FIGURE 6

Total volatile solids observed in sediments under the Moonbeam salmon farm as a function of time (lines) and distance (metres) from the perimeter of the farm on the downcurrent transect (300 °M) and at a remote control station

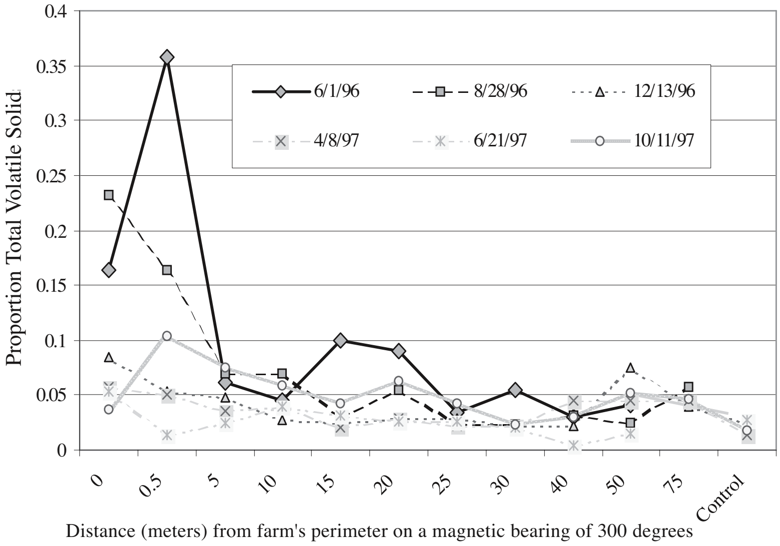
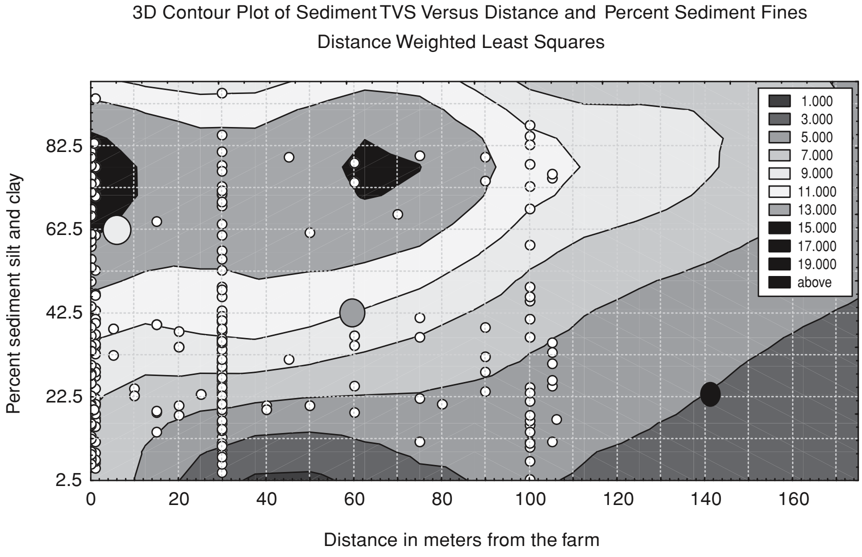


Figure 6 describes the proportion TVS observed in sediments from just before peak biomass in August 1996 through a six-month fallow period, which ended in October 1997. Sediment TVS adjacent to the netpen perimeter declined rapidly from a peak of 35 percent at peak biomass to values indistinguishable from background by June 1997, three months following completion of harvest. Increased TVS extended to at least 75 m. Samples were not collected beyond 75 m because the sediment texture changed at that point from muddy sand to sandy gravel, which continually fouled the grab. Brooks (2000b) reported the results of evaluating 676 sediment samples collected at 34 British Columbia salmon farms between 1996 and 2000. The TVS data are summarized in Figure (7). Each of the large filled circles represents the TVS value equal to the upper 90th percentile observed at British Columbia reference stations with percent fines (< 63 µm fraction) equal to 22.5 percent (lower right), 42.5 percent (center) or 62.5 percent (upper right). Exceedances of this 90th percentile TVS benchmark occurred at distances up to 80 m in fine-grained sediments; to 60 m at sites with approx. 42.5 percent fines and to 140 m downcurrent from sites located in erosional environments with < 22.5 percent sediment fines. The biological implications of exceeding the upper 90th percentile TVS observed at a reference station sharing the same water depths and grain size distribution were not investigated in that study, but Brooks (2001) provides a detailed description of the macrobenthic response to a suite of physicochemical endpoints. Figure (7) strongly suggests that salmon farm effects extended beyond 100 m and Brooks (2001) found measurable, albeit small, effects at distances up to 205 m from farms near peak biomass.

