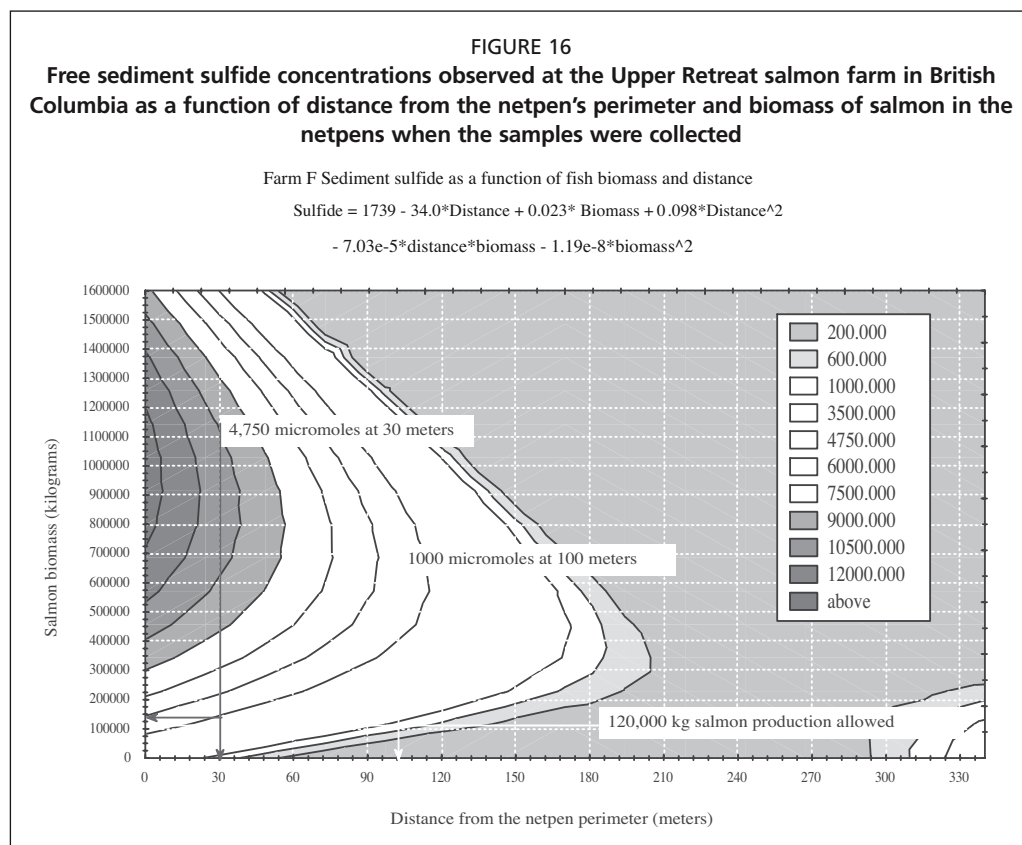


describe the number of taxa and abundance of macrofauna as a function of distance from the perimeter of a salmon farm in British Columbia located in an area of relatively slow currents. At the time of the study, the farm was producing 1 500 tonnes of salmon during each 20 month growout period followed by a six month fallow. There has been no proliferation of any taxa at this farm. The macrobenthic community was dominated by mollusks, which are less likely to proliferate than are annelids.

The question arises as to the maximum cultured biomass that can be grown at a site without exceeding the sediment's assimilative capacity for labile organic matter. Figure 16 describes a methodology developed by Brooks (2001) for assessing this question. However, the method is backward looking – not predictive. It requires a comparison of time series of sulfide concentrations and/or redox potentials with fish biomass during a production cycle.

In general, numerous studies of this kind have found that free sulfides increase rapidly during the early stages of production when salmon biomass is still small and feed rates are low. In the case of Upper Retreat, a performance standard allowing 1,000 $\mu\text{M S}^-$ at 100 m distance from the netpen would have restricted production to < 120 000 kg. It should be stated that the author monitors several broodstock holding sites in British Columbia where the maximum biomass is generally < 50 000 kg. Detectable effects have rarely been observed in sediments at these sites. The spatial extent and degree of benthic effects do not appear to increase linearly with increasing production. Current production rates in British Columbia have increased to 3 500 to 4 000 tonnes per farm. Ongoing monitoring has not observed significant increases in the benthic footprint of these farms (Brooks, unpublished). However, chemical remediation times at these higher production levels have not been determined.

