form of dissolved and/or particulate organic waste is very high as is the probability that at least small numbers of Atlantic salmon will continue to escape from culture sites. These hazards would be scored 3 to 5. In contrast, the probability of a major fuel spill associated with salmon farming is small and would receive a score of 1.

Environmental consequences of the hazard
This is evaluated on a scale of 1 to 5. The consequences of eutrophication can vary significantly from enhancement to ecosystem wide negative effects. A middle score (1.5 to 3.5) should be assigned to consequences that can vary from negative to positive. The consequences of disease transfer from cultured to wild stocks could be significant and would be judged a 4 or 5, even though the probability of occurrence might be small. The consequences of dissolved nutrient releases in an area where primary production is light limited would be small (score of 1 or 2), whereas the same degree of eutrophication in a nutrient limited waterbody would receive a high score of 4 or 5.

Confidence intervals for environmental cost assessments
Understanding the precision of cost estimates is increasingly identified as a necessary component of ERA and LCA. High scores (4 or 5) should be assigned where there is sufficient empirical evidence, models, and theory to make reasonably accurate predictions that have been field verified. High scores are also associated with strong consensus among scientists studying the effect. Hazards that have not been well explored, or for which there is little descriptive empirical evidence, would be assigned low values of 1 or 2. Hazards for which there is little scientific consensus would also receive low scores in this column. The value of assessing environmental costs in the absence of factual information may be questionable.

Total score
A total score was achieved by summing the scores for the first three metrics and multiplying them by the score for *Confidence.* Other scoring approaches might be considered.

It must be acknowledged that many of the possible effects associated with salmon aquaculture are controversial with a variety of scientific opinions available. The assignments made in Table 1 are those of the author and they would likely vary by jurisdiction and/or reviewer. Constructing such a table is best accomplished by a multidisciplinary team of experts representing differing points of view. In addition, it should be noted that numerical values would likely differ by jurisdiction. For instance, primary production is not light limited in all salmon producing areas of the world and in nutrient sensitive areas it is likely that the environmental costs associated with dissolved nutrient additions from fed aquaculture would rank much higher than they do in the Northeast Pacific. The same is true for genetic interactions. In areas where cultured fish are also found in the wild (such as raising Atlantic salmon in the Atlantic Ocean), the potential for genetic interaction between escaped cultured salmon and their wild brethren may be quite high. Assuming some adaptation to culture through genetic selection in the cultured stock, the consequences of escapes and transfer of the culture phenotypes to wild fish could carry far more significant consequences in the Atlantic than it does in the Northeast Pacific where there is almost no potential for interbreeding between cultured Atlantic salmon and wild Pacific salmon (NRC, 1997). This procedure is not defined for purposes of evaluating the environmental consequences of the various hazards. It is designed to estimate the value of assessing the environmental cost associated with each hazard given the current state of knowledge. The assumption is that it is more profitable to spend time on analyses that will lead to dependable estimates of major stressors than it is to examine hazards for which there is insufficient information available upon which to base reliable estimates or on hazards that are not likely to significantly adversely affect the environment. That does not mean that low scoring hazards should not be researched. That determination is better assessed as the product of the probability and consequences of occurrence.

Accurate accounting of the costs associated with the hazards listed in Appendices 1 and 2 would be a major undertaking that is beyond the scope of this paper. As an exercise to show the level of detail required, the following assessment will address the environmental costs associated with nearfield organic enrichment in marine environments as this is a well studied hazard giving a relatively high confidence for the assessment. The *Total Score* in column 6 is a relative measure of the benefit to be derived from conducting a risk assessment. Highest total scores are achieved for well studied hazards that can cause high environmental costs. Well studied hazards for which there is scientific consensus will result in high confidence risk assessments. On the other hand, lower confidence will be achieved in assessing controversial hazards until the opposing points of view are better reconciled. The scores in Table 1 can be ranked to determine the order in which risk assessments should be undertaken at the current time. However, in terms of future research needs, hazards that can create significant environmental costs and that have a high probability of occurrence are those that should receive priority in terms of research funding.

