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Chemical and Biological Remediation of Marine Sediments at a Fallowed Salmon Farm, Centre Cove, Kyuquot Sound, B.C.

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Executive Summary

The marine finfish aquaculture industry has been operating in British Columbia since the 1970s. The organic waste deposited in the vicinity of open net pens can cause measurable changes to sediment chemistry and benthic infauna. The British Columbia Ministry of Environment (MoE) has been monitoring the sediment chemistry and biology in the vicinity of finfish farms since the mid-1990s.

Centre Cove, in Kyuquot Sound on the west coast of Vancouver Island, is the location of a farm site that was operational from the mid-1980s through to 2002. The impacts at this site were atypical relative to fish farm sites along the B.C. coast in that they were far more significant with respect to the free sulphide and metal concentrations in sediment. The MoE conducted a sampling program at Centre Cove from 2000 to 2008 to analyze the trends in sediment chemistry over time, with increasing distance from the farm, and in comparison to other studies at similar farm sites.

Sediment was analyzed for sulphide, copper and zinc concentrations and oxidation reduction potential. Data were analyzed statistically using a multiple linear regression to determine the change over time and with distance from the farm. Results indicate that the sediments at the site had high sulphide, copper and zinc concentrations and low oxidation reduction potential at the start of the study. In subsequent years results have shown the site to be undergoing a slow but steady remediation from the impacts of organic enrichment although not necessarily from metal contamination. Evidence of initial impacts includes sulphide concentrations as high as 10,553 µM, and copper and zinc concentrations as high as 220.9 µg/g and 1062.0 µg/g, respectively. Oxidation reduction potential was as low as -324.4 mV. Sulphide concentrations have decreased and oxidation reduction potential has increased over the course of the study, indicative of the gradual improving trend over time. Metal concentrations have decreased only slightly. Macrobenthic infaunal samples collected in 2008 support the conclusion that the Centre Cove site is still organically-enriched, with the presence of organic carbon-tolerant species such as *Ophryotrocha* sp., *Capitella capitata* and *Nephtys cornuta* at stations close to the farm centre.

As expected, all parameters showed statistically significant improvement with increasing distance from the net pens. All parameters also improved over time, but only the decrease in sulphide concentration was statistically significant. Multiple linear regressions suggest that it could take up to 15 years of fallowing for the sulphide concentrations at the site to return to background sulphide conditions. This is much longer than almost all other sites in British Columbia and suggests that sites with slow current speeds and highly depositional environments are not well-suited for aquaculture operations.

It is recommended that further monitoring studies be carried out to explain the noted increases in sulphides in 2008, and to evaluate metal speciation and bioavailability including separation of farm-derived from natural metal concentrations. Also, a thorough reassessment of the site should be conducted in five years to evaluate the progress of remediation.

1.0 Introduction

Marine finfish aquaculture can have measurable impacts on the marine environment, including changes to the benthic sediment chemistry and infauna, primarily in the immediate vicinity of the farms. The extent of the impact is determined by farm practices, the size of the farm and by the nature of the receiving environment. Open net cage finfish aquaculture, as occurs in British Columbia, introduces organic and inorganic matter into the environment through fish waste and uneaten fish feed. This material settles to the seafloor and results in a gradient of organic enrichment from the cages outward (Gowen & Bradbury, 1987). In more dynamic sites, these changes can be relatively short lived, while in relatively calm water sites, they can persist for many years (Pearson & Black, 2001).

Natural marine sediments typically have an oxic layer overlying an anoxic layer. Oxygen, which can be delivered to the sediments by diffusion from overlying water and by mechanical infusion, is consumed as the organic matter is broken down. When oxygen demand exceeds supply, the sediments become anoxic and reducing. The organic enrichment from farm waste can cause a decrease in sediment oxygen content. This pattern is more prevalent in fine-grained sediments (>60% silt and clay) because in such conditions, infusion is not as effective at delivering oxygen to the sediment (Brooks & Mahnken, 2003; Gowen & Bradbury, 1987).

Sediments that have been organically-enriched are often reducing, dark in colour, and have ammonia and sulphide concentrations that are elevated above background conditions. This occurs as sulphate or nitrate-reducing bacteria degrade organic carbon and produce ammonia and hydrogen sulphide gasses (Brooks & Mahnken, 2003). Hargrave *et al*. (1997) evaluated the impacts of salmon aquaculture on Canada’s east coast and found that sulphide concentration and oxidation reduction potential in surface sediments were sensitive indicators of benthic organic enrichment. These are the two primary indicators used by the British Columbia Ministry of Environment (MoE) when monitoring farm impacts.

In addition to the chemical changes caused by organic enrichment, the benthic biological community can be altered and declines in diversity can be observed (Pohle *et al*., 2001). For example, organic carbon-tolerant and opportunistic species such as *Capitella capitata, Ophryotrocha* cf. *vivipara, Nephtys cornuta* and the genera *Lumbrineris* and *Glycera* dominate the macrobenthic community at sites impacted by organic enrichment (Brooks *et al.*, 2003). As the site recovers, sensitive species return and species diversity increases.

The finfish aquaculture industry in British Columbia has grown substantially since its introduction to the coast in the early 1970s. As of 2008, the industry consisted of 130 farms with a total annual production of approximately 80,000 tonnes. Atlantic salmon (*Salmo salar*) is the dominant species produced, accounting for over 90% of the production (MoE, 2008).

In 2000, the MoE (then called the Ministry of Environment, Lands and Parks) undertook an extensive benthic sampling program, sampling 32 farms, to serve as an audit of the industry's monitoring program and to provide data to support the development of performance based standards. The Finfish Aquaculture Waste Control Regulation (FAWCR) was subsequently enacted September 12, 2002. The MoE has continued its annual benthic monitoring audit program.

The MoE has conducted additional monitoring at selected farm sites to assess potential long-term impacts to the environment. The Centre Cove site has been monitored since 2000 and was selected as the benthic impacts were more severe relative to other aquaculture sites. Chinook salmon (*Oncorhynchus tshawytscha*) was raised on site from the mid-1980s to 2002. The area is highly depositional in nature and subject to low current speeds, both of which likely limit the rate of recovery.

The objectives of this report are to i) examine the change in benthic conditions with increasing distance from the net pens, ii) examine the change in benthic conditions over time, and iii) compare the impacts at this site with impacts at other farm sites with similar characteristics. The intent is to learn more about the unique characteristics of this site, to interpret the findings in relation to the rate of recovery, and to provide research to support environmental regulatory decision-making.

2.0 Methods

2.1 Study Site Description

The Centre Cove farm site is located in Kyuquot Sound on the northwest coast of Vancouver Island (Figure 1). The farm is situated on the east side of Whiteley Island, at the northeast end of Kyuquot Channel, at a latitude and longitude of 50º 0'N and 127º 12'W (Figure 2). The distance to the nearest active finfish farm, which has been operating since 2003, is 700 m. Data suggest that it is not influencing the chemical and biological characteristics at the Centre Cove farm site. All other nearby farms are at least 2.6 kilometres away, and have not been operational since 2004.

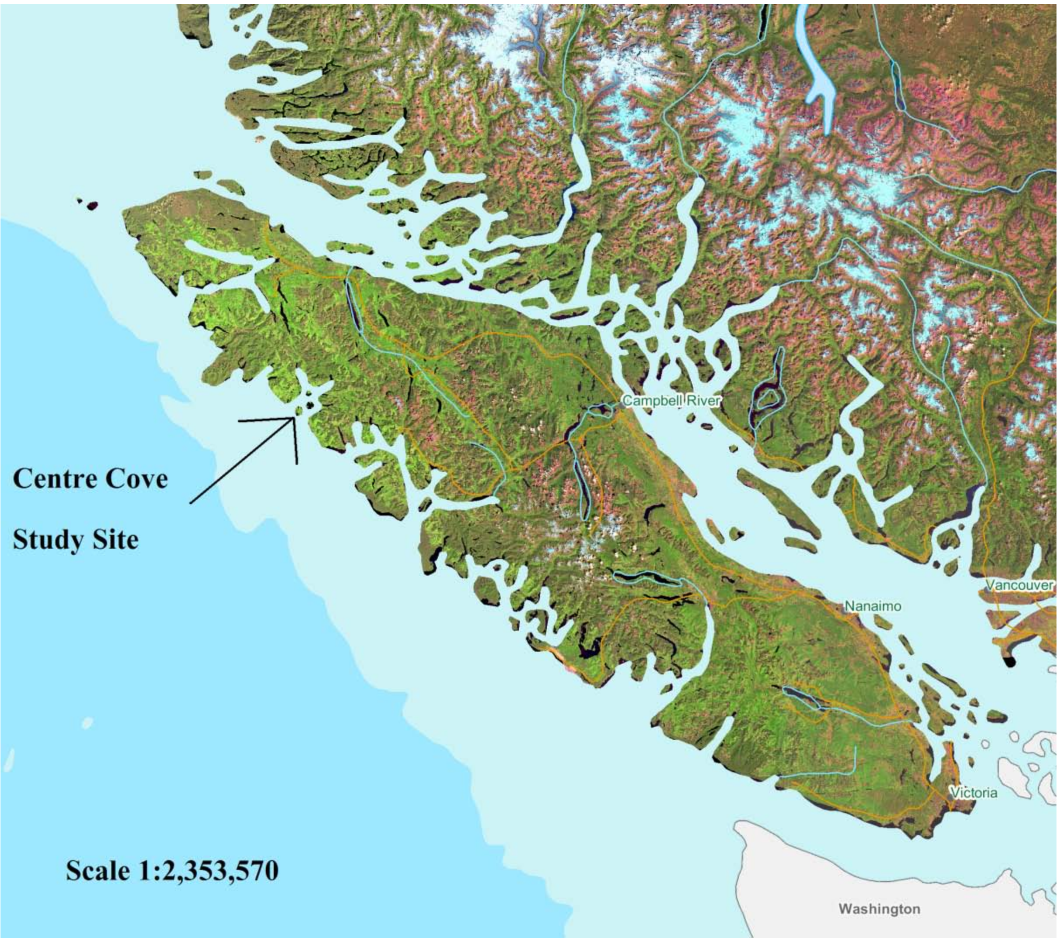

Figure 1. General location of Centre Cove study site, northwest Vancouver Island, British Columbia.

