Characterization of the spatial pattern of benthic sulfide concentrations at six salmon farms in southwestern New Brunswick, Bay of Fundy

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ABSTRACT

Chang, B.D., Page, F.H., Losier, R.J., McCurdy, E.P., and MacKeigan, K.G. 2011. haracterization of the spatial pattern of benthic sulfide concentrations at six salmon farms in southwestern New Brunswick, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2915: iv + 24 p.

Spatially-intensive sediment sulfide sampling surveys were conducted during the summer months at six salmon farms in southwestern New Brunswick, Bay of Fundy, Canada. One of the six farms was also sampled during the following spring to examine seasonal changes. Grab samples were taken at 20−57 locations around the fish cages and up to 100−150 m away. The sulfide distribution under farms was spatially patchy. The highest sulfide levels measured were generally found near cages; however, sulfide levels were low near most cages, as well as at most locations away from cages. At most farms, any areas of hypoxic sediments were mostly confined within the cage array areas, and were not found beyond 60–100 m from the cage edges. Only two farms had any anoxic sediments; at one of these, some anoxic sediments were located outside the cage array. At four of the six farms, the mean sulfide levels from the annual regulatory monitoring (conducted in August-October) were significantly different from the mean of the summer survey samples taken nearest to the regulatory monitoring locations. This may have been due to differences in the dates between the sampling and monitoring events and/or small-scale spatial heterogeneity of the sulfide levels. The one farm that was sampled both in summer and the following spring showed different sulfide levels on the two dates, with considerably lower levels in the spring.

RÉSUMÉ

Chang, B.D., Page, F.H., Losier, R.J., McCurdy, E.P., and MacKeigan, K.G. 2011. Characterization of the spatial pattern of benthic sulfide concentrations at six salmon farms in southwestern New Brunswick, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2915: iv + 24 p.

Des relevés d'échantillonnage des sulfures dans les sédiments ont été effectués au cours de l'été à six fermes salmonicoles dans la baie de Fundy, au sud-ouest du N.-B., Canada. Un échantillonnage a également été effectué à une de ces six fermes le printemps suivant afin d'étudier la variation saisonnière. Le nombre de sites de prélèvement d'échantillons instantanés a varié de 20 à 57 par ferme, et la distance maximale entre les sites les plus éloignés et les cages d'élevage a varié de 100 à 150 mètres. La répartition des sulfures sous les fermes était très irrégulière. En général, les concentrations de sulfures les plus élevées ont été observées près des cages. Toutefois, les concentrations étaient faibles à la plupart des sites d'échantillonnage. Les sédiments hypoxiques étaient principalement confinés dans les zones des réseaux de cages, et aucun sédiment hypoxique n'a été recueilli au-delà d'une certaine distance (de 60 à 100 m) par rapport aux extrémités des cages. Des sédiments anoxiques ont été

observés à deux fermes seulement, et à une de ces fermes, des sédiments anoxiques ont été recueillis à l’extérieur de la zone du réseau de cages. À quatre des six fermes, la concentration moyenne de sulfures calculée dans le cadre des travaux de surveillance réglementaire annuelle (menés d’août à octobre) était significativement différente de la moyenne obtenue à partir des échantillons des relevés estivaux prélevés à proximité des sites de surveillance réglementaire. Ce résultat s’explique peut-être par des différences entre les dates d’échantillonnage et de surveillance ou par une hétérogénéité spatiale à petite échelle des concentrations de sulfures. À la seule ferme où des échantillons ont été prélevés à l’été et au printemps, les résultats montrent une variation saisonnière des concentrations de sulfures, celles au printemps étant considérablement plus faibles que celles à l’été.

INTRODUCTION

There are currently more than 90 finfish farm leases in the southwestern New Brunswick (SWNB) portion of the Bay of Fundy. About 90% of these farms are approved for growing Atlantic salmon (*Salmo salar*). The size of the salmon farms varies considerably, ranging from 2–47 ha (average 17 ha), holding from 0–640 000 fish (average about 340 000 fish per active farm) (estimates for 2009, based on data provided by the New Brunswick Department of Agriculture, Aquaculture and Fisheries).

Annual regulatory monitoring of benthic conditions must be conducted under all operating farms as part of the Environmental Management Program (EMP) of the New Brunswick Department of Environment (NBDENV). This monitoring, designated as Tier 1, must be conducted between 1 August and 31 October each year (NBDENV 2006, 2007). The results of the Tier 1 monitoring may trigger the need for additional monitoring: Tier 2, within 20 d of Tier 1, and Tier 3, in the following spring. The main purpose of the regulatory monitoring is "to accurately evaluate the condition of the marine sediments under marine finfish cage aquaculture sites" (NBDENV 2006).

Tier 1 monitoring protocols require one transect and three sediment samples for each 100 000 fish (or part thereof) on site, with a minimum of two transects (6 samples) at farms holding ≤200 000 fish (Fig. 1; NBDENV 2007). Transects start at the outer edge of cages located on the outer perimeter of the cage array, extending away from the cage array; transect locations are based on water current patterns and the relative fish biomass per cage, with priority given to cages with higher biomasses. At each transect, three sediment samples are taken at the cage edge, in close proximity to each other; no Tier 1 samples are taken directly under cages (due to diver safety issues) or outside the cage array. For the sizes of farms currently in SWNB, from 6–21 samples (from 2–7 transects) are collected per farm. For licensed farms with no fish on site at the time of monitoring, no transects are required, but 6 sediment samples must be taken at the same locations as the most recent monitoring. For farms located at water depths <30.5 m, sediment core samples are to be collected by divers. For deeper sites, surface-deployed grab samplers can be used to collect sediment samples (transects are not required). Total sulfides (S) are measured in 5-ml subsamples taken from the top 2 cm of each core (one subsample per core) or grab (three subsamples per grab), for a total of three measurements per sample location. The site rating (Table 1) is based on the average sulfide concentration of all subsamples collected at a farm.