TABLE 1

Estimates of environmental hazards and possible costs associated with salmon aquaculture in the Northeast Pacific. Each metric is evaluated qualitatively on a score of one to five. The total score is the sum of the first three multiplied by the fourth (Confidence) and represents a relative measure of the benefit to be derived from conducting a risk assessment

	Empirical evidence	Probability of occurrence	Consequences of occurrence	Confidence in the assessment	Total Score
Freshwater eutrophication	4	4	4	3	36.0
Marine sediment enrichment	4	5	3.5	3.5	43.8
Marine water eutrophication	3	1	2	4	24.0
Sediment contamination by Zn & Cu	3	3	3	2	18.0
Depletion of dissolved oxygen	2	1	1	4	16.0
Disease transfer from cultured to wild fish	2	2	5	1	9.0
Genetic interaction between Atlantic & Pacific salmon	1	1	2	5	20.0

ENVIRONMENT COSTS ASSOCIATED WITH ORGANIC ENRICHMENT FROM SALMON AQUACULTURE

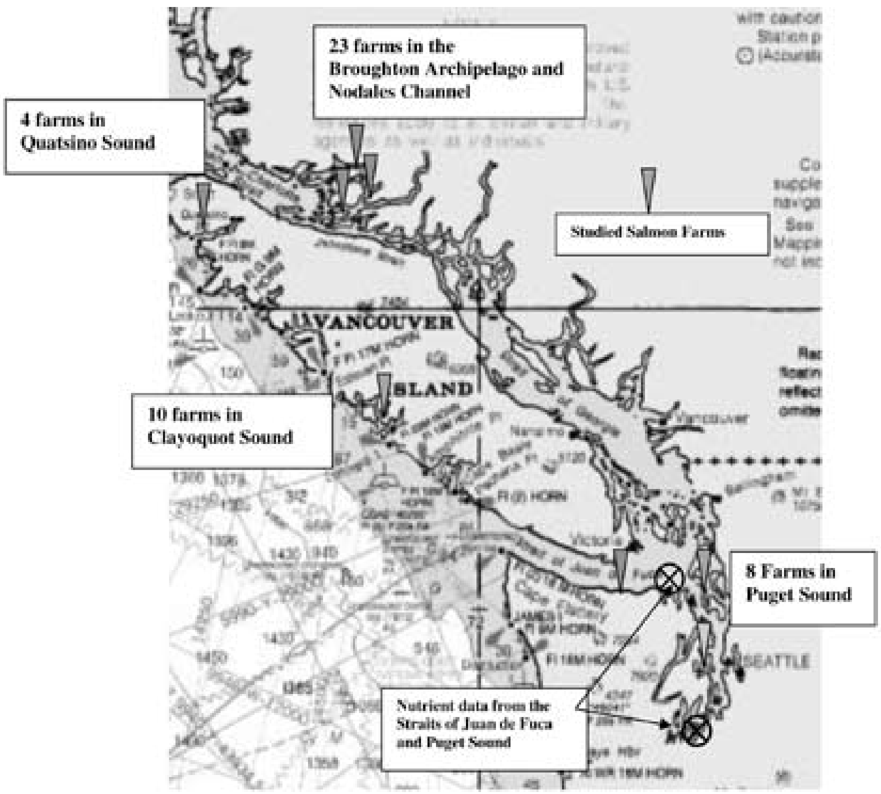
The purpose of the following sections is to show the amount of effort and detailed work, analyses required to effectively estimate environmental costs associated with only this one type impact of salmon aquaculture.