Sediment carbon and nitrogen. Sediment carbon and nitrogen monitoring was required by the Washington State Department of Natural Resources as a condition of Aquatic Land Leases for salmon farms between 1989 and 1995. Because phosphorus is seldom limiting in marine environments, it has not been measured in association with marine aquaculture in either Washington State or British Columbia. Figure 8 describes sedimented organic carbon and Figure 9 is for sediment nitrogen at four Northeast Pacific salmon farms selected because they represent a range of hydraulic regimes

FIGURE 7

Sediment TVS as a function of distance from the perimeter of British Columbia salmon farms located in environments characterized by different proportions of silt and clay in the sediment grain size distribution. The circles filled in blue represent the upper 90th percentile TVS observed at British Columbia reference stations having 22.5, 42.5 and 62.5 percent sediment silt and clay



with maximum harmonically driven current speeds varying between 10 cm/sec in Port Angeles, Washington (Brooks, 1995a) to 125 cm/sec at Orchard Rocks in Rich Passage, Washington State (Brooks, 1995b). Arrow Pass is located in the Broughton Archipelago of British Columbia and data there was collected as part of a two year study reported in Brooks (2000). The point that needs to be made is that significant differences in sediment carbon and nitrogen were not observed as a function of distance

FIGURE 8

Percent sediment carbon observed downcurrent from four Northeast Pacific salmon farms with maximum harmonically drive current speeds varying between 10 and 125 cm/sec (Brooks 1995a; 1995b; 1995c and 2000b)

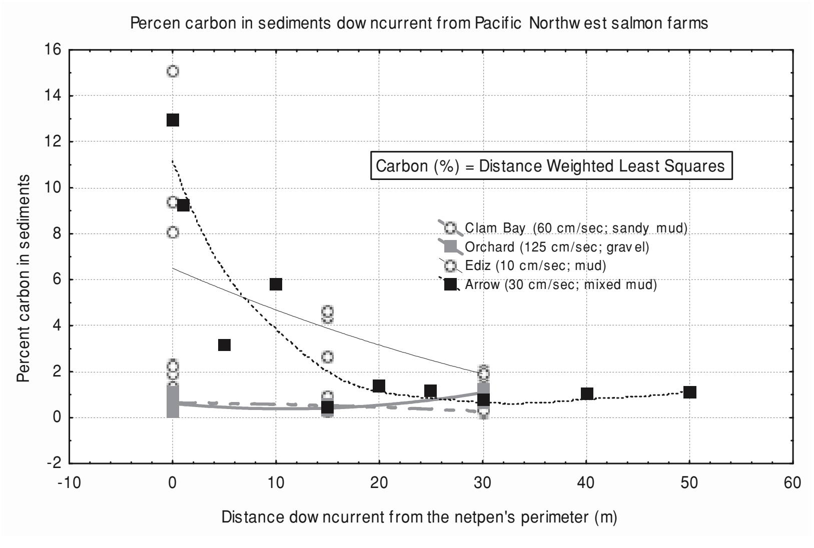
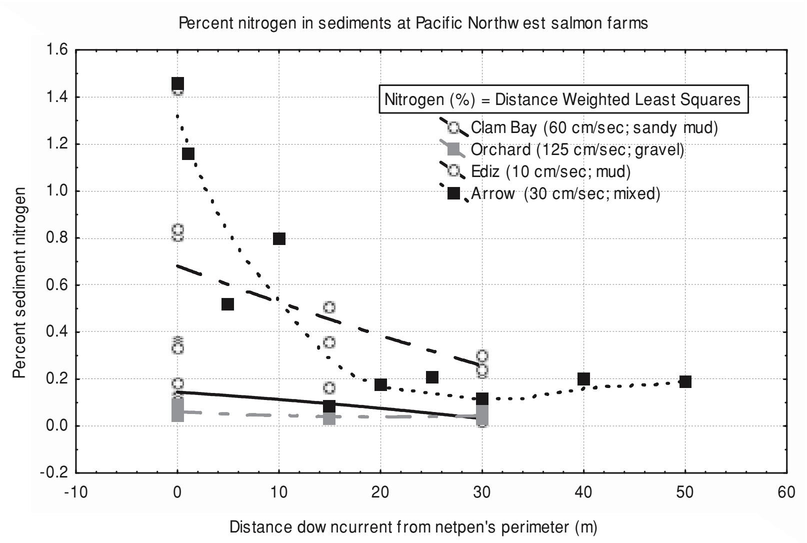