Since 2006, EMP monitoring has been linked to the possible need for a Fisheries Act Authorization (FAA), due to the likelihood of causing a harmful alteration, disruption or destruction (HADD) of fish habitat. If the average Tier 1 sediment sulfide concentration is 3000–4500 µM, the farm is likely causing adverse environmental effects on marine benthic sediments, and a FAA *may* be required. If the average Tier 1 sulfide concentration is 4500–6000 µM, the farm is causing adverse benthic conditions, and a FAA *will likely* be required. If the average Tier 1 sulfide concentration is 6000 µM or more, the farm is causing severe damage to the marine benthic habitat, and a FAA *will likely* be required (NBDENV 2006).

The purpose of the Tier 1 monitoring is to provide an indication of the general magnitude of organic enrichment in sediments under fish farms; it was not designed to provide a description of the temporal or spatial variability of organic enrichment. In this study, we examined the effectiveness of the Tier 1 monitoring for providing accurate estimations of the overall seafloor impact from salmon farms. We conducted spatially-intensive summer sampling surveys at six salmon farms in SWNB, to examine small-scale variability in sediment sulfide levels. We also conducted a spring survey at one of the farms. The results were compared to the results of the EMP Tier 1 monitoring in the same year. The data were also to be used for comparisons with predictions by models such as DEPOMOD (Cromey et al. 2002); those analyses will be presented in a separate report. Some preliminary results from this project have been previously reported (Page et al. 2007, 2009; Chang et al. 2009).

METHODS

Spatially-intensive sampling surveys were conducted at six salmon farms, sites A–F (Table 2). Each farm was sampled once in summer (late July–September of 2005, 2006, or 2007). Site A was also sampled in May 2006. All farms had been stocked with Atlantic salmon (*Salmo salar*) smolts one or two years prior to sampling. Sites A and C were actively feeding all cages at the time of the sampling survey and the Tier 1 monitoring. Site B was harvested by late May 2006, about three months prior to the sampling survey and the Tier 1 monitoring. Site D completed harvesting around the time of the sampling survey, 3–4 three months prior to the Tier 1 monitoring (there were no fish on site at the time of Tier 1 monitoring). Site E had completed harvesting by July 2007, just before the sampling survey and 3–4 months prior to the Tier 1 monitoring; the site was restocked starting in October 2007 and had new smolts at the time of the Tier 1 monitoring. Site E was a large site with two cage arrays; sampling was conducted at only one of the arrays. Site F was actively feeding at the time of sampling and Tier 1 monitoring; however, feeding data were not available for this site. Site A had thirteen 100-m circumference circular cages and one 50-m cage. Site B had 70-m cages. All other sites had 100-m cages. Data on the amount of feed added per cage (total feed added from the introduction of the year-class to the month of the sampling survey) were obtained from the farm operators (except for site F).

At each farm, samples were collected using surface-deployed Hunter-Simpson grabs at 20–57 locations: within the cage array, at the outer edges of some cages, and at distances of approximately 25, 50, and 100 m from the edge of the cage array. The differences in the numbers of sampling locations among farms were due to differences in the sizes of farms and local topography. The fewest number of sampling locations was at site B, where rock ledges limited the number of locations outside the cage array. Sample locations were recorded using GPS. In 2005, a grab which collected 0.096 m^2 of sediment (32 × 30 cm) was deployed from the CCGS Pandalus III (12.8 m in length). In 2006 and 2007, a similar, but smaller grab, which could be deployed from a smaller boat (7.3 m long), was used; this grab collected 0.024 m^2 of sediment (16 × 15 cm). The grabs were designed with protective covers, to minimize disturbance to the sediment surface layer. From each grab sample, three spatially scattered 5-ml syringe samples of sediment were collected from the top 2 cm of sediment. The sediment samples were stored on ice for transport to the laboratory, where they were stored in a refrigerator for subsequent analyses for sediment sulfide concentrations. All samples were analyzed for total sulfides within 2 d of sampling, following the method described by Wildish et al. (1999, 2004).

The arithmetic means of the sulfide values for each sample location were mapped using MapInfo Professional (version 8.0) software. Cage locations were estimated based on the sample locations. Contour plots were produced using MapInfo Vertical Mapper (version 3.0). Grid files were created using the Natural Neighbor (Simple) interpolation technique; default values were used for Cell Size (0.0), Aggregation Distance (0.0), and Surface Solution Type (smoothed, without overshoot). Contours were then created from the grid files using the Grid Contour tool.

The mean and individual sulfide values were also plotted vs. the distance from the edge of the cage array. The edge of the cage array was defined by a polyline connecting the sample locations along the outside edges of the outer cages in the array. All sample locations within the cage array area were given a distance value of 0 m.

Sediment sulfide data from the EMP Tier 1 monitoring in the same year as the summer surveys (Table 3) were provided by NBDENV. The arithmetic means of the EMP Tier 1 sulfide values were compared to the arithmetic means of the summer survey data collected from the locations nearest to the EMP Tier 1 locations. We also compared the latter data with the arithmetic means of all other summer survey locations within the cage arrays. For the spring 2006 sampling survey at site A, comparisons were made with additional EMP monitoring data collected at Tier 1 locations in June 2006 by Sweeney International Management Corp.

RESULTS

Baseline data (collected before a farm began operating) were only available for site A, where the pre-farm sulfide values ranged from 46–265 µM, with an arithmetic mean of 138 µM (data collected in February 2001 by E. Garnier, Dominator Marine Services Inc., Saint John, NB). Sediment sulfide data for individual samples taken within the cage arrays during the summer surveys are given in Table 4. EMP Tier 1 monitoring data for the same years as the summer surveys are given in Table 5. For both sets of data, differences among replicates from the same location were sometimes large, as indicated by high standard deviations and coefficients of variation.

Figure 2 shows the mean sulfide values at each sample location for the summer surveys at all six sites, as well as the data from the EMP Tier 1 monitoring from the same year. Figure 3 shows contour plots derived from the summer survey sulfide values; also indicated are the total amounts of feed added to each cage up to the date of sampling (where available). The amount of feed added varied widely among cages at sites A and B: at site A, the amount added per cage to 22 September 2005 ranged from 27–126 t; at site B, the amount added per cage through May 2006 ranged from 34–128 t (there was no feeding after early May 2006). At the other sites, the feeding rates were relatively even among the cages: at site C, the amount of feed added per cage to 12 September 2006 ranged from 188–244 t; at site D, the amount of feed added per cage from January 2006 to July 2007 ranged from 162–220 t; and at site E, the amount of feed added per cage through May 2007 ranged from 210–279 t (no feed was added to the cage array that was sampled after May 2007).