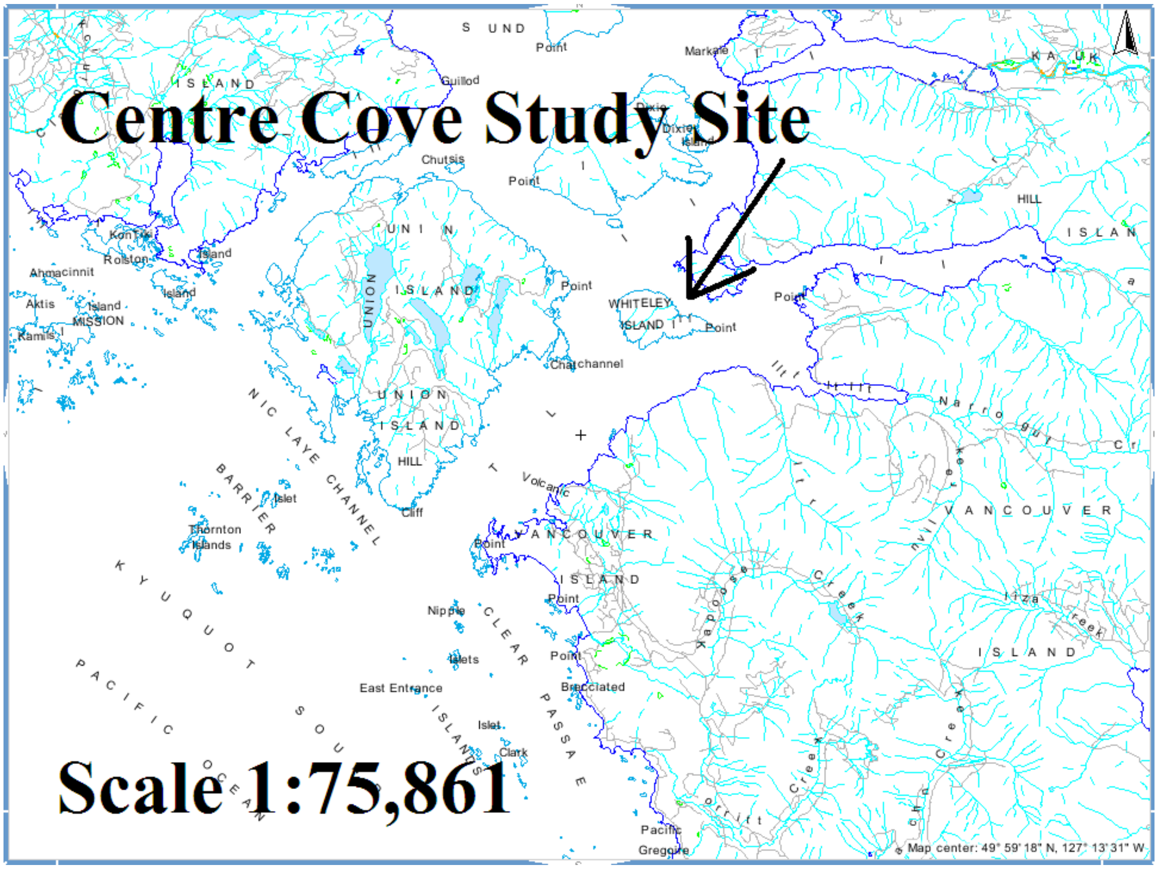

Figure 2. Whitely Island, location of Centre Cove study site, in Kyuquot Sound, Vancouver Island.

The Centre Cove area is highly depositional with low current speeds. During the course of the farm’s operation, the net pens underwent several relocations in an effort to find better currents, circulation and associated water quality. Their most recent location was to the northwest of the cove itself (Figure 3). The mean annual tidal range in this area is 2.89 m and the maximum is 4.48 m (Nutreco Canada, 2001). Tidal circulation in Centre Cove is weak and indicates a well-developed back-eddy. Tidal flow increases significantly and becomes more laminar as one proceeds beyond the two outer points defining the cove (Marine Harvest Canada, 2001; Nutreco Canada, 2001). In 2001, the mean current speed on the outer edge of the net pens was measured at 3.4 cm/s at a depth of 15 m, and 2.1 cm/s at a depth of 5 m above the bottom (Greg Gibson, Marine Harvest, personal communication, Feb 3, 2009).

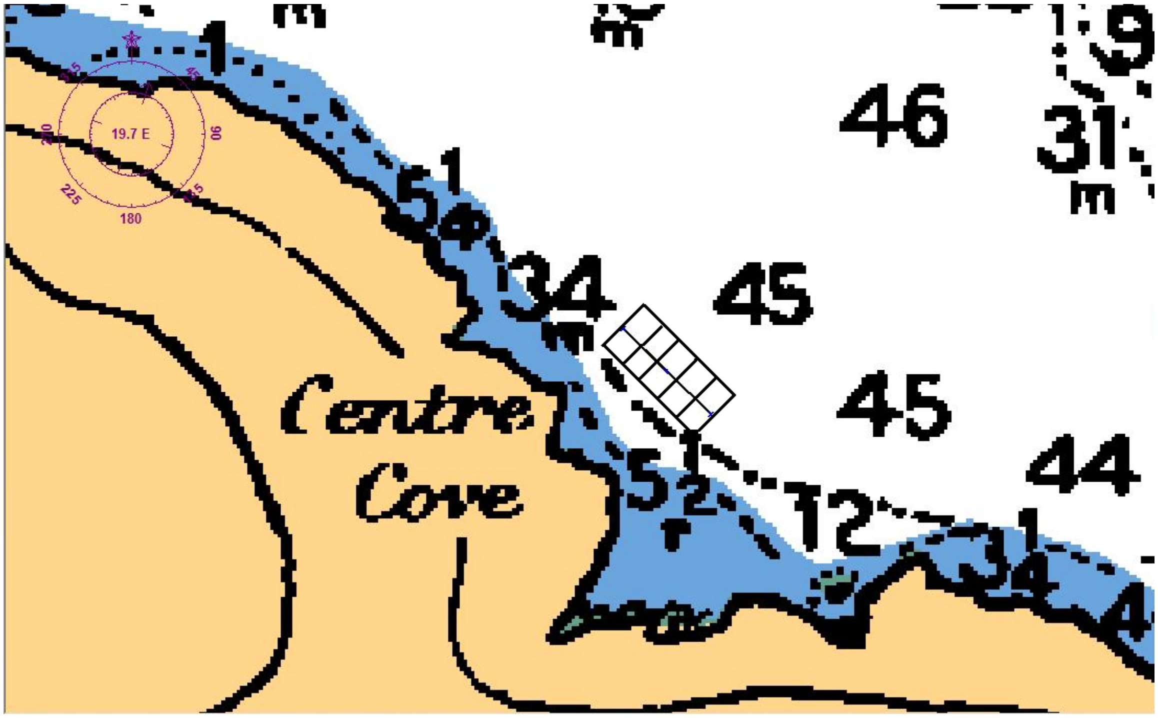

Figure 3. Approximate location of net pens at Centre Cove prior to their removal in 2002.

2.2 Sampling Methods

The MoE has sampled the Centre Cove site annually since 2000. Stations were sampled along two transects extending from the net pen edge in the direction of the dominant (northwest) and sub-dominant (southeast) currents, in the zones of maximum waste deposition. It was expected that the northwest transect would show the most extensive impact due to the dominant current direction and subsequent higher organic deposition in this direction. The sampling locations were not identical each year, but stations were sampled consistently at distances of 0 m and 30 m from the net pen edge. As well, the edges of the tenure were sampled at distances of 294 m and 656 m from the net pens, on the northwest and southeast sides of the net pens, respectively. Samples were also taken at various other distances (e.g. 100 m and 250 m from the net pen edge) depending on priorities and sampling objectives in a given year. See Tables 6 and 7 (Appendix 1) for a list of all stations sampled by year.

Note that the 0 m stations were measured from the edge of the net pens and were sampled with the sampling vessel tied to the net pen system, when it was present. When the system was not present, GPS coordinates from previous years were used to identify sampling locations. For statistical purposes, the distance from the centre of the footprint, i.e. under the netpens, was calculated for each station. This distance differs from the distance from the net pen edge; for example, a station that is 0 m from the net pen edge is approximately 60 m from the centre of the footprint.

The sampling methods did not remain constant from 2000 to 2007, as protocols evolved and new equipment was obtained. In 2000-2002, the methods described in *Interim Monitoring Program* (MELP, 2000) were followed. On September 12, 2002, the FAWCR and associated *Protocols for Marine Environmental Monitoring* (PMEM) came into effect. Thus, in 2002 and subsequent years, sampling methods and objectives were based on the FAWCR and PMEM (MWLAP, 2002a; MWLAP, 2002b).

Sediments were sampled using a 0.1 m^2 Van Veen, and once on board, were examined for a number of observable parameters that indicate organic enrichment. These included colour and odour, presence of gas bubbles, gelatinous texture, fish feed/feces and the bacteria *Beggiatoa*. The top two centimetres of sediment was removed for further chemical analysis. Normally, three replicates were obtained per station, although this was not always possible due to lack of sediment at some sites. Oxidation reduction potential and free sulphide concentration were measured in the field, and samples were shipped to a certified lab for analysis of copper, zinc, total volatile solids, total phosphorus and sediment grain size. Prior to measurement of sulphide concentrations, and on intervals no more than 3 hours apart, sulphide meters and probes were calibrated using a three-point calibration with standard solutions. One out of every 20 samples was duplicated with a subsample for quality assurance and quality control.

In 2000, 2001 and 2008, biological samples were collected and processed in the field, as outlined in the IMP and the PMEM. For this, the entire sediment grab sample, except the portion of the top two centimetres removed for chemical analysis, was rinsed on a 1.0 millimetre screen using a low-pressure showerhead and screened seawater. Analyses have shown that partial or complete removal of the top layer of sediment does not bias the samples (Wright *et. al.*, 2007). All organisms left on the screen were put in plastic containers with 10% buffered formalin. The formalin was later rinsed off with water and replaced with isopropyl alcohol for preservation. Samples were then forwarded to a certified lab for taxonomic analysis. Note that due to methodology problems in 2000 and 2001, only those samples collected in 2008 are analyzed in this report. In this year, samples were collected at the 0 m, 30 m, and 100 m stations on both transects, and two stations at the edge of tenure on the northwest transect.

2.3 Statistical Analyses

Line graphs were produced for sulphide, copper and zinc concentration and oxidation reduction potential using only the data from the three consistent sampling stations, 0 m and 30 m from the net pens and the edge of tenure stations on the northwestern and southeastern sides of the farm. Statistical analyses were performed using data from all stations, including the locations that were not sampled every year (e.g. 100 m, 250 m and several stations near the edge of tenure).

Though data from all available years are summarized in the line graphs, statistical analyses were only completed on the sediment data collected from 2002 to 2008, because this represents the last year of fish production and the first six years of fallowing and expected subsequent recovery. Statistics were completed using JMP version 7.0.

A log transformation was applied to all sediment data to stabilize the variance, which was found to increase with the mean during preliminary analyses. A log transformation was not applied to the oxidation reduction potential data because many values were negative. Data were separated by transect because depositional and recovery rates were expected to be different on either side of the farm due to varying currents.

Multiple linear regressions were performed on sulphide, copper, zinc and oxidation reduction potential using the transformed data where applicable, with date and distance as the factors. The interaction between date and distance was included in preliminary analysis, and where it was found to be non-significant, it was then excluded from the final analysis (northwest transect: for sulphide p=0.1165, for oxidation reduction potential, p=0.3837, for copper p=0.0635; southeast transect: for sulphide p=0.6127, for oxidation reduction potential p=0.8384, for copper p=0.7063, for zinc p=0.9960).