The reports cited in this paper generally result from studies of farms representing worst cases where adverse benthic effects have been observed. Brooks (1994b and 1995b) documented sediment chemistry and infauna down current from a salmon farm located in a well-flushed passage in Washington State with maximum current speeds in excess of 125 $\text{cm}\cdot\text{sec}^{-1}$. The water was shallow (15-18 m MLLW) with sediments



dominated by large gravel, cobble and rock mixed with small amounts of sand, silt, clay and broken shell. The site was used for final grow-out as part of a complex, which produced approximately 3 000 tonnes of Atlantic salmon per year. Monitoring results demonstrated the positive environmental effects associated with this farm, which had been operating continuously for more than 10 years in the same location at the time of the study. A total of 3 953 infaunal organisms distributed in 116 species were observed at the 60 m control station in 1994. The abundance and diversity of benthic infauna was enhanced at all stations closer to the farm with a maximum of 7 350 animals distributed in 173 species observed at the 30 m station. On the periphery of the farm, 4 207 animals were observed, distributed in 142 species. Annelids dominated the infaunal community and *Capitella capitata* (16 percent) and *Prionospio steenstrupi* (17 percent) were abundant in the immediate vicinity of the farm. However, arthropods and surprisingly mollusks (*Mysella tumida* and *Macoma* spp.) were well represented in these samples. The abundance and diversity of infaunal organisms was positively correlated with sediment TOC, suggesting that organic carbon was limiting the infaunal community in this area. Significant numbers of fish, shrimp and other megafauna were observed during each annual video survey at this site, which appeared to function as an artificial reef. Three salmon farms located in close proximity to each other all shared the same characteristics. They appeared to attract megafaunal predators and to enhance the infaunal and epifaunal communities.

Changes in the local fish community

Salmon farms are known to function as fish aggregating structures. The structures attract numerous fish species, which frequently take up residence between the containment and predator nets. There are no published reports documenting this community. Brooks (1994b and 1995b) identified large numbers of pile perch (*Rhacochilus vacca*), shiner perch (*Cymatogaster aggregata*), herring (*Clupea pallasii*), lingcod (*Ophiodon elongatus*), bay pipefish (*Syngnathus leptorhynchus*) and several species of sole

(*Pleuronichthys* spp.) at a well-flushed net-pen site in Washington. At another site nearby, located over a sandy bottom, sea cucumbers (*Parastichopus californicus*) and geoducks (*Panopea abrupta*) had proliferated. All of these populations were closely associated with the farms (within 30 m). It should be added that one of these facilities is located in shallow water (15–18 m MLLW) and fast currents (115 cm/sec). The second facility is located in a moderately well flushed environment with maximum currents of 60 cm/sec and water depths of 22–30 m MLLW.

Chemical and biological remediation of sediments

Chemical and biological recovery of sediments under salmon farms is well documented in the literature by, *inter alia*, Ritz, Lewis and Ma Shen (1989), Anderson (1992), Mahnken (1993), Brooks (1993a), Brooks (1999), Brooks *et al.* (2003c), Brooks, Stierns and Backman (2004), Lu and Wu (1998), Karakassis *et al.* (1999) and Crema *et al.* (2000). Brooks *et al.* (2003c) have defined chemical and biological remediation as follows:

Chemical remediation

Chemical remediation is the reduction of accumulated organic carbon under and adjacent to salmon farms to a level at which aerobic organisms can recruit into the area. It appears that initially high levels of sedimented organic carbon decline exponentially and approach baseline conditions asymptotically. Chemical remediation is accomplished through chemical, biological and physical processes.