The locations of the 45 salmon farms included in the database upon which the following discussion is based are described in Figure 3. All of these sites have relatively cool water varying between approx. 6 or 7°C in winter and 16°C in summer. In 2003, British Columbia and Washington State produced approximately 65 000 tonnes of mostly Atlantic salmon (*Salmo salar*) and small amounts of coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) salmon. Salmon farms in the Northeast Pacific are generally located in water depths of 18 to over 100 ms with average current speeds varying between 3 and >25 cm/sec. Maximum harmonically driven current speeds vary between 10 and 125 cm/sec.

Dissolved oxygen

Weston (1986) reviewed the effects of salmon culture on ambient concentrations of dissolved oxygen (DO) and concluded that salmon farms could decrease these levels by 0.3 ppm. Brooks (1991, 1993a, 1993b, 1993c, 1994a, 1994b, 1995a, 1995b, 1995c) observed decreases of as much as 2 ppm in water passing through a large, poorly flushed farm in Puget Sound. Statistically significant reductions in DO were not observed by Brooks (1994b, 1995b, 1995c) at farms in well-flushed passages. In no cases were DO levels within 6 m of the downstream farm perimetres depressed below 6 mg/L, a minimum level for optimum culture of salmonids. Winsby *et al*. (1996) suggested that

FIGURE 3
Site map describing the general location of 45 salmon farms monitored between 1991 and 2005 that have generated data forming the basis of the analysis presented herein



depressed oxygen levels were associated with the water column immediately overlying anaerobic sediments and that salmon farming had minimum potential to adversely oxygen concentrations in the water column. These results suggest that salmon farms do not currently impose a cost on Northeast Pacific environments associated with the consumption of oxygen. However, naturally depressed oxygen concentrations associated with upwelling have severely stressed cultured fish, leading, in a few cases, to mortality. This affects the overall environmental cost of salmon production because the dead salmon represent a wasteful sink of valuable resources associated with feed and other fixed costs that are not realized as human food. This issue is presented as an example of the importance of management (siting) on the environmental costs associated with Category III hazards.

Dissolved nutrient loading in the Northeast Pacific

Salmon and most other fish excrete 75 - 90 percent of their ammonia and ammonium waste across gill epithelia (Gormican, 1989) or in concentrated urea (Persson, 1988; and Gowen *et al.* 1991). Brett and Zala (1975) reported a constant urea excretion rate by sockeye salmon of 2.2 mg N/kg per hour. Nitrogen and phosphorus are also dissolved from waste feed and feces during and after their descent to sediments. All of these dissolved forms of nitrogen are readily available for uptake by phytoplankton. Silvert (1994a) suggested that 66 to 85 percent of phosphorus in feed is lost in a dissolved form to the environment at salmon farms. However, phosphorus is plentiful in Northeast Pacific marine environments (Figure 4) and seldom limits primary production (Brooks, 2000a; 2006).

Statistically significant increases in soluble nutrients at salmon farms have infrequently been observed in Puget Sound (Rensel, 1989; Brooks, 1994a; 1994b; 1995a; and 1995b). Prior to 1995, Aquatic Lands Leases (ALLs) for salmon farms in Washington State required monitoring of NO_3, NO_2 and total ammonia (NH_3 + NH_4). Worst case concentrations observed between 1989 and 1995 are summarized in Table 2. Consistent with these results, monitoring by Pease (1977); Rensel (1988 and 1989), and Parametrix (1990) documented small increases in dissolved nitrogen within and on

FIGURE 4

Dissolved inorganic nitrogen, orthophosphate and chlorophyll *a* recorded in the Straits of Juan de Fuca at Admiralty Head (WDOE, 1998; 2002)