For biological results from 2008, total abundance, total number of taxa and a Shannon-Wiener Index were calculated for each station.

3.0 Results

3.1 Sample Observations

Observable organic enrichment indicators such as black sediment, strong hydrogen sulphide odour, gas bubbles, gelatinous sediment, fish feed and feces and *Beggiatoa* were present at most stations at the start of the study and most declined or were absent by 2008 (Table 1).

Table 1. Summary of field observations of sediment grabs at Centre Cove, 2000-2008. Note that EOT refers to Edge of Tenure.

	sampling year	0m NW*	30m NW	EOT NW (294 m)	0m SE	30m SE	EOT SE (656 m)
Beggiatoa (y/n)	2000	y	n				
	2001	n			n	n	
	2002	y	n				
	2003		n	n	y	n	n
	2004	y	y	y	n	n	n
	2005	n	n	n	n	n	n
	2006			y			
	2007		y	n		n	
	2008	y	y	n	n	n	
Odour (0-4) 0=none, 1=mild 2=moderate 3=strong 4=very strong	2000	4	1				
	2001	0			3	3	
	2002	4	2				
	2003		4	3	4	4	0
	2004	2	3	3	4	2	0

Table 1. (continued...)

	2005	2	2	2	2	1	0
	2006			3			
	2007		3	3		2	
	2008	2	3	1	2	2	
Black Sediment (y/n)	2000	y	n				
	2001	n			y	n	
	2002	y	y				
	2003		y	y	y	y	n
	2004	n	y	y	y	n	n
	2005	y	n	y	y	y	n
	2006			y			
	2007		y	y		y	
	2008	y	y	n	y	y	
Feed/Feces (y/n)	2000	y	n				
	2001	n			y	n	
	2002	y	y				
	2003		y	n	y	y	n
	2004	n	n	n	y	n	n
	2005	n	n	n	n	n	n
	2006			n			
	2007		n	n		n	
	2008	n	n	n	n	n	
Gaseous/Gelatinous (y/n)	2000	y	n				
	2001	n			`	y	
	2002	y	y				
	2003		y	y	y	y	n
	2004	y	y	y	y	n	n
	2005	n	n	n	n	n	n
	2006			y			
	2007		n	y		y	
	2008	n	n	n	n	n	

note: a blank cell indicates no data
*in 2001, the results indicate that this station was not located in the area of waste accumulation; reported results are thus not representative

3.2 **Sediment Chemistry**

The average mud fraction (<63 µm) of the farm stations ranged from 21.71 % to 71.82 %, compared to a range of 10.58 % to 83.10 % for the reference stations (Table 2). The average sulphide, copper and zinc concentrations were 65.9 µM, 11.9 µg/g and 45.3 µg/g respectively and the average oxidation reduction potential was 172.1 mV at the reference stations. These values were stable throughout the study (Table 3).

Table 2. Number of replicates, depth and sediment grain size of Centre Cove sampling stations; note that EOT refers to edge of tenure.

			Average Sediment Grain Size		
Site	Number of Replicates	Average Depth (m)	Gravel >2mm (%)	Sand <2mm (%)	Mud <63um (%)
0m NW	15	82	8.79	30.47	60.73
30m NW	18	75	3.00	27.65	69.34
EOT NW	16	77	3.17	28.81	68.02
0m SE	14	79	1.63	26.55	71.82
30m SE	18	76	4.56	27.20	68.24
EOT SE	9	44	36.58	41.72	21.71
Ref 1	3	36	3.50	48.50	48.00
Ref 2	3	41	1.20	84.70	14.10
Ref 3	3	73	2.80	14.11	83.10
Ref 4	3	67.1	2.24	87.18	10.58
Ref 5	3	54	26.37	59.08	14.55
Ref 6	3	72	30.29	53.16	16.55

Table 3. Sediment chemistry of reference stations for the Centre Cove study site.

Site	Number of Replicates	Average Sulphide (µM)	Average Oxidation reduction potential (mV)	Copper (µg/g)	Zinc (µg/g)
Ref 1	3	33.0	55.1	9.8	58.1
Ref 2	3	27.3	142.0	11.6	45.4
Ref 3	3	200.2	181.5	16.8	50.0
Ref 4	3	24.4	188.7	10.2	37.0
Ref 5	3	24.6	297.7	11.7	42.3
Ref 6	3	86.1	167.5	11.3	38.7
Average		**65.9**	**172.1**	**11.9**	**45.3**

Over the course of the study, there was a wide range of sediment chemistry values at the farm stations. The highest sulphide value was 10,553 µM from the 30 m northwest station in 2002. The lowest oxidation reduction potential, -324.4 mV, was from the 100m southwest station in 2001. The highest copper concentration was 220.9 µg/g at the 0 m southeast station in 2004. The highest zinc concentration was 1062.0 µg/g at the northwest edge of tenure station in 2005. See Tables 6 and 7 (Appendix 1) for complete data.

It is not possible to report on trends from 2000 to 2002, when fish were still on site, because samples were not taken at consistent locations in these years. From 2002 to 2008 sulphide and metal concentrations decreased and oxidation reduction potential increased with time and with increasing distance from the centre of the footprint; however, not all results were statistically significant.

3.2.1 Northwest Transect

On the northwest transect, $\log_{(\text{mean free sulphide concentration})}$ decreased significantly with time ($t_{(0.05,24)}$=-2.62, r^2=0.56, p=0.0151) and with distance from the centre of the footprint ($t_{(0.05,24)}$=-3.46, r^2=0.56, p=0.0020) (Figure 4). See Tables 8-15 (Appendix 2) for parameter estimates from the linear regressions.

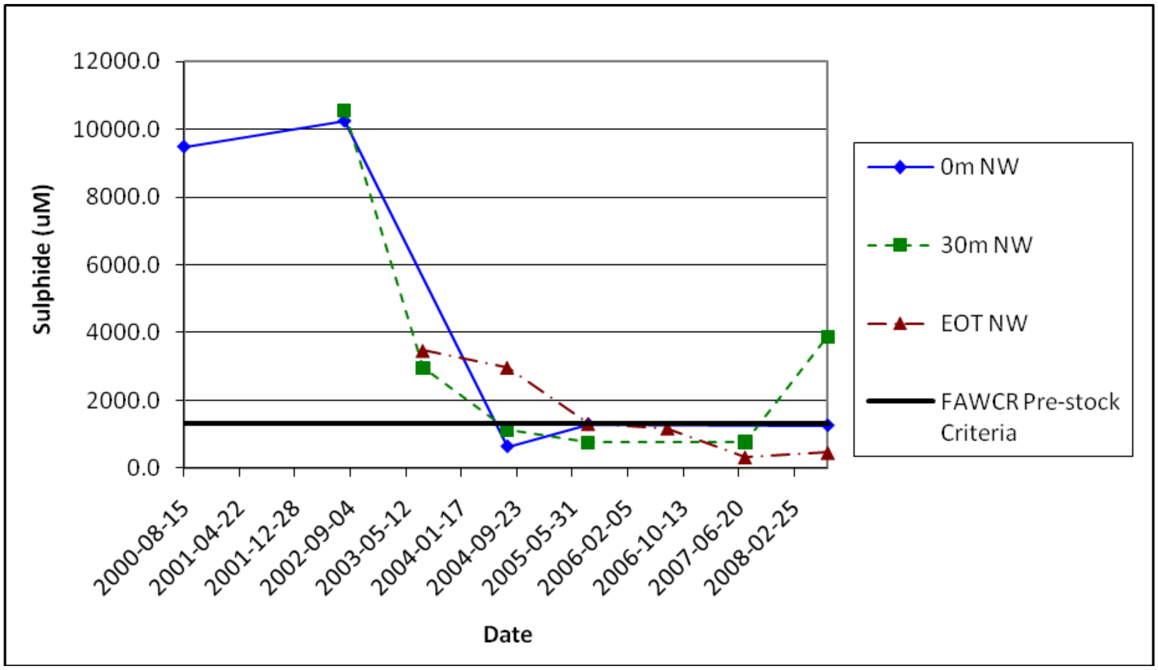

Figure 4. Sulphide concentrations on the northwest side of the Centre Cove farm, 2000 to 2008.

Oxidation reduction potential increased and $\log_{(\text{copper})}$ and $\log_{(\text{zinc})}$ decreased with time and with distance from the centre of the footprint, but only the changes over distance were statistically significant (oxidation reduction potential $t_{(0.05,24)}$=3.42, r^2=0.44, p=0.0023, $\log_{(\text{copper})}$ $t_{(0.05,24)}$=-3.27, r^2=0.39, p=0.0032, $\log_{(\text{zinc})}$ $t_{(0.05,24)}$=-2.18, r^2=0.57, p=0.0010) (Figures 5, 6 & 7). Note that the interaction between time and distance was significant for $\log_{(\text{zinc})}$ (p=0.0398).

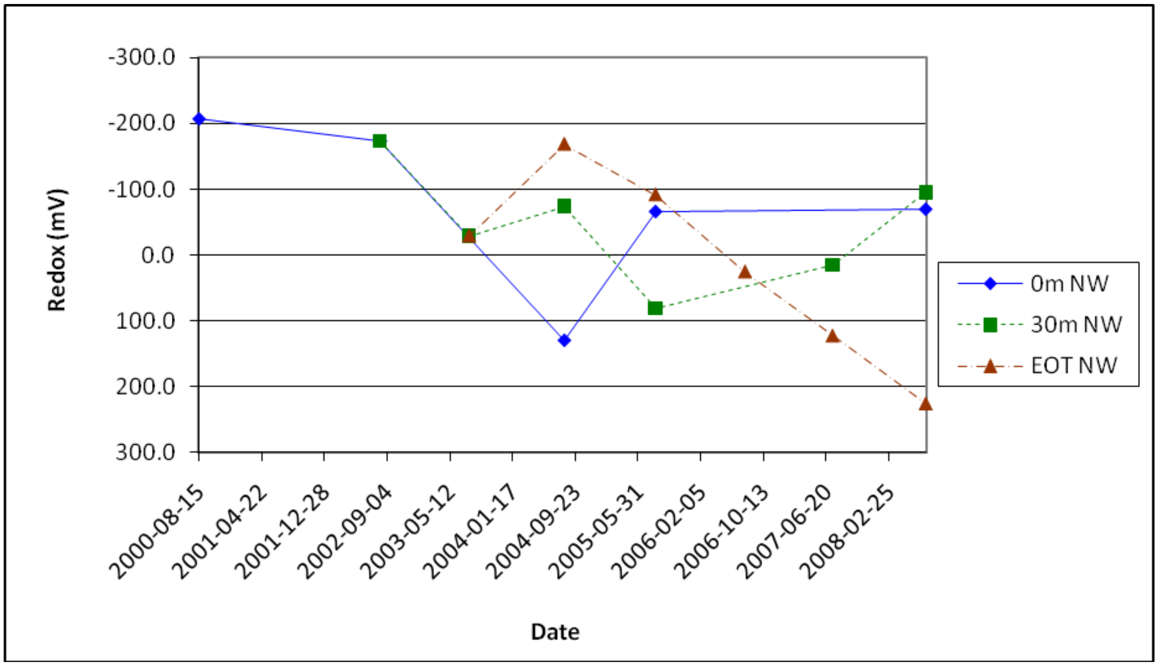

Figure 5. Oxidation reduction potential on the northwest side of the Centre Cove farm, 2000 to 2008.