FIGURE 9

Percent sediment nitrogen observed downcurrent from four Northeast Pacific salmon farms with maximum harmonically drive current speeds varying between 10 and 125 cm/sec (Brooks, 1995a; 1995b; 1995c; 2000b)



from the Clam Bay netpens where V_{max} = 60 cm/sec (Brooks, 1995c) or at Orchard Rocks (V_{max}= 125 cm/sec) suggesting that these endpoints were not sensitive indicators of the biological effects that have been observed there (Brooks, 1995a; 1995b; 1995c; 2000b).

Table 3 is a matrix of Pearson Correlation Coefficients describing the covariance of transformed (ArcSin(Sqrt(Percent/100))) sediment carbon and nitrogen with sediment carbon, maximum current speed and distance from the netpen's perimeter. Statistically significant correlations are bolded. Sediment carbon and nitrogen concentrations were highly correlated (p = 0.94), suggesting that both are associated with intact organic molecules and not necessarily with inorganic nitrogenous bi-products of the catabolism of waste (NH_4^+, NH_3, NO_3, NO_2). Sediment carbon was not significantly correlated with either current speed or distance. However, the insignificant correlations indicated that carbon decreased with increasing current speed and distance from the farms. Sediment nitrogen was significantly and negatively correlated with both current speed and distance. However, the correlation with distance is poor suggesting that it is not a sensitive indicator of chemical change. These data suggest that neither carbon nor nitrogen were sensitive indicators of benthic effects at these farms and that sedimented carbon (measured as either TVS or TOC) was a reasonable surrogate for sedimented nitrogen. It is acknowledged that these endpoints have proven useful in other parts of the world. However, due to the paucity of data for Northeast Pacific aquaculture sites, they will not be further discussed in this report.

TABLE 3

Matrix of Pearson Correlation Coefficients describing the relationship between sediment carbon and nitrogen and maximum current speed and distance from the netpen perimeters described in Figures 9 and 10 (Brooks, 1995a; 1995b; 1995c; 2000b). Percent carbon and nitrogen were transformed (ArcSin(Sqrt X/100)) for the analysis

	Correlations (1996 Sediment Carbon and Nitrogen) Marked correlations are significant at p < .05000 N=75 (Casewise deletion of missing data)		
Variable	**Maximum Current Speed (cm/sec)**	**Distance (m)**	**TCarbon**
TCarbon	-0.16	-0.20	1.00
TNitrogen	-0.35	-0.26	0.94

Sediment oxidation reduction potential (Redox). Oxygen is delivered to sediments by diffusion from the overlying water column, and by mechanical infusion of overlying water into the sediments. This last transport mechanism is important in coarse-grained sediments with high porewater volume. Infusion is also enhanced by bioturbation. Mechanical infusion becomes less important as the sediment modal grain size decreases and likely has little affect on sediment redox potentials in fine-grained sediments containing >60 percent silts and clays. However, healthy infaunal communities can infuse oxygen and sulfate into the top 4 to 6 cm of fine-grained sediments. Oxygen is consumed biologically by prokaryotes and eUnited Kingdomaryotes and chemically through chemical oxidation in sediments. In sediments with high organic content, bacterial catabolism of organic materials can create significant BOD along aerobic pathways. When this BOD equals the diffusion and infusion of oxygen from the overlying water column, the sediments are at their assimilative capacity for organic matter. As organic inputs increase further, oxygen levels drop, and the sediments become reducing – leading to the exclusion of some infauna. Therefore, unlike TVS, reduced redox potential affects infaunal communities, regardless the form of TVS.