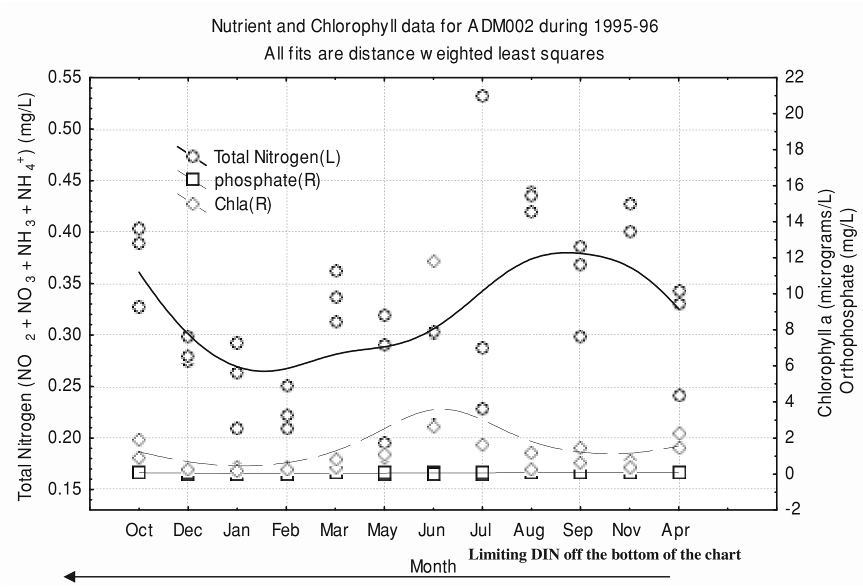


TABLE 2
Water column dissolved inorganic nitrogen (µmoles/L) and unionized ammonia (in parentheses measured in mg/L) in the vicinity of salmon farms in Puget Sound, Washington (Brooks, 1993a; 1993b; 1993c; 1994a; 1994b; 1995a; 1995b; 1995c)

Farm	Dissolved Inorganic Nitrogen (µM)		
	100' upstream	20' upstream	100' upstream
A (1995)	9.58	14.87 (0.0002)	11.43
B (1994)	21.34	22.87 (0.0004)	23.04
C (1989)	22.51	25.83 (0.0003)	23.87
D (1994)	12.54	11.80 (0.0003)	12.15
E (1995)	5.47	5.16 (0.0002)	5.18
F (1995)	10.70	10.83 (0.00001)	11.85
G (1995)	6.06	6.21 (0.0002)	5.71
H (1994)	9.78	11.34 (0.0001)	10.80

the perimeter of salmon farms. However, all of these authors agreed that the quantity of dissolved nitrogen added by even several farms would have no measurable effect on phytoplankton production. Gowen, Weston and Ervik (1988) studied a Scottish loch with restricted water exchange to the open sea and a large salmon farm. They concluded that the farm had no measurable effect on phytoplankton density. Similar results have been found in other salmon farming regions (Soto and Norambuena, 2004).

In general, the variability between replicate samples taken at the 6 m downstream station was as great, or greater, than observed increases in nitrogen between upstream and downstream stations. No significant increases in nitrogen were observed at any of the 30 m downstream stations at any time. The greatest increase in reported DIN between upcurrent and downcurrent stations was 0.09 mg/L or 8 percent of the mean DIN values observed by Weston (1986) in Puget Sound and the highest observed level of toxic unionized ammonia (NH_3) reported by Rensel (1989) inside salmon netpens was 0.0004 mg/L, which is lower by a factor of 87.5 than the U.S. Environmental Protection Agency (USEPA) chronic exposure (4-day) concentration limit of 0.035 mg/ L at pH = 8 and T = 15^{o}C when sensitive salmonid species are present.

Burd (1997) estimated that upwelling delivered approximately 2 000 tonnes of nitrogen to coastal British Columbia and Puget Sound environments each day. River inputs added 100 tonnes and sewage inputs were estimated at 70 tonnes. At that time British Columbia salmon farms were producing approx. 22 000 tonnes of salmon/year and it was estimated that they added another 6 tonnes of DIN/day. Scaling linearly to current production of 58 000 tonnes suggests that in 2005, salmon farms contributed approx. 15.8 tonnes DIN to coastal environments or 0.7 percent of the total 2 185.8 tonnes.