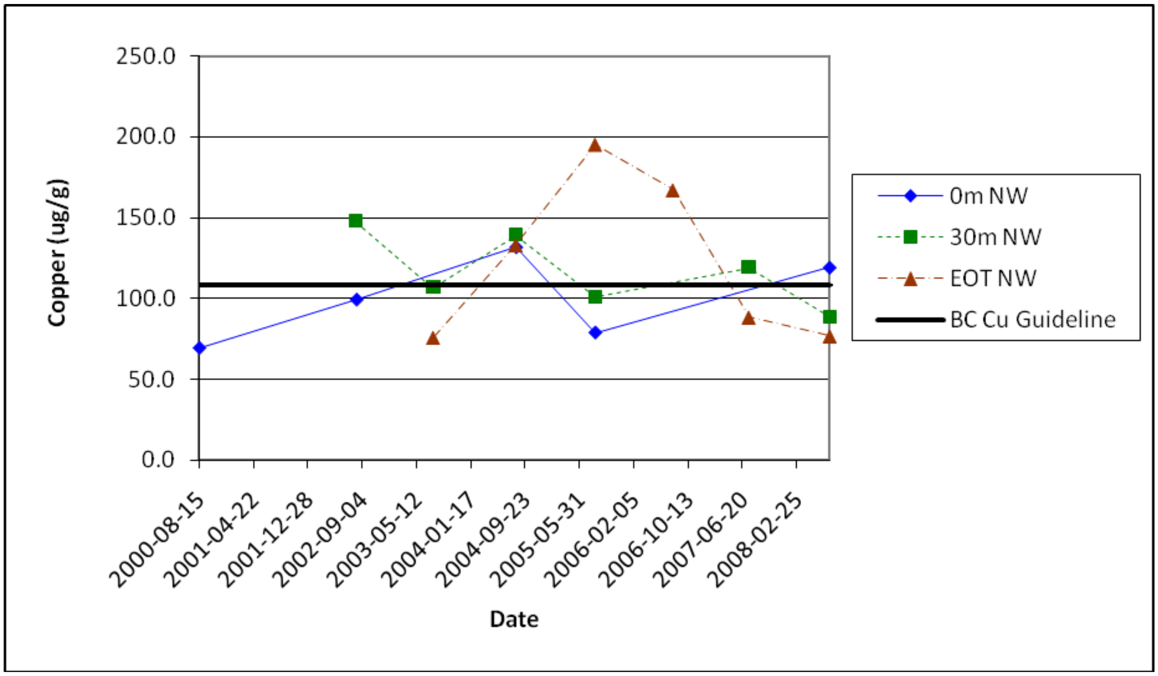

Figure 6. Copper concentrations on the northwest side of the Centre Cove farm, 2000 to 2008.

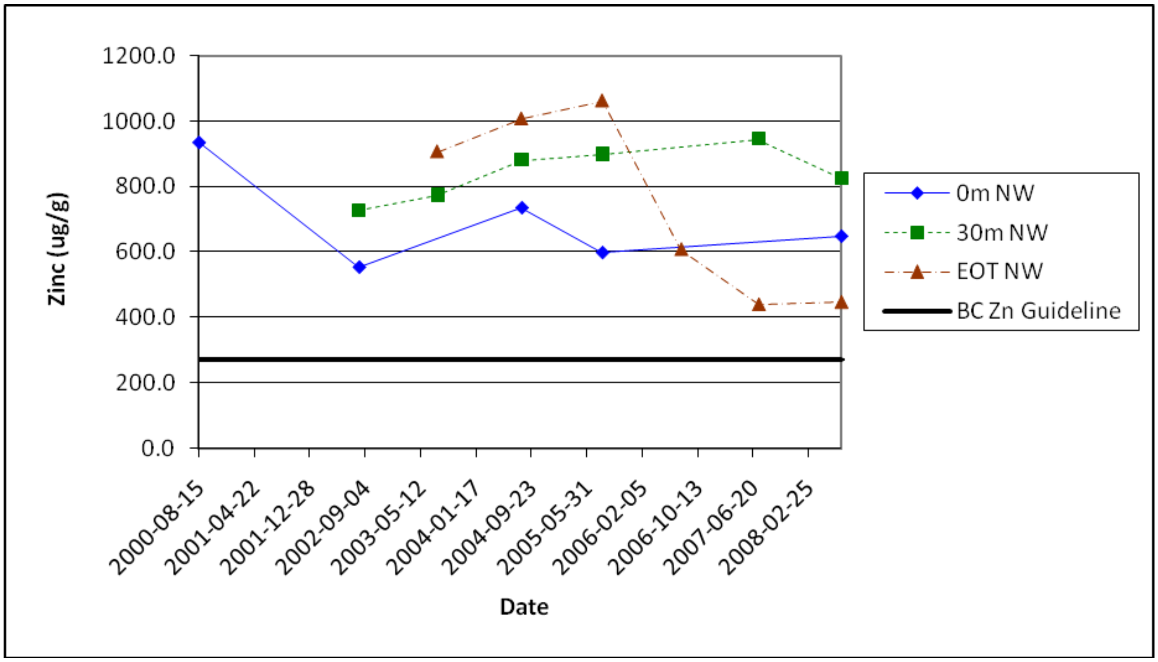

Figure 7. Zinc concentrations on the northwest side of the Centre Cove farm, 2000 to 2008.

3.2.2 Southeast Transect

On the southeast transect, $\log_{(\text{mean free sulphide concentration})}$ decreased significantly with time ($t_{(0.05,10)}$=-2.84, r^2=0.86, p=0.0177) and with distance from the centre of the footprint ($t_{(0.05,10)}$=-7.93, r^2=0.86, p<0.0001) (Figure 8).

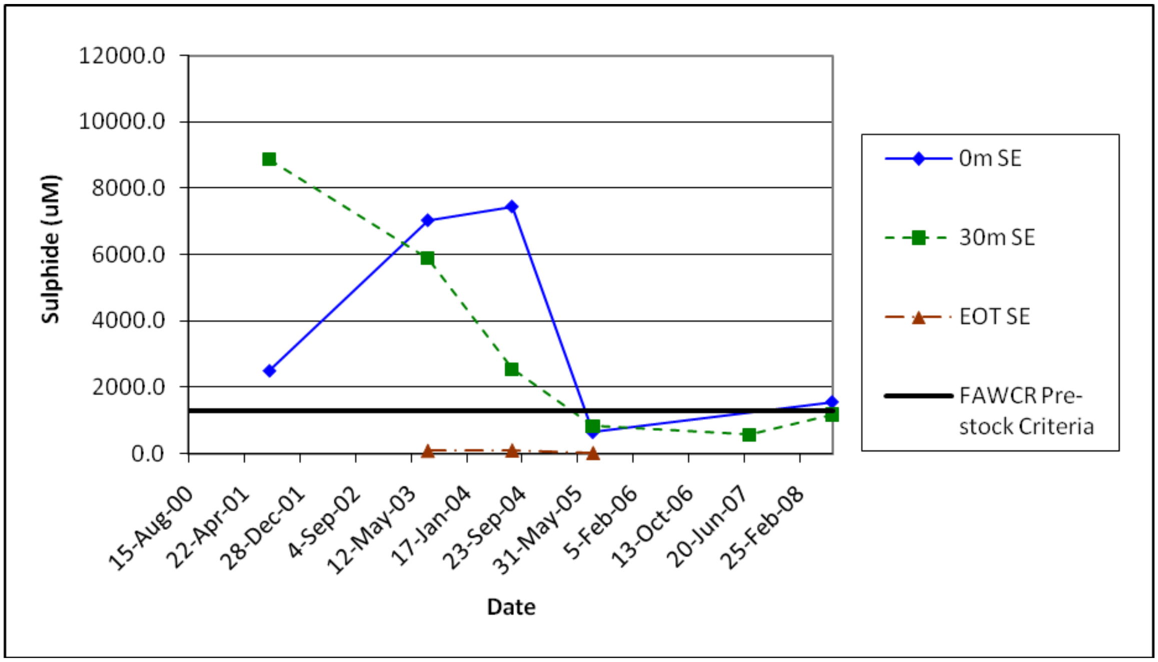

Figure 8. Sulphide concentrations on the southeast side of the Centre Cove farm, 2000 to 2008.

Oxidation reduction potential increased and $\log_{(copper)}$ and $\log_{(zinc)}$ decreased with time and with distance from the centre of the footprint, but only the changes over distance were statistically significant (oxidation reduction potential $t_{(0.05,10)}=3.48$, $r^2=0.55$, $p=0.0060$, $\log_{(copper)}$ $t_{(0.05,10)}=-5.22$, $r^2=0.73$, $p=0.0004$, $\log_{(zinc)}$ $t_{(0.05,10)}=-6.23$, $r^2=0.80$, $p<0.0001$) (Figures 9, 10 & 11).

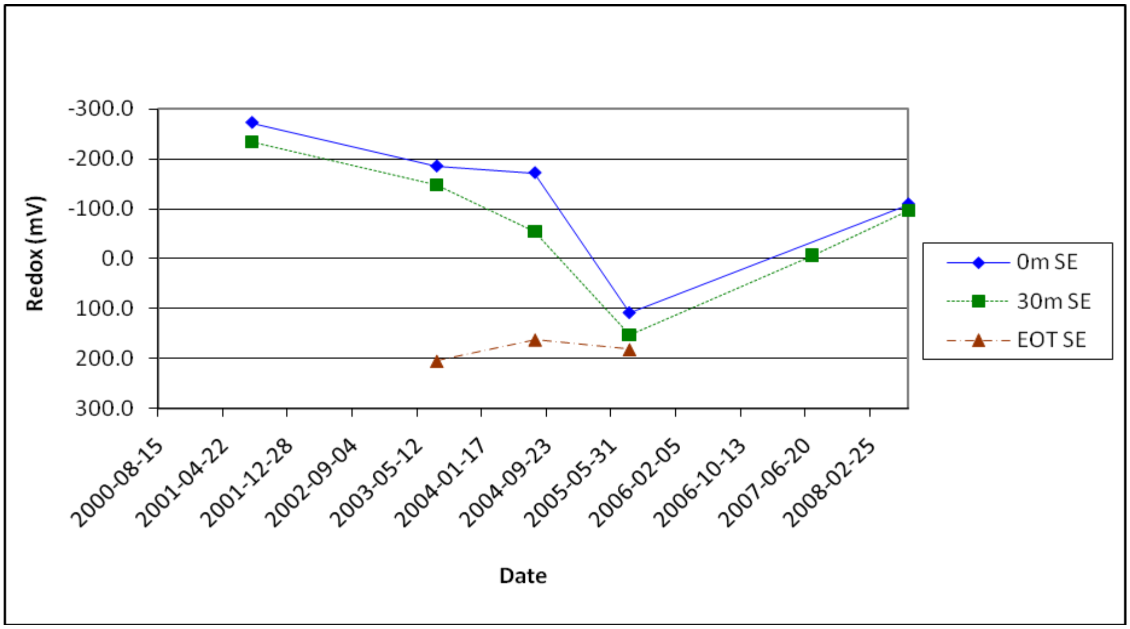

Figure 9. Oxidation reduction potential on the southeast side of the Centre Cove farm, 2000 to 2008.