There was high spatial variability within the cage arrays in the summer surveys. The areas of highest sulfide concentrations occupied relatively small portions of the areas under the cages.

Anoxic sediments (based on the classification in Table 1) were only found at sites A and C, comprising <1–4% of the seafloor sampled (Tables 6 and 7). Hypoxic sediments were found at all six sites, comprising <1–36% of the seafloor sampled. Oxic sediments were found at all six sites, comprising 60–100% of the seafloor sampled.

There was a general trend of decreasing sulfide values with increasing distance from the cage array, but there was considerable variability both between and within distances at each site (Fig. 4). At site A, sulfide values were still mostly above the pre-farm baseline values at 125 m from the cage array (the maximum distance sampled at this site) in the summer survey, and some anoxic and hypoxic values occurred outside the cage array; Hypoxic A values were obtained up to 100 m away from the cage array. At site B, all samples taken outside the cage array were either Oxic A or Oxic B, with no clear trend with distance from the cage array. At site C, all samples taken outside the cage array up to 50 m away were Oxic A or Oxic B, and all samples taken beyond 50 m away from the cage array were Oxic A. At site D, all samples taken outside the cage array were Oxic A. At site E, some Hypoxic A samples were taken at 40 m from the cage array, and Oxic B results were obtained at 50 m; beyond 50 m, all results were Oxic A, except for one Oxic B sample. At site F, all samples taken outside the cage array were either Oxic A or Oxic B, and all samples beyond 60 m from the cage array were Oxic A.

The number of sample locations for the EMP Tier 1 monitoring at these farms ranged from 2–5 locations (6–15 samples). The time difference between the EMP Tier 1 monitoring and the summer surveys ranged from 6–105 d. At sites A, B, and E, the means of the EMP Tier 1 monitoring sulfide values were significantly lower than the means of the summer survey data collected within the cage arrays (two-tailed t-test, $p<0.05$; Table 8); the EMP Tier 1 monitoring was conducted 19 d later than the summer surveys at site A, 6 d earlier at site B, and 86 d later at site E. At site F, the mean of the EMP Tier 1 monitoring sulfide results was significantly higher than the mean of the summer survey data collected within the cage array ($p<0.05$); the EMP Tier 1 monitoring at site F was conducted 25 d earlier than the summer survey. At sites C and D, the means of the Tier 1 monitoring results and the means of the summer survey data collected within the cage arrays were not significantly different ($p>0.05$); the EMP Tier 1 monitoring at site C was conducted 33 d earlier than the summer survey, while at site D, the EMP Tier 1 monitoring was conducted 105 d later than the summer survey.

At sites A, B, and E, the means of the EMP Tier 1 monitoring sulfide values were significantly lower than the means of the summer survey locations nearest to the Tier 1 locations (two-tailed t-test, $p<0.05$; Table 8). At site F, the mean of the EMP Tier 1 monitoring sulfide results was significantly higher than the mean of the summer survey data collected from the locations nearest to the Tier 1 locations ($p<0.05$). At sites C and D, the means of the Tier 1 monitoring results and the means of the summer survey data collected from the locations nearest to the Tier 1 locations were not significantly different ($p>0.05$). The distances between EMP Tier 1 sample locations and the nearest summer survey locations were quite small, averaging 16 m (range: 2–39 m). When comparing the mean sulfide values for the summer survey locations located nearest to the Tier 1 locations with the means of all other summer survey locations within each cage array, we expected the mean of the near Tier 1 locations might be higher than the mean of the other locations, since the Tier 1 locations were chosen to be at the edges of cages with higher biomasses. However, we found no significant differences at five of the six sites (one-tailed t-tests, p>0.05; see Table 8). A significant difference was found only at site B, where the mean sulfide values near Tier 1 locations were lower than the mean of all other locations within the cage array; as previously noted, this site was harvested about 3 months prior to sampling.

For the spring survey of 24 May 2006 at site A (Table 9 and Fig. 5), the mean of the sediment sulfide data collected within the cage array was significantly lower than the mean of the equivalent data from the summer survey of 22 September 2005 (two-tailed t-test, p<0.05), even though the feeding rate was higher in May 2006 (307 t of feed added to the farm in May 2006, compared to 199 t in September 2005). The amount of feed added per cage to 24 May 2006 ranged from 55–299 t. Most sulfide values in May 2006 had decreased to oxic levels at about 60 m from the cage array, although there were some hypoxic sediments 124 m from the cage array. There were no anoxic areas in May 2006, and the areas of hypoxic sediments were reduced (and mostly in different locations), compared to in September 2005 (Tables 6 and 7).

The mean of the sulfide values collected at Tier 1 locations as part of additional EMP monitoring at site A on 14 June 2006 (998 µM; see Table 9) was significantly lower than the mean of the spring survey data collected within the cage array on 24 May 2006 (1 775 µM; two-tailed t-test, p<0.05). The mean of the June 2006 EMP monitoring was also significantly different from the mean of the spring survey data collected at the locations nearest to the Tier 1 locations (2 361 µM; two-tailed t-test, p<0.05). The mean of the spring survey data collected at locations nearest to the Tier 1 locations (2 3612 µM) was also significantly different from the mean of all other spring survey data collected within the cage array (1 565 µM; one-tailed t-test, p=0.04).

DISCUSSION

The main purpose of this study was to investigate whether the limited number of sample locations in the EMP Tier 1 monitoring protocols (triplicate samples from 2–5 locations at our study sites) was sufficient to provide an accurate assessment of the organic enrichment of sediments under salmon farms in SWNB. The spatially-intensive sampling that we conducted in summer resulted in mean sulfide values that were significantly different from the EMP Tier 1 monitoring at four of the six study sites, and would have resulted in different site classifications (Table 10). At site E, the lower mean sulfide levels in the EMP Tier 1 monitoring may have been related to the timing of the sampling events: the EMP Tier 1 was conducted about four months after harvesting of the site, while the summer survey was conducted only one month after harvesting was completed. However, the relative timing of sampling was similar at site D, where there was no significant difference in the mean sulfide levels between the two sampling events (the EMP Tier 1 monitoring at site D was conducted about three months after harvesting, while the summer survey occurred as harvesting was ending). At sites A, B, and F, the EMP Tier 1 sulfide values were significantly different than the summer survey results, even though the timing of the two sampling events was relatively close at these sites (6–25 d apart).