Other factors affecting primary production

In the Pacific Northwest, wind-driven vertical-mixing drives a significant proportion of the standing biomass of phytoplankton below the compensation depth where cell respiration equals photosynthesis and where phytoplankton populations no longer multiply. Where water freely circulates, flood tides replenish nutrients from offshore upwelled water. When coupled with the atmospheric and geographical factors that reduce light availability, the result is that primary productivity is generally light limited, not nutrient limited. This is especially true during winter months. In other words, there is insufficient light to use the nutrients already available in the water column. Adding nutrients to a light limited system does not increase plant growth. There are sheltered, poorly flushed, shallow embayments with long residence times (>10 to 20 days) where salinity and temperature induced stratification results in a stable water column allowing phytoplankton to remain above the compensation depth. When these conditions appear in the spring or summer, significant blooms can occur following several days or weeks of clear sunny weather. These blooms eventually wane because winds increase vertical mixing; cloud cover reduces the available light; or nutrients are depleted in the surface water. In this last situation, nutrient input from intensive aquaculture could further stimulate plant growth, exacerbating the problem. In addition, shallow bays having significant freshwater input and minimal flushing, are not considered good sites for net-pen grow out operations. However, they might be deemed appropriate as smolt introduction sites.

The last point to consider in this discussion is that nitrogenous compounds are released from fish farms into currents that generally average greater than 4 to 12 cm/sec and acoustic Doppler current meter studies at British Columbia salmon farms have revealed net transport (resting current) speeds of 1.0 to 5.0 cm/sec. At temperatures of 10–15°C, it takes one to two days for an algal cell to divide, even if all of its photosynthetic needs are met (Brooks, 2000). An algal bloom may result in cell densities increasing from a few thousand cells/ml to a million or more. That requires eight or nine cell generations, which takes a minimum of 8–16 days. In open bodies of water, moving with a net speed of even 2 cm-sec^{-1}, a phytoplankton population would move 14 km from the location at which nutrients were added during creation of a bloom. Recall that the barely significant increases in nitrogen observed 6 m downstream from farms in Puget Sound were generally not detectable 30 m downstream. Within a single algal cell division (one to two days), the water passing through the farm would have traveled at least 1.7 km. It is difficult to conclude that nutrient additions from a farm, generally undetectable at 30 m downstream, would have any affect on primary production even if the water body was nutrient limited.

Supporting these theoretical arguments are studies conducted by Banse, Horner and Postel (1990); Parsons *et al.* (1990); Pridmore and Rutherford (1992); Taylor (1993); Taylor, Haigh and Sutherland (1994); Taylor and Hatfield (1996) and Taylor and Horner (1994) who examined phytoplankton production and blooms of noxious phytoplankton in the Pacific Northwest and concluded that nitrogen levels and phytoplankton production at salmon farms were determined by ambient conditions and that aquaculture added little to the abundant nutrients supplied in upwelled water. These conditions are specific to the Northeast Pacific and the conclusions should not be extended to other regions without careful consideration. This issue was reviewed because it is an example of the importance of siting in minimizing the environmental costs associated with Category II hazards.

Benthic effects associated with solid waste

From an environmental point of view, it is sedimented waste that currently appears to carry the highest environmental costs in association with fed aquaculture. This is a Category II hazard that appears to create quantifiable and inevitable environmental costs in the near-field.