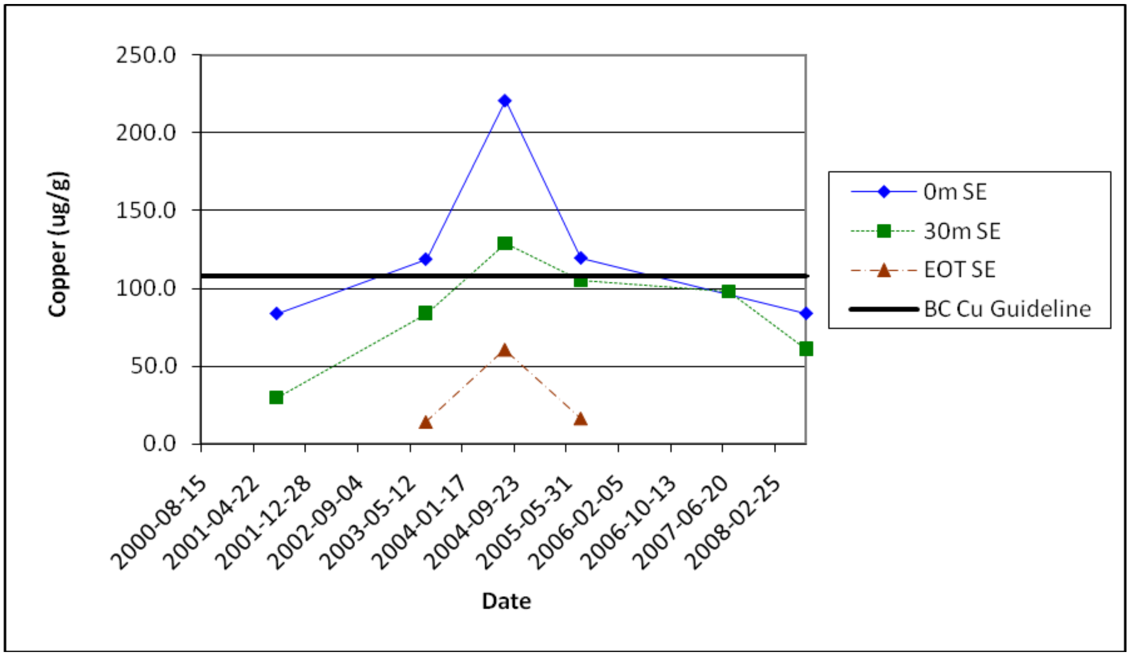

Figure 10. Copper concentrations on the southeast side of the Centre Cove farm, 2000 to 2008.

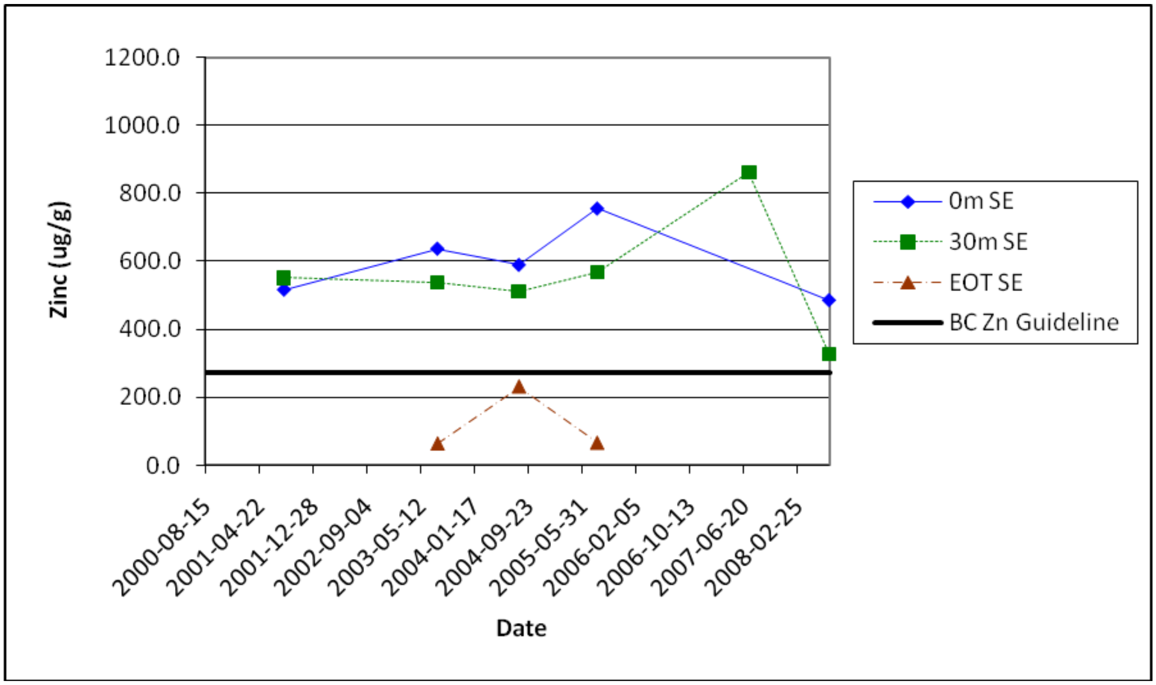

Figure 11. Zinc concentrations on the southeast side of the Centre Cove farm, 2000 to 2008.

3.3 Macrobenthic Invertebrate Analysis

In 2008, the abundance and diversity of invertebrates were generally low at the stations near the farm and increased away from the farm (Table 4, Figures 12 and 13). The abundance of invertebrates ranged from a mean of 13 to 240 individuals at the 30 m southeast station and northwest edge of tenure, respectively. The total number or taxa ranged from 5 to 77, at the 0 m southeast and at the northwest edge of tenure stations, respectively. The Shannon-Wiener Diversity Index (H') ranged from 0.29 to 5.00 at the 0 m southeast station and at a station that was 50 m northwest of the northwest edge of tenure (referred to as edge of tenure (2) hereafter), respectively.

On both the northwest and southeast transects, samples at 0 m and 30 m were dominated by *Capitella capitata* complex and *Nephtys cornuta* (Tables 5a-h). The 100 m station on the northwest transect was also dominated by these species, as well as *Dorvillea longicornis* and *Micrura alaskensis.* The 100 m station on the southeast transect was dominated by *Aphelochaeta glandaria* and *Foxiphalus similis* and to a lesser extent by *C. capitata* complex. The edge of tenure on the northwest transect was dominated by *Axinopsida serricata* and *Mediomastus* sp. The edge of tenure (2) station was dominated by *A. serricata.*

Table 4. Total number of taxa, total abundance and Shannon-Wiener Diversity Index; from samples taken in 2008 only.

	Northwest Transect					Southeast Transect		
Phylum	**50m NW of EOT NW**	**EOT NW**	**100m NW**	**30m NW**	**0m NW**	**100m SE**	**30m SE**	**0m SE**
Annelida	30	62	18	3	6	37	10	3
Arthropoda	7	8	1	0	0	5	0	0
Cnidaria	0	0	2	0	0	0	0	0
Echinodermata	2	0	0	0	0	0	0	0
Extoprocta	0	0	0	1	1	0	1	0
Mollusca	21	6	2	1	1	4	3	2
Nemertea	1	1	1	1	1	0	0	0
Sipuncula	1	0	0	0	0	0	0	0
Total Abundance	**206**	**240**	**41**	**18**	**15**	**62**	**13**	**16**
Total Number of Taxa	**62**	**77**	**24**	**6**	**9**	**46**	**14**	**5**
Diversity Index (H')	**5.00**	**1.35**	**1.02**	**0.51**	**0.66**	**1.76**	**0.78**	**0.29**

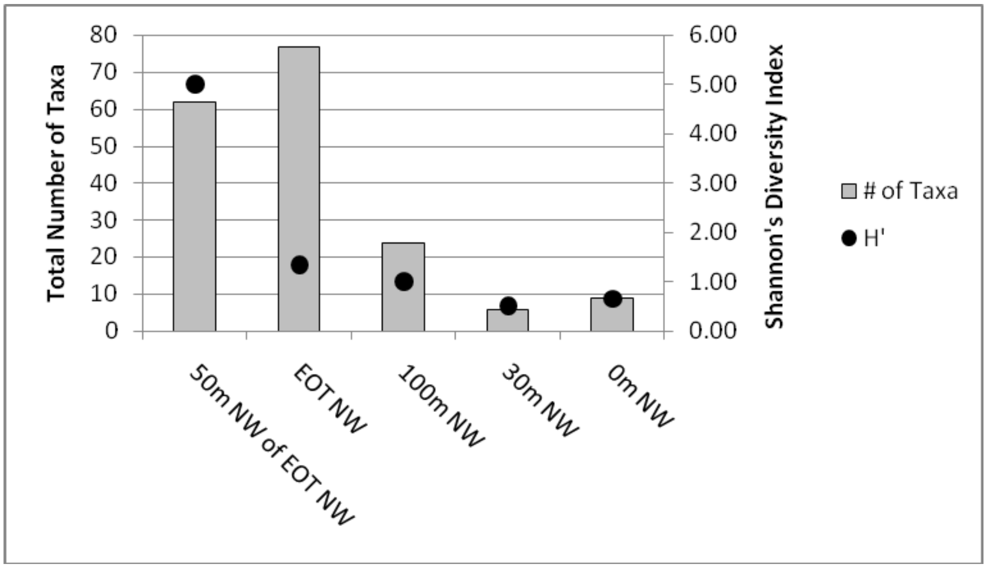

Figure 12. Total number of taxa and Shannon-Wiener Diversity Index at each station on northwest transect; from samples taken in 2008 only.