Our survey data indicated considerable heterogeneity of sulfide levels under the farms, as indicated by the often large differences in sulfide values from samples taken in close proximity, as well as the sometimes large differences in sulfide values among replicates from the same location (both in the surveys and the EMP Tier 1 monitoring). The high impact areas were generally quite small: anoxic samples were only found at two of the farms in summer, and in the case of site A, there were no anoxic samples in the following spring. The spatial heterogeneity in sulfide levels at site A in September 2005 appeared to have some relationship with the feeding rates at this farm: feeding rates were quite variable among cages, and the highest sulfide levels appeared to be near the cages receiving the most feed. However, spatial heterogeneity of sediment sulfide levels was also observed at sites C, D, and E, where the feeding rates were relatively similar among cages. This suggests that small-scale differences in water circulation and/or seafloor topography may be important factors in determining the spatial distribution of organic deposition on the seafloor under fish farms (Page et al. 2007, 2009; Chang et al. 2009).

The high degree of spatial heterogeneity of sediment sulfides suggests that the limited number of locations sampled in the EMP Tier 1 monitoring may not be sufficient to provide an accurate rating of a farm's benthic impact. Nevertheless, when we compared the average sulfide values for just those survey samples taken nearest to the EMP Tier 1 locations with the average sulfide values of all other samples taken within the cage array, we found significant differences at only one farm (site B). This suggests that, at least at our study sites and dates, the EMP Tier 1 monitoring protocols for the number and location of samples could produce reasonably accurate ratings of the organic enrichment. However, in our study, the mean of the summer survey data collected at just those locations nearest to the EMP Tier 1 monitoring locations was significantly differrent from the mean of the EMP Tier 1 monitoring results at four of the six sites. One possible reason is the differences in locations between the EMP Tier 1 monitoring locations and the nearest summer survey locations, which although small (averaging 16 m), may have been significant in relation to the fine-scale spatial heterogeneity in sediment sulfide levels. As previously mentioned, high variability was sometimes observed among triplicate subsamples taken from the same grab sample. A high degree of variability in sediment sulfide levels, at a spatial scale of ±5 m, has also been reported near salmon farms in British Columbia (Brooks and Mahnken (2003). Another reason for the differences between summer survey and EMP Tier 1 monitoring results could be temporal variations in sulfide levels, since there were sometimes large differences between the dates of the summer surveys and the EMP Tier 1 monitoring, although, as mentioned above, the differences in dates cannot explain some of the differences, or lack of differences, observed. Another factor could be differences in the probes and laboratories used in the sulfide analyses, although our sampling surveys and the EMP Tier 1 monitoring used the same protocols. In an inter-laboratory calibration experiment involving five independent analysts/probes using similar methods and equipment, Wildish et al. (2004) found mean sulfide values ranging from 2484–5678 µM for salmon farm sediment samples and 435–884 µM for reference site samples (each analyst received five replicate subsamples of farm sediment and five replicate subsamples of reference site sediment).

The results from the one site where we conducted both summer and spring surveys showed considerable changes between the dates: the sulfide levels were much lower in the spring survey, even though the feeding rates were higher than in the previous summer. Resuspension of sediments and aeration may have occurred between the two sampling dates. Anecdotal information from farm workers and divers suggests that winter storms often clean the seafloor under farms. Sediments may also recover somewhat during the winter because feeding rates and fish metabolism decrease when water temperatures are low.

Another problem with the EMP Tier 1 monitoring protocols is that sampling is restricted to locations within the cage array area. In our surveys, we found some anoxic sediments outside the cage array at site A, and some hypoxic sediments outside the cage array at site E. As a result, monitoring only within the cage array at these sites would underestimate the magnitude and extent of seafloor impacts.

Overall, the results indicated that most of the farms studied were not causing large organic enrichment impacts on the seafloor. At most sites, hypoxic or anoxic sediments were confined to small areas under the cage arrays. Both the EMP Tier 1 monitoring and our summer survey results produced ratings of oxic or Hypoxic A at most sites, which according to the Fisheries and Oceans Canada determinations, means that it is unlikely that HADDs had occurred. However, the two data sets produced different sulfide results for the individual farms, indicating that there is considerable small-scale spatial and/or temporal variability in sediment geochemistry under salmon farms, and hence variability in the regulatory rating.

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Table 1. Quantitative sediment geochemical ratings used in the Environmental Management Program for marine salmon farms in SWNB, since 2006 (based on NBDENV 2006).

Site classification	*Sediment sulfide level (µM)*	*Actions*
Oxic A	<750	Tier 1 monitoring; follow OBMP[1]
Oxic B	750 – 1500	Tier 1 monitoring; follow OBMP[1]
Hypoxic A	1500 – 3000	Tier 1 monitoring; adjustments to OBMP[1]
Hypoxic B	3000 – 4500	Tiers 1 & 2 monitoring; additional OBMP[1]; FAA[2] may be required
Hypoxic C	4500 – 6000	Tiers 1, 2 & 3 monitoring; enhanced OBMP[1]; FAA[2] likely required
Anoxic	>6000	Tiers 1, 2 & 3 monitoring; consult NBDENV[3] & DFO[4]; FAA[2] likely required

[1] Operational Best Management Practices
[2] Fisheries Act (Canada) Authorization
[3] New Brunswick Department of Environment
[4] Fisheries and Oceans Canada

Table 2. Sites where spatially-intensive sampling surveys were conducted. Surveys were conducted at all sites in summer; site A was also surveyed in the following spring. At site E, sampling was conducted at only one of the two cage arrays.