Waste feed. The amount of waste feed depends on feeding efficiency, which is principally influenced by feed composition, feeding methods, water currents at the site, and net-pen configuration. Beveridge, Phillips and Clarke (1991) stated that up to 30 percent of feed was lost during the early years of salmon farming. Rosenthal, Scarratt and McInerney-Northcott (1995) noted higher losses for wet feeds (up to 35 percent), than for dry feeds. Weston (1986) suggested that less than 5 percent of dry feed was lost at Puget Sound salmon farms. This is consistent with the research by Gowen and Bradbury (1987), who reported dry feed losses of 1–5 percent. Findlay and Watling (1994) reported maximum feed loss rates of between 5–11 percent, and that the average feed wastage was <5 percent. Dry and semi-moist feeds are now used exclusively in the Northeast Pacific and current feed loss rates are estimated at between 3 percent and 5 percent (J. Mann, EWOS Canada Ltd., personal communication). Modern monitoring systems incorporating feedback cones and underwater video or acoustical devices described by Mayer and McLean (1995) are now commonly used to monitor feeding behavior in efforts to minimize losses of uneaten feed from net-pens. Most of the current feed loss is associated with abrasion and breakage in automatic feeders, which can result in the disintegration of 4–5 percent of the pellets. Optimum feeding systems, with short delivery distances that are operated by compressed air valves, may reduce disintegration to <0.5 percent of the pellets (J. Mann, EWOS Canada Ltd., personal communication). The results of this review are reasonably consistent and indicate that at this time, 5 percent or less of the dry feed delivered to cultured salmon in net-pens is lost to the environment. These low rates are due to the combination of improved feedback technologies and the practice of quickly feeding the fish to satiation once or twice each day. Improvements in feed delivery systems to minimize pellet disintegration will probably reduce losses further. This assessment will assume feed losses are 5 percent. It should be noted that wasted feed is accounted for in the computation of the economic food conversion ratio (FCR), but not in the calculation of a biological FCR.

Fish feces. Weston (1986) estimated that 25–33 percent of the feed consumed by fish was ejected as feces. Modern diets are approximately 87–88 percent digestible (J. Mann, EWOS Canada Ltd., personal communication). The remaining ash consists primarily of calcium and inorganic phosphate, and represents 8.0–8.5 percent of the feed. This implies that approximately 12.5 percent of the weight of ingested feed will be ejected in feces. Subtracting the 87.7 percent that is digested and assimilated by the fish and 8.25 percent for ash, leaves about 4 percent of the feed that is ejected as labile organic material in the feces. If 5 percent of the feed is uneaten (Findlay and Watling 1994) and feces contribute organic matter equivalent to 4 percent of the feed weight, then approximately 8.8 percent of the labile organic compounds delivered in feed is discharged from the net-pen structure in particulate form, contributing to biological oxygen demand (BOD) in sediments.

Fish carcasses as organic wastes. Winsby *et al.* (1996) reviewed the mortality of fish at BC salmon farms in 1994. Their data suggested approximately 2 000 tonnes of salmon died at farms that year, or approximately 9 percent of the total production of 22 000 tonnes. They concluded that most of the salmon carcasses were removed to government approved compost disposal locations. No inappropriate disposal of salmon carcasses has been documented in the literature. Losses of farmed salmon are generally restricted to individual fish, which may have been attacked and killed by predators; died as a consequence of toxic algal blooms; or as a result of disease. Codes of Practice require physical removal of carcasses on a daily basis and therefore they do not contribute to BOD in the environment.

Quantification of solid organic waste from salmon aquaculture. Ackefors and Enell (1989) estimated the total organic output from salmon farms on the order of 2.5 tonnes wet weight/tonnes of fish produced. Gowen, Weston and Ervik (1991) cited three studies assessing the flux of carbon through salmon net-pens. In all three cases the harvested fish retained 21–23 percent of the carbon in feed and it was estimated that 75–80 percent of the carbon was lost to the environment mostly in a dissolved form as CO_2. Merican and Phillips (1985) estimated that 35.6 percent of the carbon, 21.8 percent of the nitrogen, and 65.9 percent of the phosphorus were lost to the environment in solid form. Other estimates of the total suspended solids output from intensive net-cage culture of fish by Kadowaki *et al.* (1980); Warrer-Hansen (1982); Enell and Lof (1983); and Merican and Phillips (1985) range from 5–50 g suspended solids/m^2-day. All these publications are more than 15 years old and therefore these values do not reflect recent improvements in fish feed and feeding technologies.