There is a rich literature describing oxygen uptake in sediments and the resulting redox potential measured using ORP probes and field meters. Measurements of sediment redox potential have been found to be highly variable (Brown, Gowen and McLusky, 1987; Hargrave *et al.*, 1993; 1995; Wildish *et al.*, 1999), which detracts from their use in regulatory programs (Wildish *et al.*, 1999). Henderson and Ross (1995) noted that, "Eh, sulphide and carbon values across the whole study area showed remarkable variation, as other workers have reported and could not be easily used to generalize on the degree of impact." However, GESAMP (1996) lists redox potential as having moderate usage, low cost and high value. Brown, Gowen and McLusky (1987) observed seasonal trends in sediment redox at salmon farm sites with highest levels reported in February followed by a decline in May and August. Sediment redox was constantly reducing within three metres of the cages (-146 to -186 mV), seasonally reducing at 11 m from the cages (-185 mV in May) and positive Eh was observed in February and August. Sediment redox was positive at all stations in all seasons at a distance of 15 m and beyond. Hargrave *et al.* (1993) observed similar seasonal trends with increased oxygen uptake, increased ammonium flux, and increased abundance of *Capitella capitata* during summer months (July through September). Interestingly, there appeared to be a direct relationship between the abundance of *C. capitata* and sediment redox. Pamatmat *et al.* (1973) observed oxygen consumption rates in Puget Sound that ranged from 4 to 56 ml O_2/m^2-hr. Bacteria, meiofauna and infauna accounted for 10 to 50 percent of this consumption and chemical oxidation accounted for the rest. These authors observed that oxygen uptake in sediments under the Clam Bay salmon farm were significantly higher at 125 ml O_2/m^2-hr. However, the oxygen consumption rates declined significantly with distance and reached reference levels within 30 m of the farm. Meijer and Avnimelech (1999) used microprobes to examine oxygen tension in sediments and water in organically enriched freshwater fishponds. They found that absent bioturbation, oxygen penetrated the sediments only to a depth of a few millimetres. The calculated oxygen consumption of 45 to 50 mg O_2/m^2-h was related primarily to biological (bacterial) activity. Negative Eh values were reported at all sediment depths > approx. 2.0 mm with high fish production. Redox potential was positive above a sediment depth of 20 mm at low levels of production and sediment redox was positive at all depths less than 30 mm when nitrate was added to the ponds. The other interesting point made in this paper is that even though sediments were highly reducing at depths greater than 1 to 2 mm, the overlying water was essentially oxygen saturated at a height of 1.0 mm above the sediments – emphasizing the independence of oxygen concentrations in the water and in sediments – even when the sediments were anaerobic. A similar conclusion was reached by Cross (1990) who did not observe decreased dissolved oxygen concentrations in bottom water at seven of eight farms surveyed when compared with local reference stations. Reduced bottom water dissolved oxygen concentrations of 3.1 to 3.5 mg/L were observed at the eighth farm. In contrast, EVS (2000) reviewed other reports indicating that sediment oxygen demand can lead to depressed oxygen levels in the overlying water (Gowen, Weston and Ervik, 1991; Tsutsumi *et al.,* 1991).

In summary, sediment redox potentials are dependent on sediment grain-size distribution, depth of the benthic boundary layer, bioturbation, organic loading and oxygen tension in the overlying water column. A variety of conditions have been observed, but the literature suggests increased oxygen demand and the potential for reducing conditions in sediments within 10 to 15 m from many (but not all) salmon farms. The literature also suggests that BOD will increase in summer and decrease in winter in enriched sediments. This will result in lower redox potential and increased biological effects in summer and lower responses in winter. The literature also suggests a great deal of variation for redox readings in sediments from a single sample station. No information was obtained that would help partition the variance into instrument, method, technician or true environmental compartments.