Site	No. of cages	Year stocked	Date of survey	Time of harvest
A	14	2004	22-Sep-2005 24-May-2006	Aug-2006 – Aug-2007
B	27	2004	24-Aug-2006	Apr-2006 – May-2006
C	15	2005	12-Sep-2006	Nov-2006 – Feb-2007
D	10	2005	24-Jul-2007	Jun-2007 – Jul-2007
E	2 × 9	2005	31-Jul-2007	Jan-2007 – Jun-2007
F	14	2006	28-Aug-2007	Fall 2007 – Jul-2008

Table 3. Dates and numbers of sediment samples collected in Environmental Management Program (EMP) Tier 1 monitoring and spatially-intensive summer and spring surveys at six salmon farms in SWNB. Triplicate samples were taken at all locations, except for 3 locations (all outside the cage array) at site E which had no replicates. At site E, only one of the two cage arrays was sampled. The EMP data for the spring survey at site A are from additional EMP monitoring conducted at the Tier 1 locations at this site on 14 June 2006.

	EMP Tier 1 monitoring			Summer and spring sampling surveys		
Site	Date	No. of locations	No. of samples	Date	No. of locations	No. of samples
Summer surveys						
A	11-Oct-2005	7	21	22-Sep-2005	57	171
B	18-Aug-2006	2	6	24-Aug-2006	20	60
C	10-Aug-2006	5	15	12-Sep-2006	33	99
D	06-Nov-2007	2	6	24-Jul-2007	41	123
E	25-Oct-2007	2	6	31-Jul-2007	34	96
F	03-Aug-2007	4	12	28-Aug-2007	55	165
Spring survey						
A	14-Jun-2006	7	21	24-May-2006	55	165

Table 4. Sediment sulfide values (µM) for samples taken within the cage arrays in summer surveys at six salmon farms in SWNB. Individual values for each replicate subsample (r1–r3) are given. Also given are arithmetic means, standard deviations (SD), and coefficients of variation (CV = SD/mean). At site E, data were only collected at one of the two cage arrays on the site. Not included are values from samples collected outside the cage arrays.

Site	Location number	Distance from array centre (m)	Sulfide concentration (µM)					
			r1	r2	r3	Mean	SD	CV
A	4	148	1 660	2 130	14 100	5 963	7 050	1.18
22-Sep-05	5	48	1 070	1 320	2 560	1 650	798	0.48
	6	48	3 240	3 940	6 230	4 470	1 564	0.35
	7	153	1 310	2 660	2 940	2 303	872	0.38
	11	156	1 180	1 450	2 330	1 653	601	0.36
	12	60	4 590	5 550	9 620	6 587	2 670	0.41
	13	82	1 390	2 040	3 100	2 177	863	0.40
	14	36	3 420	3 790	4 590	3 933	598	0.15
	15	66	4 340	4 680	4 930	4 650	296	0.06
	16	126	2 370	2 400	3 110	2 627	419	0.16
	17	159	932	1 220	2 010	1 387	558	0.40
	18	141	1 680	2 920	3 240	2 613	824	0.32
	19	126	1 730	2 210	3 660	2 533	1 005	0.40
	20	56	3 730	3 890	5 350	4 323	893	0.21
	21	29	2 130	2 630	3 300	2 687	587	0.22
	22	70	3 970	4 610	6 230	4 937	1 165	0.24
	23	76	2 950	6 130	6 700	5 260	2 021	0.38
	24	164	5 450	6 040	8 430	6 640	1 578	0.24
	25	168	1 550	1 860	2 590	2 000	534	0.27
	all					3 600	2 345	0.65
B	1	159	780	1 610	1 610	1 333	479	0.36
24-Aug-06	2	83	935	1 500	1 520	1 318	332	0.25
	3	35	2 270	1 630	1 250	1 717	515	0.30
	4	84	313	422	446	394	71	0.18
	5	145	650	630	630	637	12	0.02
	6	105	2 880	4 290	2 390	3 187	986	0.31
	7	37	910	1 090	1 490	1 163	297	0.26
	8	45	1 400	1 260	1 000	1 220	203	0.17
	10	159	3 830	3 900	3 500	3 743	214	0.06
	11	83	1 690	1 510	1 100	1 433	302	0.21
	12	56	1 960	2 080	1 870	1 970	105	0.05
	all					1 647	1 033	0.63

Table 4 (continued).

Site	Location number	Distance from array centre (m)	Sulfide concentration (µM)					
			r1	r2	r3	Mean	SD	CV
C	2	138	1 990	767	1 110	1 289	631	0.49
12-Sep-06	3	70	1 490	1 340	1 380	1 403	78	0.06
	4	56	1 610	1 270	950	1 277	330	0.26
	5	73	1 630	1 480	1 320	1 477	155	0.10
	6	68	620	978	780	793	179	0.23
	7	142	1 870	2 540	4 410	2 940	1 316	0.45
	8	73	3 000	2 710	2 490	2 733	256	0.09
	9	144	6 630	7 690	5 690	6 670	1 001	0.15
	10	130	3 140	2 440	1 610	2 397	766	0.32
	11	133	2 200	1 910	2 320	2 143	211	0.10
	12	84	427	330	382	380	49	0.13
	13	165	1 460	1 370	1 590	1 473	111	0.08
	all					2 081	1 657	0.80
D	1	156	2 850	3 540	2 970	3 120	369	0.12
24-Jul-07	2	129	4 920	4 830	4 720	4 823	100	0.02
	3	113	1 620	2 100	1 800	1 840	242	0.13
	4	131	1 260	1 130	1 070	1 153	97	0.08
	5	147	600	501	680	594	90	0.15
	6	140	355	314	410	360	48	0.13
	7	101	1 040	1 320	930	1 097	201	0.18
	8	80	1 440	1 130	1 270	1 280	155	0.12
	9	93	2 110	2 010	1 820	1 980	147	0.07
	10	122	1 940	1 950	1 760	1 883	107	0.06
	22	88	1 470	1 410	1 750	1 543	181	0.12
	23	31	421	677	572	557	129	0.23
	24	75	801	291	776	623	288	0.46
	25	95	622	505	468	532	80	0.15
	26	75	772	809	850	810	39	0.05
	27	75	2 140	2 450	1 710	2 100	372	0.18
	28	107	940	990	973	968	25	0.03
	29	150	2 080	1 590	1 120	1 597	480	0.30
	31	167	1 090	917	1 310	1 106	197	0.18
	32	134	880	881	1 160	974	161	0.17
	33	109	1 020	1 260	1 410	1 230	197	0.16
	34	103	3 840	2 220	3 470	3 177	849	0.27
	35	127	2 270	1 800	2 320	2 130	287	0.13
	all					1 542	1 054	0.68

Table 4 (concluded).