Gowen and Bradbury (1987) estimated organic waste sedimentation rates of 27.4 g/m^2-day under Irish salmon farms, and an average of 8.2 g/m^2-day immediately adjacent to the perimeter of the net-pens. Gowen *et al.* (1988) measured average rates of 82.2 g dry weight/m^2-day on the perimeter of a net-pen in Washington, and Cross (1990) estimated an average overall sedimentation rate of 42.7 g TVS/m^2-day with a maximum of 94.5 g total volatile solids (TVS)/m^2-day at seven salmon farms in BC. More recent work by Findlay and Watling (1994) in Maine measured sedimentation rates on the perimeter of salmon farms at between 1.0–1.6 g carbon/m^2-day, and Hargrave (1994) summarized sedimentation rates from less than one to over 100 g carbon/m^2-day from salmon cage operations.

Brooks (2001) derived a theoretical estimate of contemporary TVS loading near fish farms. Given a feed with 11 percent moisture content and FCR of 1.2, the feed provided (1.2 kg x 89 percent dry matter) or 1.07 kg dry feed/kg of fish produced. When coupled with the previously given estimate for the percent labile organic waste of 8.8 percent this equals 0.094 kg solid organic waste/kg of fish produced. A salmon farm producing 1 500 tonnes of salmon during a 16 to 20 month production cycle would therefore discharge 141 tonnes of particulate organic waste on a dry weight basis. Furthermore, assuming a fish density of 10 kg/m^3 in cages 15 m deep and a grow-out cycle of 18 months, the annual sediment load on average would be:

(10 kg fish/m^3 x 15 m deep x 0.094 kg TVS/kg fish)/548 days = 25.7 g TVS/m^2-day

The load would, in reality, be lower at the beginning of the grow-out cycle and increase towards maximum biomass. Brooks (2001) analyzed sediments collected in canisters deployed 5 m above the bottom at varying distances from seven farms in BC and at reference stations. The mean loading of volatile solids on the perimeter of these farms was 39.2 g TVS/m^2-day. The mean deposition of volatile material at the control stations was 6.3 g TVS/m^2-day and the contribution by the farm was approximately 32.9 g TVS/m^2-day. These studies were completed near peak salmon biomass and the observed values would therefore be greater than the theoretical average of 25.7 g TVS/m^2-day calculated above. Nonetheless, these observed and theoretical values are reasonably close.

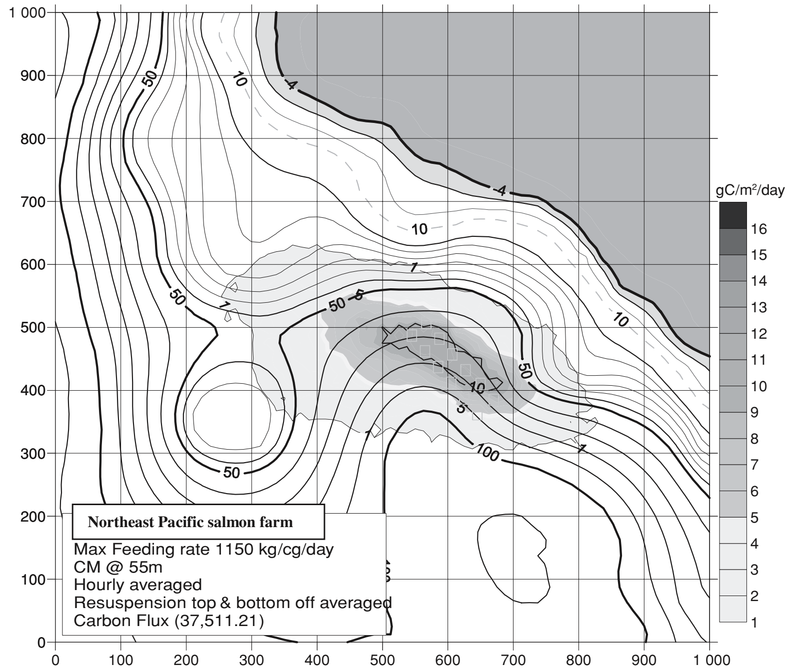
Site specific models, such as DEPOMOD (Cromey, Nickell and Black, 2002) are now used in British Columbia to predict the deposition of organic carbon associated with proposed salmon farms. Figure 5 is an example of the model's output. Several comparisons between DEPOMOD predictions and empirical evidence in the form of sediment physicochemical changes have been made by Brooks (unpublished). In general, these comparisons show remarkably similar patterns of responses when resuspension is turned off in the DEPOMOD program. The model only predicts deposition rates of organic carbon and it does not yet include modules predicting more meaningful physicochemical or biological responses.