Sediment free sulfides ($S^=$). Numerous sources of organic carbon contribute to sediment accumulations in coastal waters. These include authochthonous sources like benthic diatoms and dead infaunal organisms and allochthonous sources such as planktonic detritus, drift macroalgae, eelgrass and terrigenous inputs – particularly in forested regions. These organic materials are degraded aerobically on the surface of sediments. However, oxygen penetration in muddy or sandy sediments is typically restricted to the top few millimetres or centimetres (Heij *et al.,* 1999 or Wang and Chapman, 1999). Below that depth, the oxidation of organic matter rapidly depletes free oxygen and organic matter is oxidized by the reduction of sulfate to sulfide by *Desulfovibrio* and *Desulfotomaculum* bacteria (Kristensen *et al.,* 2000). The importance of sulfate reduction should not be underestimated (Luckge *et al.,* 1999). Kristensen *et al.* (2000) observed that sulfate reduction rates in the top 10 cm of sediment under netpens accounted for 75 to 118 percent of the CO_2 flux across the sediment water interface. They also observed that sediment metabolism beneath the netpens (525 to 619 mM CO_2/m^2-d) was ten times higher than at a local control station (24 to 70 mM CO_2/m^2-d). In the absence of sufficient sulfate, further catabolism of organic matter is accomplished by methanogenic bacteria, producing ammonium (NH_4^+) by stripping oxygen from NO_4. Figure 10 is a simplified diagram describing the cycling of sulfur in marine sediments. Other pathways involving organic sulfur have been omitted and only major pathways included. It should be noted that hydrogen sulfide (H_2S) dissociates in water as a function of pH (i.e. $2H_2S \Rightarrow 2HS^- + H_2$). At pH 6.0, 91 percent of sulfide is in the hydrogen sulfide form. At pH 7.0 this decreases to 50 percent and at pH = 8.0, typical of seawater, only 9 percent of sulfide is in the H_2S form (Wang and Chapman, 1999). The S^{2-} form readily complexes with iron in seawater (Heijs *et al.,* 1999) and has rarely been observed as a dominant free form of sulfur in marine environments (Wang and Chapman, 1999).

Chanton, Martens and Goldhaber (1987) observed that the quantity of sulfate reduced by heterotrophic bacteria was greater than the quantity of reduced sulfur buried in the form of iron sulfide or pyrite. That is because much of the total soluble sulfides ($S^=$) were oxidized to sulfate in the aerobic zone of the sediments or at the sediment water interface in the presence of the sulfur oxidizing bacterium *Beggiatoa.* One can think of sulfate as a recyclable fuel that drives the engine. The end products of anaerobic metabolism in sediments are buried iron sulfide and pyrite, carbonate, and a variety of forms of soluble sulfur ($S^=$) including hydrogen sulfide. These soluble sulfur compounds continue the cycle until either the organic substrate is exhausted or the soluble sulfides are bound by metals and sulfate is exhausted. Dissociated sulfides ($S^=$ or

HS^-) and hydrogen sulfide (H_2S) comprise most of the soluble sulfides measured using silver/sulfide probes. These soluble forms plus FeS represent the acid volatile sulfide (AVS) portion, and all of this plus pyrite is referred to as chromium reducible sulfur (CRS). Just as it is important to maintain adequate oxygen for aerobic respiration, it is equally necessary to maintain adequate sulfate levels in sediments to sustain the anaerobic pathways described in Figure 10. Once the supply of sulfate is depleted, *Desulfovibrio sp.* bacteria can no longer catabolize complex organic matter and the system shifts to slower methanogenic processes. Therefore, sediment characteristics that enhance the diffusion and/or infusion of seawater will not only sustain aerobic metabolism at high levels of organic input, but they will sustain anaerobic pathways for longer periods of time when the assimilative capacity is exceeded.

Kristensen *et al.* (2000) observed that decreased sulfide concentrations as a function of depth to 15 cm were associated with a lack of carbon substrate and not due to reduced sulfate concentrations. Data in Cranston (1994) from areas with low organic inputs also revealed adequate sulfate concentrations – even in very deep sediments. However, Cranston (1994) also presented data for a site with high organic carbon content where sulfate was depleted and a significant portion of the carbon residue was buried. That is likely why some salmon farms, located in fine-grained sediments, take a long time to remediate. In some environments, both free oxygen and sulfur pathways are overwhelmed by the oxygen demands of first, aerobic organisms, and then of sulfur reducing bacteria. It appears that the top few millimetres are where most of the action occurs with respect to both aerobic and anaerobic catabolism. The colonies of *Beggiatoa* bacteria are a healthy sign in that they are catalyzing the breakdown of underlying organics by efficiently oxidizing sulfide and recycling sulfate back into surficial sediments.

FIGURE 10

Major sulfur pathways in marine sediments