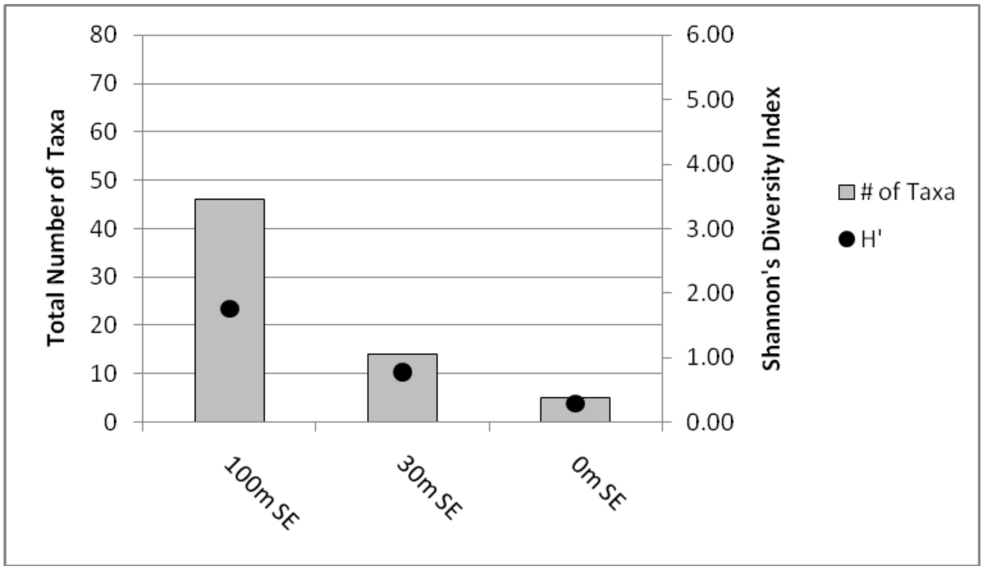

Figure 13. Total number of taxa and Shannon-Wiener Diversity Index at each station on southeast transect; from samples taken in 2008 only.

Tables 5 (a-h). Ten most abundant taxa observed at each station in 2008. Where a tie occurred for 10th place, all species in that position are shown. Unless otherwise specified, means are based on three replicates per station.

(a)

0m NW	**Mean # Individuals**
Capitella capitata Cmplx.	6.3
Nephtys cornuta	4.0
Ophryotrocha sp.	2.3
Armandia brevis	0.3
Axinopsida serricata	0.3
Bryozoa Indet. Colony fragment	0.3
Dorvillea sp.	0.3
Ophelina acuminata	0.3
Palaeonemertea	0.3
(only 9 taxa present)	

(b)

30m NW	**Mean # Individuals**
Capitella capitata Cmplx.	10.0
Nephtys cornuta	3.7
Ophryotrocha sp.	3.3
Bryozoa Indet. Colony fragment	0.3
Lineidae Indet.	0.3
Macoma carlottensis	0.3
(only 6 taxa present)	

(c)

100m NW	**Mean # Individuals**
Capitella capitata Cmplx.	7.3
Dorvillea longicornis	6.7
Nephtys cornuta	6.7
Micrura alaskensis	6.0
Eteone longa	2.3
Armandia brevis	1.3
Podarkeopsis glabrus	1.3
Macoma carlottensis	1.0
Nebalia pugettensis	1.0
Mediomastus sp.	0.7
Polycirrus sp.	0.7
Prionospio (Minuspio) multibranchiata	0.7

(d)

EOT NW	**Mean # Individuals**
Axinopsida serricata	63.0
Mediomastus sp.	46.3
Prionospio steenstrupi	8.3
Heteromastus filobranchus	8.3
Macoma carlottensis	7.7
Scoletoma luti	6.7
Laonice cirrata	6.0
Decamastus gracilis	5.3
Galathowenia oculata	5.3
Ampharete acutifrons	4.7

Table 5. (continued...)

(e)

50m NW of EOT NW	Mean # Individuals *
Axinopsida serricata	41.0
Terebellides californica	12.0
Aphelochaeta sp.	10.0
Syllis sp.	10.0
Decamastus gracilis	9.0
Thyasira flexuosa	9.0
Galathowenia oculata	8.0
Mediomastus sp.	7.0
Alvania rosana	6.0
Eudorella pacifica	6.0
Leptognathis gracilis	6.0
Pholoides aspera	6.0

(f)

0m SE	Mean # Individuals
Nephtys cornuta	13.0
Capitella capitata Cmplx.	2.0
Axinopsida serricata	0.3
Macoma carlottensis	0.3
Prionospio steenstrupi	0.3
(only 5 taxa present)	

(g)

30m SE	Mean # Individuals
Nephtys cornuta	7.0
Macoma carlottensis	1.0
Dorvillea longicornis	0.7
Spiophanes berkeleyorum	0.7
Aphelochaeta sp.	0.3
Axinopsida serricata	0.3
Eteone sp.	0.3
Heteromastus filobranchus	0.3
Ophelina acuminata	0.3
Pectinaria californiensis	0.3
Phyllodoce groenlandica	0.3
Polydora sp.	0.3
Solemya reidi	0.3
Triticella elongata Colony fragment	0.3

(h)

100m SE	Mean # Individuals**
Aphelochaeta glandaria	10.5
Foxiphalus similis	10.5
Capitella capitata Cmplx.	9.0
Lumbrineris japonica	5.5
Nephtys cornuta	4.5
Chaetozone sp.	3.0
Polycirrus sp.	3.0
Scoletoma luti	3.0
Ampharete acutifrons	2.5
Axinopsida serricata	2.5
Westwoodilla caecula	2.5

*Only one replicate at this station

**Only two replicates at this station

4.0 Discussion

4.1 Chemical Trends with Distance From the Farm

All parameters showed a significant decrease in the effects of organic enrichment with increasing distance from the centre of the former footprint. This was to be expected, as impacts from open net pen aquaculture show a gradient from the cages outward (Gowen & Bradbury, 1987).

4.2 Chemical Trends Over Time

All of the parameters on both transects showed improvement with time, but only sulphide results were statistically significant. Sulphide is a strong indicator of benthic impacts (Hargrave *et al*., 1997), so the significant decrease in sulphide concentrations reinforces the conclusion that remediation from the effects of organic enrichment is occurring at Centre Cove.

On the northwest side of the farm, sulphides at the 0 m station were elevated at the start of the study, then decreased in 2004, and then increased in 2005 and remained at that level in 2008. Sulphides at the 30 m station followed a similar pattern. They were elevated above the FAWCR pre-stocking standard of 1300 µM until 2004, then remained below the standard until 2008, when they were found to be well above the standard. Note that the concentration in 2008 was over five times the level measured the previous year, and oxidation reduction potential was correspondingly lower than the previous year. The elevated value in 2008 was unexpected and may be due to the heterogeneous nature of the benthic environment. Throughout the course of the study at the edge of tenure station, sulphide concentrations remained elevated above background conditions. This exceeds the chemical standard in the FAWCR and would normally trigger biological monitoring at an operational farm. All reference station sulphide concentrations were below 201 µM throughout the study. The persistence of elevated sulphide levels at the edge of tenure station 300m from the original position of the net-pen structures for six years post-operation is very unusual in British Columbia.

According to an organic enrichment gradient proposed by Wildish *et al.* (2001), in 2008 the 0 m and 100 m northwest stations could be considered hypoxic and polluted, the edge of tenure northwest station oxic and transitory, and the 30 m northwest station anoxic and grossly polluted.

Copper concentrations have been quite variable on the northwest side of the farm. By 2008, only the concentration at 0 m was above the provincial guideline of 108 µg/g. However, there does not appear to be a strong downward trend in these data, as indicated by the lack of statistically significant results for this parameter. Zinc concentrations on the northwest transect remain elevated above the provincial guideline of 271 µg/g. The concentration at the 30 m station was three times the guideline in 2008. As with copper, zinc does not appear to show a strong downward trend. The fact that there was a statistically significant interaction between date and distance for zinc on the northwest transect suggests that the rate of decrease of zinc concentration varied from year to year on this transect. Also, the lack of statistically significant decreases in copper and zinc may suggest that the metals remain bound to sediment particles and have not been released and dispersed (Cooper & Morse, 1998; Wright & Welbourn, 2002).

On the southwest side of the farm, sulphides at the 0 m station were elevated at the start of the study, decreased in 2005, but then increased again in 2008. Sulphides at the 30 m station were elevated above the FAWCR pre-stocking standard until 2005, and have remained below since then. However, similar to the 30 m northwest station, the sulphide value in 2008 was over twice the value measured the year before and oxidation reduction potential was lower than the previous year. Again, this was unexpected and could be due to natural heterogeneity of the sediments. Similar increases in sulphide occurred at several stations, suggesting a broader change may be occurring. This could be due to changes in oceanographic conditions of warmer water or decreased near-bottom oxygen conditions, variables which could be measured for seasonal and annual variation in future studies. It is also possible that an external source of organic matter, such as terrestrial runoff or erosion during storm events, affected the site in 2008 (Karakassis *et al*., 1999).

According to the organic enrichment gradient noted above (Wildish *et al.*, 2001), in 2008 the 0 m southeast station could be considered hypoxic and polluted, and the 30 m and 100 m southeast stations oxic and transitory.

Copper concentrations on the southeast transect at all three stations peaked in 2004 and were below the provincial guideline at all stations by the end of the study. The peak in 2004 was unexpected and may be the result of a modification in analytical laboratory methodology. However, samples from the northwest side of the farm were in the same sample batch and did not show this trend. Zinc concentrations on the southeast transect were variable, and although they decreased in 2008, they remained elevated above the provincial guideline at the 0 m and 30 m stations. Both metals showed a slight downward trend, which suggests that the benthic environment on the southeast transect may be more conducive to metal remediation. It is important to note that the source of these two metals differs and as such the dispersion rates may also differ. Zinc is found in fish feed and feces, whereas copper is used as an antifouling agent on fish farm nets.

With respect to the provincial guidelines for copper and zinc, these guidelines are working guidelines for sediment, and are chosen because they represent the probable effects level, or the level which if exceeded, may cause increasing effects on aquatic life (Nagpal *et al*., 2006).

It is interesting to note that neither copper nor zinc decreased significantly over time. Both metals are soluble in the presence of oxygen, but may precipitate as sulphides under anoxic conditions, making them less bioavailable in an impacted environment. However, as oxygen levels increase during the remediation process, they may become bioavailable once again (Wright & Welbourn, 2002). Brooks *et al*. (2003) state that zinc could become more toxic as sediment sulphide concentrations decline, and Cooper & Morse (1998) explain that sulphide-associated metals may become more bioavailable after a major oxidation event such as dredging.

As the zinc and copper concentrations have remained high at Centre Cove, metal toxicity may be a concern as the site remediates. The lab methodology used in this study measures all forms of metals (i.e. elemental metals as well as metal complexes) (Huang, pers. comm. May 28, 2009), so it is unknown what proportion of the metals at Centre Cove are currently bioavailable. If metals are released from their sulphide-bound state in the sediment, dilution and dispersion in the overlying water column is likely to be significant. Nevertheless, continual exposure to low levels of copper can alter the benthic community in both freshwater and marine ecosystems (Wright and Welbourn, 2002). A more detailed and focused study of metal speciation, including separation of farm-derived from natural metal concentrations as recommended by Sutherland *et al.* (2007), would be required to explain the metal trends and any potential for future impacts.

Using the line equation for the multiple regression, and using the assumption that sulphides are a good indicator of the impacts of organic enrichment, it is possible to estimate the time by which full organic remediation to background conditions will occur. A sulphide value of <100 µM will be used to represent reference station conditions at this site, because the average reference station sulphide concentration is 66 µM, and sulphide meter accuracy is questionable for readings below 100 µM (Hargrave, pers. comm., March 2, 2009).