Sediment physicochemical response to salmon farm inputs

Findlay and Watling (1994) developed a simple model for estimating aerobic carbon degradation rates (g C/m^2-d) based on the minimum two hour-average bottom current speed (cm/s). They estimated that at low bottom current speeds (<0.1 cm/s) a theoretical maximum aerobic degradation rate of approx. 4.0 g C/m^2-d could be achieved. The predicted aerobic carbon degradation rate appears to asymptotically approach a value of approx. 22 g C/m^2-d at bottom current speeds greater than 10 to 12 cm/s. Time weighted 15 m deep current speeds at many BRITISH COLUMBIA salmon farms averaged 3.5 to 9 cm/s and the two hour minimum mean surface current speeds are generally < 3 cm/s (Brooks, unpublished). Even assuming that bottom current speeds equal near surface speeds, the model of Findlay and Watling (1994) predicts a maximum

FIGURE 5

Output from the DEPOMOD program (Cromey, Nickell and Black, 2002) for a salmon farm located over a rocky bottom in British Columbia



carbon assimilation rate of approx. 17 g C/m^2-d at 3.0 cm/s. The sedimentation rates reported by Brooks (2001) at seven British Columbia salmon farms generally exceeded this value and therefore it should be expected that the assimilative capacity of sediments in the vicinity of salmon farms is exceeded and that changes in sediment chemistry will occur while the excess carbon is being assimilated. Those effects are well document in a voluminous literature describing similar benthic responses from around the world. The following paragraphs describe sediment physicochemical responses to organic inputs recorded in this literature.

Organic content of sediments. Factors affecting the accumulation of waste include fish biomass and feeding rates; fish food and fecal material particle sizes and densities; netpen configuration; water depth; current speeds; and the degradation rate of sedimented carbon which depends primarily on the availability of oxygen and sulfate. The proportion of farm derived TVS observed in sediments integrates all of these factors. In addition to farm waste, there are numerous sources of natural TVS including terrigenous material, eelgrass and macroalgae, senescent plankton, etc. Many of these natural sources are refractory creating lower biological oxygen demand (BOD) than labile farm waste. As demonstrated by Brooks (2001), these differences in the nature of TVS confound the use of sediment carbon as an indicator of benthic effects.

There is a diverse literature describing sediment organic content adjacent to salmon farms in other parts of the world (Ye *et al.*, 1991; Holmer and Kristensen, 1992; Johnsen, Grahl-Nielson and Lunestad, 1993; Hargrave *et al.*, 1995; 1997; Lu and Wu, 1998; Karakassis *et al.*, 1999). These reports demonstrate consistent, but highly variable, increases in carbon under and immediately adjacent to salmon farms. This literature also suggests that waste deposits from fish farming are locally patchy with significant variability in replicates from the same sample station. Brooks (1999) described the spatial extent and temporal behavior of TVS in sediment adjacent to a British Columbia salmon farm that produced 1 200 tonnes of Atlantic salmon in 1996.