Site	Location number	Distance from array centre (m)	Sulfide concentration (µM)					
			r1	r2	r3	Mean	SD	CV
E	1	104	1 420	1 230	964	1 205	229	0.19
31-Jul-07	6	62	1 310	887	942	1 046	230	0.22
	7	42	1 560	1 310	1 370	1 413	131	0.09
	8	65	834	932	1 220	995	201	0.20
	9	82	630	620	664	638	23	0.04
	10	104	538	431	604	524	87	0.17
	21	81	1 370	1 200	984	1 185	193	0.16
	23	103	3 140	3 370	3 680	3 397	271	0.08
	24	82	900	1 390	1 310	1 200	263	0.22
	25	30	2 330	2 610	3 040	2 660	358	0.13
	26	46	1 060	299	661	673	381	0.57
	27	82	647	520	643	603	72	0.12
	29	76	936	1 130	1 210	1 092	141	0.13
	30	90	1 871	1 750	1 960	1 860	105	0.06
	all					1 321	819	0.62
F	1	157	250	242	314	269	39	0.15
28-Aug-07	5	160	246	238	797	427	320	0.75
	8	167	362	578	422	454	111	0.25
	12	116	218	584	955	586	369	0.63
	14	73	235	140	266	214	66	0.31
	15	49	1 230	917	975	1 041	167	0.16
	18	113	644	711	906	754	136	0.18
	26	164	1 170	1 270	1 710	1 383	287	0.21
	30	157	326	248	160	245	83	0.34
	33	176	178	168	163	170	8	0.05
	37	114	1 410	1 190	1 220	1 273	119	0.09
	41	70	326	496	460	427	90	0.21
	42	46	253	430	257	313	101	0.32
	46	55	158	181	226	188	35	0.18
	47	109	175	154	202	177	24	0.14
	51	96	171	264	262	232	53	0.23
	52	44	253	281	278	271	15	0.06
	53	6	1 380	1 620	1 650	1 550	148	0.10
	54	58	386	240	393	340	86	0.25
	55	106	353	319	356	343	21	0.06
	all					533	443	0.83

Table 5. Sediment sulfide values (μM) for Environmental Management Program Tier 1 monitoring at six salmon farms in SWNB. T1–T5 are transects and r1–r3 are samples taken at the cage edge of each transect (see Fig. 1–3). Also given are arithmetic means, standard deviations (SD), and coefficients of variation (CV = SD/mean). Data for site E are from one of two cage arrays at the farm (the same array that was sampled in the summer survey).

Site	Location number	Distance from array centre (m)	r1	r2	r3	Mean	SD	CV
A	T1	170	44	162	344	183	151	0.82
11-Oct-05	T2	169	443	341	866	550	278	0.51
	T3	62	22	410	550	327	274	0.84
	T4	70	432	804	908	715	250	0.35
	T5	172	1 180	823	1 830	1 278	511	0.40
	all					611	475	0.78
B	T1	146	16	1	1	6	9	1.44
18-Aug-06	T2	138	5	6	195	69	109	1.59
	all					37	77	2.07
C	T1	126	1 470	1 600	1 510	1 527	67	0.04
10-Aug-06	T2	78	1 340	1 195	765	1 100	299	0.27
	T3	140	9 800	9 480	11 600	10 293	1 143	0.11
	T4	150	7 150	5 995	6 460	6 535	581	0.09
	T5	63	4 690	4 120	5 510	4 773	699	0.15
	all					4 846	3 558	0.73
D	T1	115	2 980	879	3 680	2 513	1 458	0.58
06-Nov-07	T2	113	359	817	214	463	315	0.68
	all					1 488	1 466	0.99
E	T2	109	426	194	211	277	129	0.47
25-Oct-07	T3	71	89	148	204	147	57	0.39
	all					212	114	0.54
F	T1	161	7 620	7 240	8 650	7 837	730	0.09
03-Aug-07	T2	45	5 130	9 460	9 800	8 130	2 604	0.32
	T3	182	2 310	2 400	2 120	2 277	143	0.06
	T4	38	2 900	5 100	4 430	4 143	1 128	0.27
	all					5 597	2 875	0.51

Table 6. Areas of seafloor within each classification, based on spatially-intensive sampling surveys at six salmon farms in SWNB. Classifications are based on sediment sulfide concentrations (Table 1). Sampling was conducted at all six salmon farms in the summer and at site A in the spring. Areas were calculated from contour plots of the sediment sulfide data.

	Area (m^2)						
Site	Oxic A	Oxic B	Hypoxic A	Hypoxic B	Hypoxic C	Anoxic	Total
Summer surveys							
A	80 540	31 550	42 240	13 720	10 510	8 040	186 590
B	51 190	37 840	23 350	3 390	0	0	115 760
C	113 230	45 140	26 930	2 340	1 760	660	190 060
D	169 190	40 280	19 000	3 200	470	0	232 130
E	72 750	31 200	13 680	480	0	0	118 120
F	233 140	20 790	180	0	0	0	254 110
Spring survey							
A	83 970	39 750	36 870	15 230	1 800	0	177 620

Table 7. Percentage of the total seafloor area falling within each classification, based on spatially-intensive sampling surveys at six salmon farms in SWNB. Classifications are based on sediment sulfide concentrations (Table 1). Sampling was conducted at all six salmon farms in the summer and at site A in the spring. Areas were calculated from contour plots of the sediment sulfide data.