On the northwest transect, the multiple regression predicts that sulphide concentrations will return to background conditions at the 30 m station (a distance of 92 m from the centre of the former footprint) by 2013, after 11 years of fallowing. On the southeast transect, the multiple regression predicts that sulphide concentrations will return to background conditions at the 30 m station (a distance of 102 m from the centre of the former footprint) by 2015, after 13 years of fallowing.

It is possible to predict the time by which full organic remediation at the site will occur. Note that the line equations for each transect will produce different predictions, even for the same location, because the trends were different on either side of the farm. The line equation for the northwest transect predicts that sulphide concentrations will decrease to 100 µM by 2015, after 13 years of fallowing. This is compared to the year 2017, after 15 years of fallowing, based on the equation for the southeast transect. Note that while the linear regression predicts a longer recovery time for the southeast transect, this side of the farm is currently less impacted than the northwest side.

4.3 Macrobenthic Invertebrate Trends with Distance from the Farm

Macrobenthic communities can be affected by inputs of farm waste and subsequent organic enrichment of the sediments below fish farms. In general, abundance and diversity of invertebrates are low at stations close to farms and increase with distance from the farm (Brooks *et al.* 2003; Karakassis *et al.* 1999; Ritz *et al.*, 1989; Weston, 1990; Wu, 1995). Also, certain taxa can be indicative of enriched sites. Communities may be dominated by a few opportunistic species when organic enrichment is high, and may then became more balanced during the remediation process as polychaetes and crustaceans are recruited to the site, followed by small bivalves (Brooks *et al*., 2003). Additionally, suspension feeders and surface deposit feeders may be dominant at unimpacted sites, whereas subsurface deposit feeders may dominate at impacted sites (Weston, 1990). Some polychaetes, such as *C. capitata* and *Ophryotrocha* spp. are known opportunists in enriched environments (Brooks, 2007; Karakassis *et al*., 1999). Others species, such as the bivalve *A. serricata*, are excluded from sediments with moderate concentrations of sulphides (Brooks, 2007).

When using the biological community to assess environmental health, diversity may be a better indicator than abundance or biomass (Brooks *et al.*, 2003; Brooks, 2007). At the onset of organic enrichment, the abundance and biomass of opportunistic species are likely to increase, and this increase is offset by declines in sensitive species such that overall abundance and biomass are reduced near sources of organic enrichment (Weston, 1990). In some cases, however, the opportunists may be so prolific that the site has greater biomass and abundance than reference conditions (Brooks *et al.,* 2003). As such, a Shannon-Wiener diversity index likely gives a more accurate representation of the environmental health than total abundance or biomass do.

At Centre Cove, the total abundance, total number of taxa and the Shannon-Wiener diversity index decreased with increasing proximity to the farm on both transects. This supports the chemical results and indicates that the gradient of enrichment decreases from the net pens outward.

There is a strong dominance of the polychaetes *C. capitata* complex and *N. cornuta* at stations close to the farm (0 m and 30 m on both transects), and to a lesser extent at both 100 m stations as well. The presence of these known opportunists (Brooks, 2007; Brooks, 2003; Karakassis *et al.*, 1999) indicates that these stations are organically enriched. The 100 m stations on both transects showed a higher diversity than the stations closer to the farms. At the 100 m northwest station, the polychaete *D. longicornis* and the nemertean *M. alaskensis* were present in addition to the species listed above. *Dorvillea* sp. is an organic carbon opportunist (Brooks, 2007), showing that even at 100m, there is evidence of organic enrichment, although the increased diversity suggests the 100m northwest station is starting to recover. At the 100 m southeast station, the polychaeta *A. glandaria* and the amphipod *F. similis* were present in higher numbers than *C. capitata.* Again, the higher diversity signifies recovery, but the presence of *C. capitata* is evidence of organic enrichment.

There are slight differences between the two transects. The 0 m and 30 m sites on the northwest transect were dominated by *C. capitata*, whereas on the southeast transect these sites were dominated by *N. cornuta.* The polychaete *Ophryotrocha* sp., another known opportunist (Brooks, 2007) was present in high numbers at the 0 m and 30 m stations on the northwest transect, but was not present at all at these distances on the southeast transect. It is unclear whether this signifies a difference in environmental health between the two transects, because all of these species are typical of enriched environments.

The communities at the northwest edge of tenure station and the edge of tenure (2) station are indicative of non-impacted conditions. The bivalve mollusc *A. serricata,* a species known to be sensitive to high sulphide concentrations and only abundant at sulphide concentrations of less than 725 µM (Brooks, 2007), was the dominant species at both of these stations. The annelid polychaete *Mediomastus* sp. was also dominant at the edge of tenure station. *Mediomastus californiensis* was numerically dominant at a non-impacted station 450 m from net pens in a study by Weston (1990), and thus the presence of *Mediomastus* sp. likely indicates non-impacted conditions at the northwest tenure edge as well.

Brooks (2007) analyzed results from a large dataset from British Columbia (634 samples, 1,363 taxa and 161,830 animals) and found that reference stations in the Kyuquot Sound area were dominated by annelid communities with strong representation by capitellids.

Comparing the results of the 2008 benthic sampling at Centre Cove to the dominant species in this dataset, there are only six taxa that dominate at both Centre Cove farm stations and Kyuquot Sound reference stations. On the northwest transect at 0 m, 30 m and 100 m stations, the only species from the reference dataset that is dominant is *C. capitata*. At the edge of tenure and the edge of tenure (2) station, there are three species from the reference set: *Heteromastus* sp., *Galathowenia oculata* and *Aphelochaeta* sp.. On the southeast transect at 0 m, again the only species from the reference set that dominates is *C. capitata*. At the 30 m and 100 m stations, this species is present, as well as four others from the dataset, *Heteromastus* sp., *Aphelochaeta* sp., *Lumbrineris* sp. and *Chaetozone* sp. There are nine taxa that dominate in the reference dataset but do not dominate at Centre Cove. This does not necessarily indicate that the biological communities at all stations at Centre Cove are impacted as compared with reference conditions, but it is clear that there is a trend toward more of the reference species at the stations farther from the net pens. This is further support for the statement that the biological community reflects the decreasing gradient of organic enrichment from the net pens outward.

Links can be made between the sediment chemistry and the effects on the biological community at Centre Cove. From the dataset analyzed by Brooks (2007), significant biological effects can be expected at sulphide concentrations above 775 µM. Compared with reference station conditions, macrofauna abundance will nearly always decline significantly at sulphide concentrations above 3,500 µM. Brooks (2007) found that there was a 50% reduction in abundance of macrofauna above 1,650 µM, a 50% reduction in species richness above 775 µM, and a 40% reduction in the Shannon-Wiener Index above 700 µM.

Many of the stations at Centre Cove have sulphide concentrations above these limits. On the northwest transect in 2008, the only stations with sulphide concentrations below 775 µM are the edge of tenure and edge of tenure (2). The 0 m, 30 m and 100 m stations had values from 1258 to 3871 µM and thus the sediment at these stations still remains inhospitable for many organisms that would normally exist there. On the southeast transect, the 0 m and 30 m stations remain elevated about 775 µM (1551 µM and 1187 µM, respectively) and the 100 m station is only slightly below (772 µM), so sediment at these stations also likely remains inhospitable for many organisms.

The sulphide concentration at the edge of tenure station on the northwest transect has decreased from 3479 µM in 2003 to 462 µM in 2008. In 2006, it was still 1190 µM. Thus, sensitive species such as *A. serricata*, which now dominates at this site, would likely have been excluded until after 2006. This suggests that within just two years, the biological community can undergo considerable change, and thus as sediment chemistry continues to improve at Centre Cove, the same biological effects are expected at the other stations.

In conclusion, after six years of fallowing, the biological community at Centre Cove is still recovering from the impacts of organic enrichment. At distances of at least 100 m from the net pens, sulphide concentrations remain elevated such that species diversity and abundance remains lower than background conditions and typical members of the macrofaunal invertebrate community are excluded. At and beyond the edge of tenure on the northwest side of the farm (>294 m from net pens), diversity and abundance are higher than other stations and sulphide-sensitive species dominate.

4.4 Comparison with Other Studies

Based on the estimates of the linear regression, the Centre Cove farm site could take up to 15 years of fallowing to return to background conditions of sulphide and oxidation reduction potential. Metal remediation may take even longer. This timeframe is substantially longer than most finfish aquaculture sites in British Columbia. In a study of five aquaculture sites, Brooks *et al*. (2003) found that remediation began as soon as fish harvesting started and fallow periods of four to six months appeared adequate for complete chemical remediation. It is important to note that Brooks *et al*. (2003) defined chemical remediation in their study as a return to reference station conditions for organic carbon and oxidation reduction potential, but a decrease in sulphide concentrations to only <960 µM. This is much higher than the <100 µM being used in this report for Centre Cove. For comparison, the linear regression model predicts that it would take up to eight years of fallow for sediments at Centre Cove to reach <960 µM, which is considerably longer than the four to six months estimated at the farms studied by Brooks *et al.* (2003). Note as well that the chemical remediation definition by Brooks *et al.*(2003) was limited to organic chemicals and did not include decreases in metal concentrations.

The extent of the benthic impact from aquaculture is determined by farm practices and by the nature of the receiving environment and may be particularly related to the current speeds of the surrounding waters (Pearson & Black, 2001). Water depth and current speed can be more important factors in determining sulphide concentrations and oxidation reduction potential than fish biomass and feeding practices (Brooks & Mahnken, 2003). Karakassis *et al*. (2000) compared three aquaculture sites in the Mediterranean and found that there was a pronounced increase in organic carbon and nitrogen at the two sites in protected waters, and a less pronounced effect at the site with strong currents. Brooks & Mahnken (2003) found that a farm with moderate current speeds (mean current speed at 15 m depth: 4.30 cm/s), remediation to was expected to be complete after six months of fallow. When taking this into account, the slow remediation at Centre Cove can be explained in part by its low current speeds; as noted above, the mean current speed is only 3.4 cm/sec at 15m depth, and only 2.1 cm/s at 5 m above the bottom.

Another important factor in determining remediation times is the sediment characteristics of the site. Centre Cove is a depositional environment with an average silt/clay fraction of 58%. Many sites with comparable sediment compositions have had long remediation times. Pohle *et al*. (2001) found that two aquaculture sites on the east coast of Canada, both with silt/clay fractions of 70-90%, had organic loading and benthic impacts that persisted for the entire six years of the study. In the Mediterranean, Karakassis *et al*. (2000) found that oxidation reduction potential was negative at an aquaculture site with a high silt/clay fraction but remained positive at a site with coarser grain size. Brooks &

Mahnken (2003) reported that British Columbia farms located in depositional areas with fine-grained sediments had higher sulphide concentrations and at greater distances from net pens than sites with 20-40% fines.