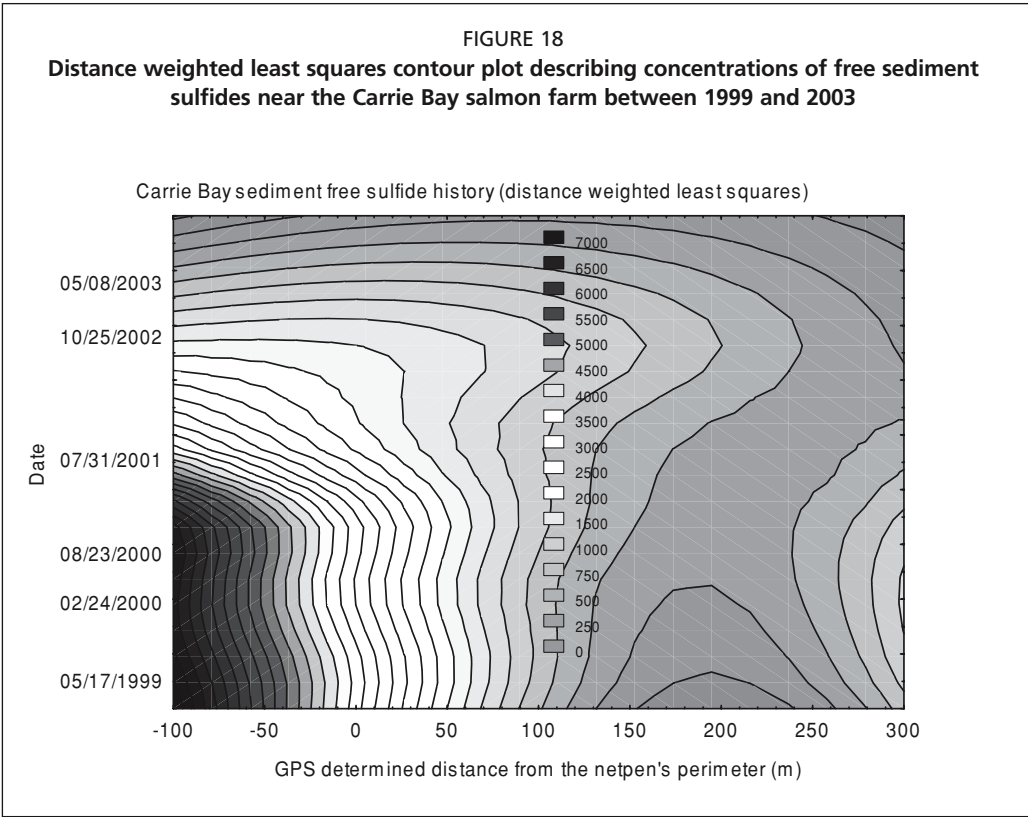
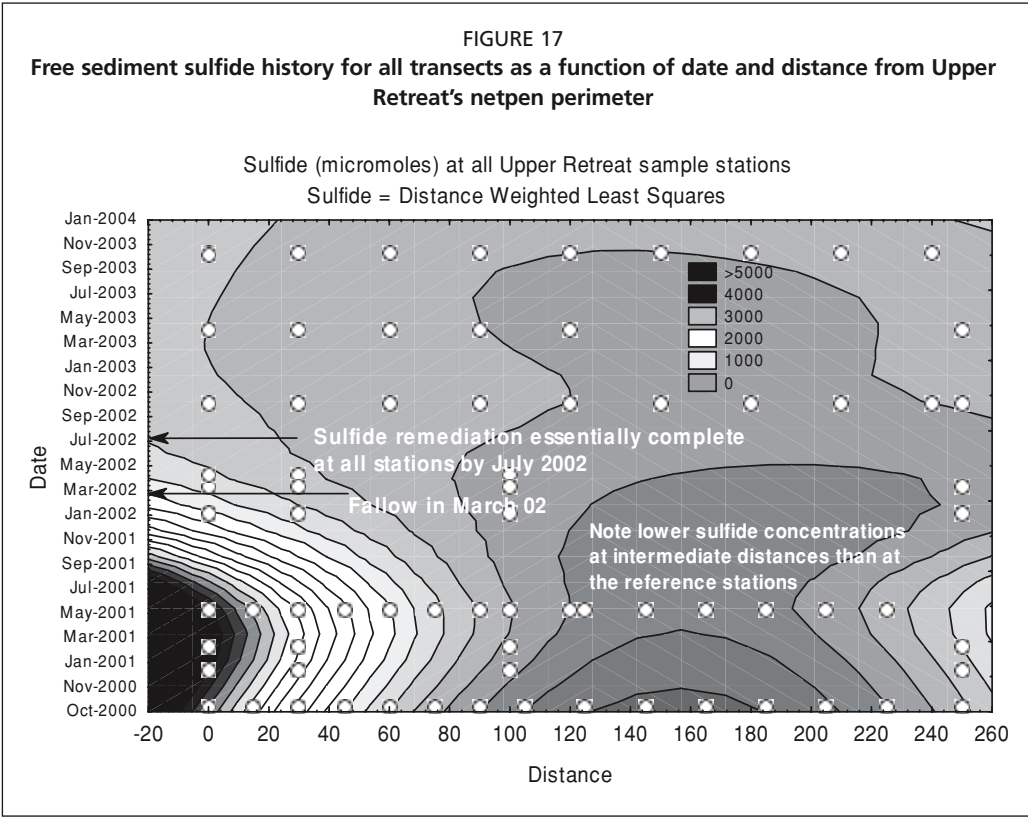
Biological remediation

Biological remediation is defined as the restructuring of the infaunal community to include those taxa representing ≥ 1 percent of the abundance observed at a local reference station. Recruitment of rare species representing < 1 percent of the reference area abundance is not considered necessary for biological remediation to be considered complete.

At two sites where long-term fallow studies were conducted by Brooks (2000b) and Brooks, Stierns and Bakman (2004), sediment concentrations of volatile solids declined rapidly as soon as harvests were started and reference physicochemical conditions were achieved within four to six months of fallow. Remediation at the Arrow Pass farm can be inferred from the temporal series of TVS curves in Figure 6. Figure 17 describes the temporal and spatial history of free sediment sulfides at the Upper Retreat salmon farm where chemical remediation was considered complete in 4 to 6 months. Brooks (unpublished) has continued to monitor the Upper Retreat salmon farm during an extended fallow period and it appears that biological remediation was complete after approximately 15 to 18 months of total fallow (six months for chemical remediation and 9 to 12 months for biological remediation).