	% of total area								
	Oxic			Hypoxic					
Site	A	B	A+B	A	B	C	A+B+C	Anoxic	Total
Summer surveys									
A	43	17	60	23	7	6	36	4	100
B	44	33	77	20	3	0	23	0	100
C	60	24	84	14	1	1	16	<1	100
D	73	17	90	8	1	<1	10	0	100
E	62	26	88	12	<1	0	12	0	100
F	92	8	100	<1	0	0	<1	0	100
Spring survey									
A	47	22	70	21	9	1	30	0	100

Table 8. Comparisons of mean sulfide (S^{2-}) values (µM) obtained in the Environmental Management Program (EMP) Tier 1 monitoring with values obtained in summer and spring surveys at locations nearest to the EMP Tier 1 locations, and at all other survey locations within the cage arrays, at six salmon farms in SWNB. n = number of sample locations (triplicate samples were taken at each location). A negative value in "No. days after EMP" indicates that the summer survey occurred before the EMP Tier 1 monitoring. Underlined values indicate significant differences ($p<0.05$) between the EMP Tier 1 results and the sulfide concentrations at the nearest survey locations (sites A, B, E, and F). Italicized values indicate significant differences between the sulfide concentrations at the survey locations nearest the EMP Tier 1 locations and the results from the rest of the survey locations within the cage array (site B).

	EMP Tier 1 (all locations)		Summer and spring survey locations: Nearest to EMP Tier 1 locations		Summer and spring survey locations: All other locations within cage array		
Site	n	S^{2-} (µM)	n	S^{2-} (µM)	n	S^{2-} (µM)	No. days after EMP
Summer surveys							
A	5	611	5	4 241	14	3 371	–19
B	2	37	2	*985*	9	*1 794*	6
C	5	4 846	5	2 643	7	1 680	33
D	2	1 488	2	1 854	21	1 513	–105
E	2	212	2	1 195	12	1 342	–86
F	4	5 597	4	494	16	542	25
Spring survey							
A	5	998	5	*2 361*	14	*1 565*	-21

Table 9. Sediment sulfide values (µM) at site A in spring 2006. Values are from a spring sampling survey on 24 May 2006 and Environmental Management Program (EMP) monitoring on 14 June 2006; for the former, only samples taken within the cage array are shown. Individual values for each replicate subsample (r1–r3) are given. Also given are means, standard deviations (SD), and coefficients of variation (CV). Excluded are two locations sampled in the June 2006 EMP, but not required for Tier 1 monitoring, and spring sampling survey locations located outside the cage array.

Location number	Distance from array centre (m)	r1	r2	r3	mean	SD	CV
Spring sampling survey (24 May 2006): samples within the cage array							
4	137	1 690	1 036	892	1 206	425	0.35
5	43	1 130	1 380	1 150	1 220	139	0.11
6	51	1 610	2 880	1 430	1 973	790	0.40
7	158	3 980	4 120	5 210	4 437	673	0.15
11	155	1 420	1 122	620	1 054	404	0.38
12	66	2 410	3 440	1 820	2 557	820	0.32
13	77	884	864	535	761	196	0.26
14	47	4 410	6 920	4 180	5 170	1 520	0.29
15	70	1 650	1 330	1 330	1 437	185	0.13
16	131	740	910	642	764	136	0.18
17	165	336	382	318	345	33	0.10
18	145	1 020	1 020	1 070	1 037	29	0.03
19	130	1 820	1 560	1 480	1 620	178	0.11
20	58	893	815	820	843	44	0.05
21	27	960	1 900	1 380	1 413	471	0.33
22	71	2 030	1 036	990	1 352	588	0.43
23	81	1 260	1 310	1 016	1 195	157	0.13
24	159	2 700	2 460	1 510	2 223	629	0.28
25	164	3 940	3 240	2 170	3 117	891	0.29
all					1 775	1 328	0.75
EMP monitoring (14 Jun 2006)							
T1	171	121	77	620	273	302	1.11
T2	165	1 130	661	533	775	314	0.41
T3	70	2 930	1 330	900	1 720	1 070	0.62
T4	61	2 800	1 330	755	1 628	1 055	0.65
T5	170	394	467	927	596	289	0.48
all					998	846	0.85

Table 10. Comparisons of site classifications derived from mean sulfide (S) values (µM) obtained in the Environmental Management Program (EMP) Tier 1 monitoring and in summer surveys at six salmon farms in SWNB. Underlined values indicate significant differences ($p<0.05$) between the EMP Tier 1 results and the sulfide concentrations at the nearest survey locations (sites A, B, E, and F). Italicized values indicate significant differences between the sulfide concentrations at the survey locations nearest the EMP Tier 1 locations and the results from the rest of the survey locations within the cage array (site B).

	EMP Tier 1 (all locations)		Summer survey locations: Nearest to EMP Tier 1 locations		Summer survey locations: All locations within cage array	
Site	S^{2-} (µM)	Classification	S^{2-} (µM)	Classification	S^{2-} (µM)	Classification
A	<u>611</u>	Oxic A	<u>4 241</u>	Hypoxic B	3 600	Hypoxic B
B	<u>37</u>	Oxic A	<u>*985*</u>	Oxic B	*1 647*	Hypoxic A
C	4 846	Hypoxic C	2 643	Hypoxic A	2 081	Hypoxic A
D	1 488	Oxic B	1 854	Hypoxic A	1 542	Hypoxic A
E	<u>212</u>	Oxic A	<u>1 195</u>	Oxic B	1 321	Oxic B
F	<u>5 597</u>	Hypoxic C	<u>494</u>	Oxic A	533	Oxic A