A further explanation for the persistence of impacts at Centre Cove can be taken from Brooks & Mahnken (2003). Organic carbon is catabolized by sulphate-fuelled bacteria under aerobic conditions. When the oxygen levels in the sediment are too low to oxidize sulphide to sulphate, a distinct possibility in fine-grained sediments such as those at Centre Cove, the supply of sulphate to fuel the catabolism is depleted. This causes the recovery of the system to stall. Sulphides would then be converted to metal complexes instead of sulphate, until the supply of metal cations was also exhausted. The sulphide in the sediment would then remain at a static level until something in the system changed that allowed the bacteria to catabolize the carbon again. It is unclear whether such a plateau in remediation has already been passed at Centre Cove, or if perhaps this plateau is only just occurring now, and remediation may take considerably longer than predicted from 2008 forward. This may, in part, explain the observed increase in sulphides in 2008 at most sampling stations.

In addition to the farm-derived sources of organic carbon, the site may be receiving carbon from external sources. Terragenous material may be coming from streams and runoff from Whitely Island and other nearby islands. Ocean upwelling and currents may bring nutrients from even farther away. Analysis of the isotope signatures of the carbon or nitrogen in the sediments at the Centre Cove site may determine whether this is the case. If the amount of externally-derived carbon at the site is significant, meaning that the site is continually receiving additional organic carbon during the fallowing period, this may, in part, explain the slow remediation. It is expected, however, that these variables would affect reference stations as well, and reference station conditions did not show any indications of organic enrichment.

5.0 Conclusions and Recommendations

Based on the assessment of the data for the entire Centre Cove farm, it appears that the site is gradually recovering from the effects of organic enrichment. Remediation of copper and zinc is occurring much more slowly and it is unclear if these metals will return to background conditions. This raises an important point that if farms are fallowed to allow recovery from organic enrichment, but not long enough to allow recovery from metal contamination, metals may accumulate in high concentrations over subsequent production cycles. As the site recovers from organic enrichment, the metal complexes may break apart which in turn may cause the bioavailability and thus toxicity of metals to increase. While farms are fallowed to accomplish remediation of organic enrichment, the remediation process could lead to negative impacts with respect to metals, a possibility which has not yet been addressed in aquaculture regulations in British Columbia.

Although the conditions at Centre Cove have improved over the course of the study, the benthic impacts from finfish aquaculture at this site are severe compared to other farm sites in British Columbia. It is estimated that a full remediation to background sulphide conditions could take 15 years from the time that fish were last on site. The persistence of impacts and the slow remediation time at Centre Cove is likely due to the site's slow current speeds and the fine sediment grain size. The MoE study at Centre Cove lends support to the idea that low current and fine-grained sediment sites in British Columbia are not well suited for intensive open net cage finfish aquaculture.

Future monitoring studies may include:

- a focus on the 30 m stations on either side of the farm, where elevated sulphide concentrations were measured in 2008, to determine whether this was due to a heterogeneous benthic environment or whether sulphide levels are increasing;
- a more detailed and focused study of metal speciation and bioavailability including separation of farm-derived from natural metal concentrations; and
- a thorough reassessment of the site in five years, including macrofaunal invertebrate analysis, to evaluate the progress of remediation.

6.0 References

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Appendix 1. Sediment Chemistry Data from the Centre Cove Farm, 2000-2008.

Table 6. Sediment Chemistry Results for the Northwest Transect at the Centre Cove farm site, 2000-2008.

Date	Station Name	# of Replicates	Latitude	Longitude	Sulphide (µM)	Redox (mV)	Copper (µg/g)	Zinc (µg/g)
2000-08-15	0m NW	3	50 00.911	127 11.760	9480.0	-207.4	69.3	936.3
	100m NW	3	50 00.954	127 11.766	9563.3	-198.7	58.0	1026.0
	250m NW	3	50 01.018	127 11.907	170.3	340.0		
2002-08-08	0m NW	3	50 00.913	127 11.694	10240.0	-174.0	99.2	554.7
	30m NW	3	50 00.923	127 11.711	10553.3	-173.0	147.7	727.0
2003-07-29	30m NW	3	50 00.914	127 11.707	2964.7	-29.0	106.8	773.7
	EOT NW	3	50 00.992	127 11.806	3478.7	-29.5	75.8	906.7
2004-08-11	0m NW	3	50 00.912	127 11.693	637.0	130.1	131.5	736.7
	30m NW	3	50 00.937	127 11.725	1125.3	-74.0	139.3	880.3
	EOT NW	3	50 00.991	127 11.804	2980.0	-168.5	133.0	1007.0
2005-08-10	0m NW	3	50 00.917	127 11.683	1286.7	-66.3	78.8	599.3
	100m from EOT NW	1	50 01.012	127 11.854	223.0	215.5	37.8	165.0
	30m NW	3	50 00.922	127 11.722	759.3	80.9	100.6	899.0
	50m from EOT NW	1	50 01.016	127 11.848	797.0	228.2	114.0	351.0
	EOT NW	3	50 00.996	127 11.806	1320.0	-91.9	195.1	1062.0
2006-08-02	EOT NW 1	2	50 01.019	127 11.847	1190.5	25.4	167.0	608.0
	EOT NW 2	1	50 01.005	127 11.870	72.5	329.0	35.2	46.0

(Table 6. continued....)

2007-07-17	30m NW	3	50 00.922	127 11.724	768.0	15.3	119.1	944.7
	60m SE of 30m NW	1	50 00.903	127 11.694	568.0	62.5	127.0	948.0
	EOT NW 1	2	50 01.019	127 11.845	331.0	122.8	88.3	439.5
	EOT NW 2	1	50 01.046	127 11.814	150.0	232.1	47.6	188.0
	EOT NW 4	1	50 01.006	127 11.857	14.8	228.9	19.6	62.0
	EOT NW 5	1	50 01.034	127 11.869	52.5	270.7	29.9	95.0
	EOT NW 6	1	50 01.052	127 11.857	44.3	263.2	19.9	70.0
	EOT NW 7	1	50 01.002	127 11.807	725.0	-107.3	52.9	300.0
2008-07-23	0m NW	3	50 00.924	127 11.710	1258.0	-69.9	118.9	649.7
	100m NW	3	50 00.955	127 11.766	1258.7	-116.7	208.5	728.3
	30m NW	3	50 00.934	127 11.718	3870.7	-95.2	88.5	825.0
	50m NW of EOT NW	1	50 01.042	127 11.870	20.2	235.0	19.8	73.0
	EOT NW	3	50 01.023	127 11.852	462.0	225.9	76.6	446.7

Table 7. Sediment Chemistry Results for the Southeast Transect at the Centre Cove farm site, 2001-2008.

Date	Station Name	# of Replicates	Latitude	Longitude	Sulphide (µM)	Redox (mV)	Copper (µg/g)	Zinc (µg/g)
2001-08-15	0m SE	2	50 00.866	127 11.620	2490.0	-272.1	83.7	518.0
	100m SE	1	50 00.830	127 11.545	3440.0	-324.4	44.8	598.1
	30m SE	3	50 00.853	127 11.600	8863.3	-233.1	29.9	551.5
2003-07-29	0m SE	3	50 00.859	127 11.614	7026.7	-185.0	118.7	638.0
	30m SE	3	50 00.856	127 11.595	5898.0	-147.8	84.1	537.7
	EOT SE	3	50 00.766	127 11.148	86.4	204.9	13.9	63.4
2004-08-11	0m SE	3	50 00.865	127 11.625	7440.0	-171.8	220.9	590.3
	30m SE	3	50 00.854	127 11.590	2556.7	-54.2	128.9	512.3
	EOT SE	3	50 00.765	127 11.139	100.0	162.9	60.9	230.3
2005-08-10	0m SE	3	50 00.861	127 11.618	638.7	108.2	119.5	755.7
	30m SE	3	50 00.858	127 11.589	843.7	151.5	105.3	568.3
	EOT SE	3	50 00.776	127 11.140	23.2	182.0	16.2	65.6
2007-07-17	30m SE	3	50 00.856	127 11.589	584.0	-6.6	97.9	861.0
2008-07-23	0m SE	3	50 00.873	127 11.590	1551.0	-109.2	83.8	487.0
	100m SE	2	50 00.850	127 11.543	771.5	76.4	60.6	298.5
	30m SE	3	50 00.860	127 11.592	1187.3	-97.2	61.1	327.3

Appendix 2. Parameter Estimates from the Linear Regressions on the Sediment Chemistry Data, 2002-2008.

For the following parameter estimates, note that a value of 2002 was subtracted from all dates, so that a date of 0 corresponded to the year 2002, the last year that fish were on site, and thus the year of expected highest impact. The distance was reported in hundreds of metres, such that a distance of 50 m would be reported as 0.5 hundreds of metres.

Table 8. Parameter Estimates for log(sulphide) on the northwest side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	9.2603261	0.572295	16.18	<.0001
Yrs since fish removed	-0.350106	0.133752	-2.62	0.0151
Distance from net pens (100s of m)	-0.707217	0.2044	-3.46	0.0020

Table 9. Parameter Estimates for redox potential on the northwest side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-166.1341	60.26072	-2.76	0.0110
Yrs since fish removed	16.132727	14.0836	1.15	0.2633
Distance from net pens (100s of m)	73.553457	21.52264	3.42	0.0023

Table 10. Parameter Estimates for log(copper) on the northwest side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	5.227366	0.275014	19.01	<.0001
Yrs since fish removed	-0.043688	0.064274	-0.68	0.5032
Distance from net pens (100s of m)	-0.32139	0.098224	-3.27	0.0032

Table 11. Parameter Estimates for log(zinc) on the northwest side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.694999	0.368357	20.89	<.0001
Yrs since fish removed	-0.153075	0.088662	-1.73	0.0977
Distance from net pens (100s of m)	-0.456485	0.121528	-3.76	0.0010
(Yrs since fish removed-3.74074)* (Distance from net pens (100s of m)-2.17852)	-0.150902	0.069246	-2.18	0.0398

Table 12. Parameter Estimates for log(sulphide) on the southeast side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	9.2440323	0.488624	18.92	<.0001
Yrs since fish removed	-0.313827	0.110665	-2.84	0.0177
Distance (100s of m)	-0.692126	0.087272	-7.93	<.0001

Table 13. Parameter Estimates for redox potential on the southeast side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-137.1702	72.69095	-1.89	0.0885
Yrs since fish removed	14.224756	16.4632	0.86	0.4078
Distance (100s of m)	45.126996	12.98317	3.48	0.0060

Table 14. Parameter Estimates for log(copper) on the southeast side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	5.2082988	0.303816	17.14	<.0001
Yrs since fish removed	-0.092537	0.068809	-1.34	0.2084
Distance (100s of m)	-0.283415	0.054264	-5.22	0.0004

Table 15. Parameter Estimates for log(zinc) on the southeast side of the farm, 2002 to 2008.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6.7557476	0.283537	23.83	<.0001
Yrs since fish removed	-0.051036	0.064216	-0.79	0.4452
Distance (100s of m)	-0.315533	0.050642	-6.23	<.0001