Not all Northeast Pacific salmon farms remediate this quickly. Carrie Bay was a salmon farm that appeared to create more extensive and dramatic benthic effects than any other site in the Broughton Archipelago of British Columbia. As soon as the extent and degree of the benthic impacts became known to management, they terminated operations there and the site was voluntarily studied during a seven year fallow period. This farm was located in a highly depositional area and benthic conditions were exacerbated by poor feeding practices. Brooks, Stierns and Backman (2004) found that chemical remediation was nearing completion but was not yet complete after five years in fallow. The sulfide history at this site during the fallow period is described in Figure 18. Chemical remediation was proceeding steadily, but was not complete in 2002 following five years in fallow. Regression analysis suggested that seven years would pass before sediment chemistry at this site returned to baseline conditions.

Future studies may extend the range of times required for chemical and biological remediation. However, at present, it appears that most salmon farm sites chemically



remediate in six months to a year in the Northeast Pacific and that biological remediation, as defined above, occurs during the next invertebrate recruiting season, which is a year or less depending on the season when chemical remediation is complete.

ASSESSING THE ENVIRONMENTAL COSTS ASSOCIATED WITH BENTHIC EFFECTS NEAR SALMON FARMS

Brooks (2001) estimated the lost fin-fish production associated with the diminished macro-invertebrate biomass within the footprint of seven salmon farms in the Broughton Archipelago. Macroinvertebrate wet tissues were weighed on a four place balance as part of the community inventories at these sites. The biomass observed at the local reference station was assumed to have been diminished within the average footprint observed at salmon farms (i.e. an area of 1.6 hectares where sulfide concentrations exceeded 4 000 μM). This biomass was assumed to replicate itself once per year and it was assumed that all of this production was consumed by a food fish at the next higher trophic level with an efficiency of 0.10. The loss of wild fish was most heavily influenced by benthic productivity at the reference station, which varied by a factor of approximately 6. Between 32 and 1 475 kg of wild fish production were predicted to be lost at these sites where between 175 010 and 1 800 000 kg of Atlantic salmon were present when the surveys were completed. The ratios of cultured salmon to lost wild fish production varied between approximately 1 000 and 34 000 (Table 4).

Overall view of nearfield effects

A detailed description of the nearfield benthic effects associated with salmon aquaculture in the Northeast Pacific has been presented to assess a portion of the environmental costs associated with this form of food production. From an overall perspective, the results presented herein suggest that there was an average loss in production of 306.9 ± 484.5 kg of wild fish at these farms where an average of $1\,081\,684 \pm 492\,374$ kg of salmon was present at the time of the surveys. The production of Atlantic salmon was, on average, $12\,624 \pm 12\,521$ times greater than the lost biomass of wild fish. The marine grow-out phase lasts approximately 18 to 20 months and adding another 24 months for chemical and biological remediation suggests that the sediments were negatively affected for 44 months. Several conservative assumptions (from the environment's point of view) were necessary to define these costs and the actual loss of wild production in the near field will likely be less, on average, than 307 kg of fish during a complete production and fallow period lasting 44 months (84 kg/year for 3.7 years).

This analysis accounts only for the near-field effects of enrichment. Brooks (2001) did not detect either physicochemical or biological effects at distances >205 m from any British Columbia salmon farm. However, as the intensity of fed aquaculture within an ecosystem increases, the potential for small, but cumulative, effects from several farms may change natural productivity in the far-field. These far-field effects are difficult or impossible to detect using point in time surveys. Detection requires long-term monitoring to establish trends. Management of cumulative effects requires inventories of all of the contributors to the effect and different management techniques, such as Total Maximum Daily Loading (TMDL) approaches. Far field effects can be serious and need to be avoided. Computer modeling may provide the best approach to determining

TABLE 4

Production of Atlantic salmon and estimated loss of wild fish due to reductions in the benthic invertebrate community biomass at salmon farms described in Brooks (2001)

Farm	Reference Station Biomass (kg macrofauna/1.6Ha)	Wild fish lost (kg)	Salmon produced (kg)	Ratio Cultured. Wild
A	300.4	110	175 010	1 589
B	172.4	59	650 000	11 024
C	121.0	38	1 100 000	28 646
D	106.0	32	1 100 000	33 951
E	543.8	311	1 800 000	1 475
F	611.7	1475	1 425 153	966
G	333.3	123	1 321 627	10 717