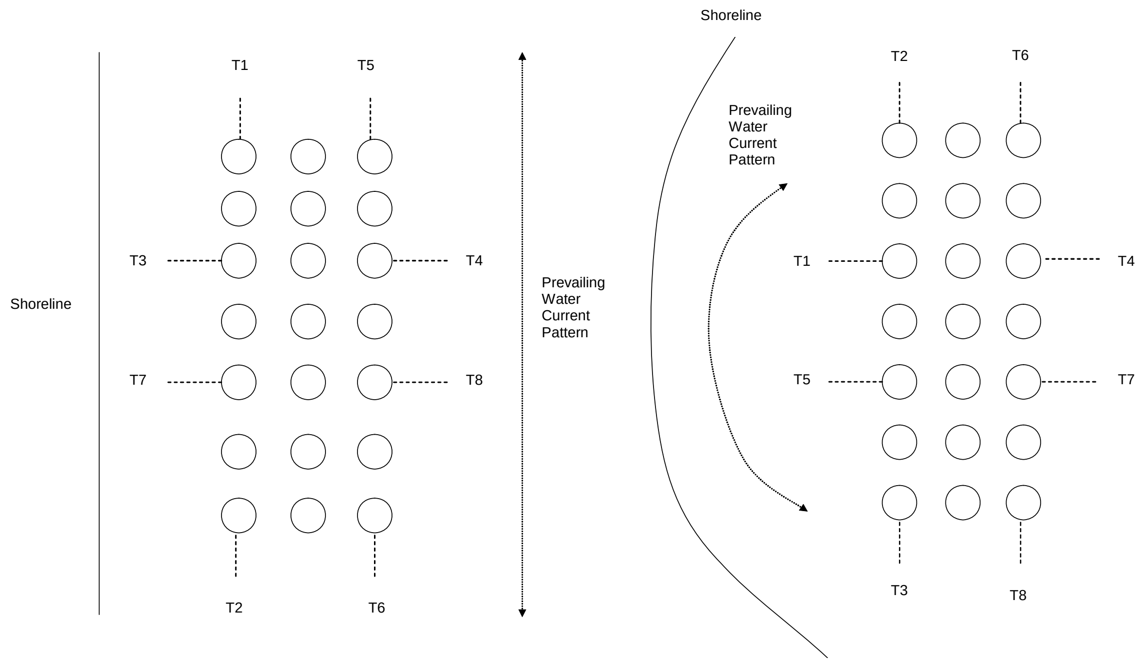

Fig. 1. Locations of transects and samples for Tier 1 monitoring in the Environmental Management Program for marine finfish farms in SWNB, since 2006 (from NBDENV 2007). When more than one transect is on the same side of a site, the transects will be positioned at separate cages, beginning in order from the highest to lowest biomass. Left: transect locations for sites with generally linear water current patterns and moderate or high current speeds. Right: transect locations for sites with generally curving water current patterns or low current speeds. For each transect, 3 sediment samples are taken at the cage edge, in close proximity to each other.

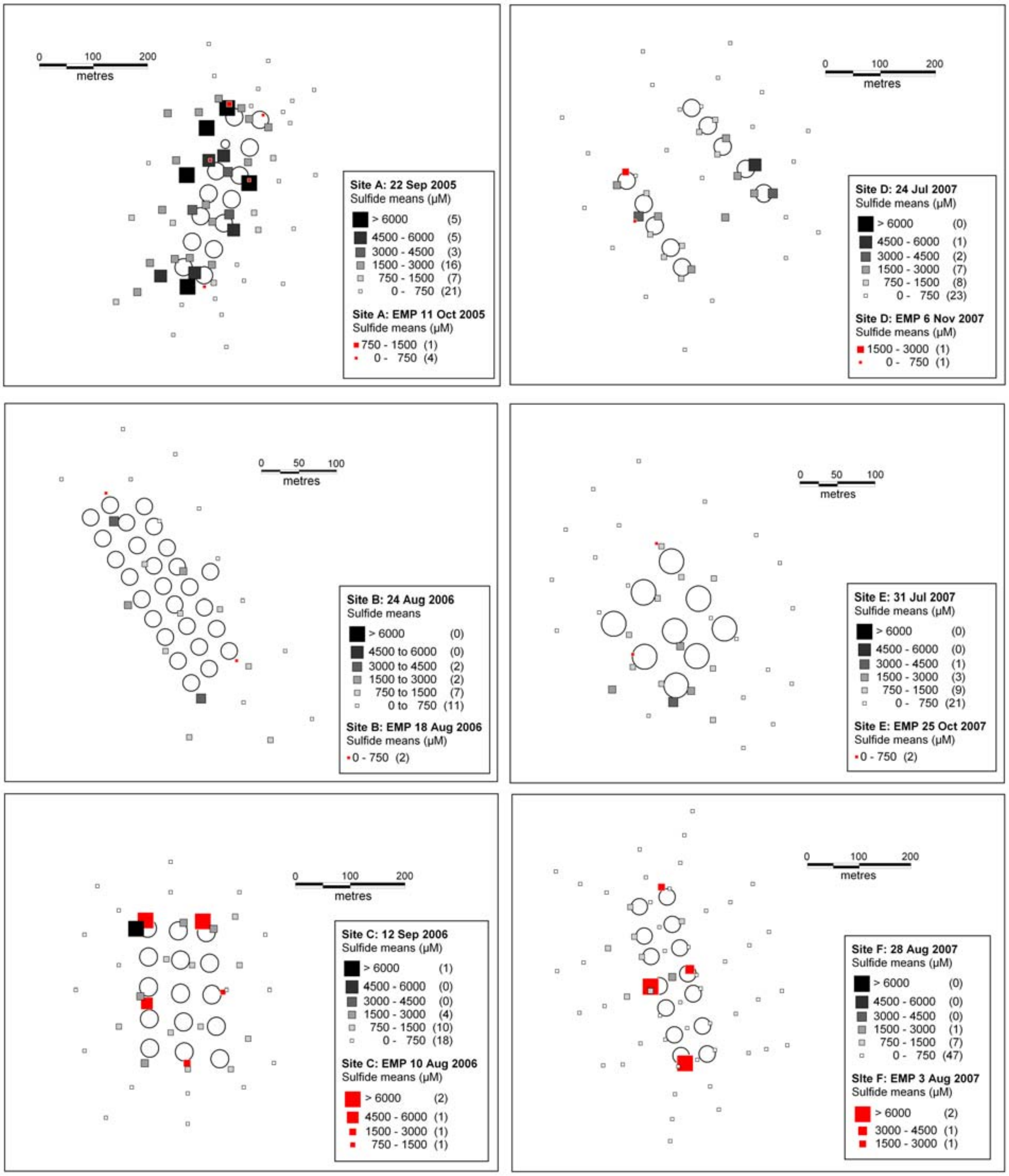

Fig. 2. Mean sulfide levels in spatially-intensive summer sampling surveys at six salmon farms in SWNB. Black and grey squares represent mean sulfide values (from triplicate subsamples at each location) for the spatially intensive summer surveys. Red squares represent mean sulfide values (from triplicate samples at each location) for EMP Tier 1 monitoring in the same year. Circles represent approximate cage locations.

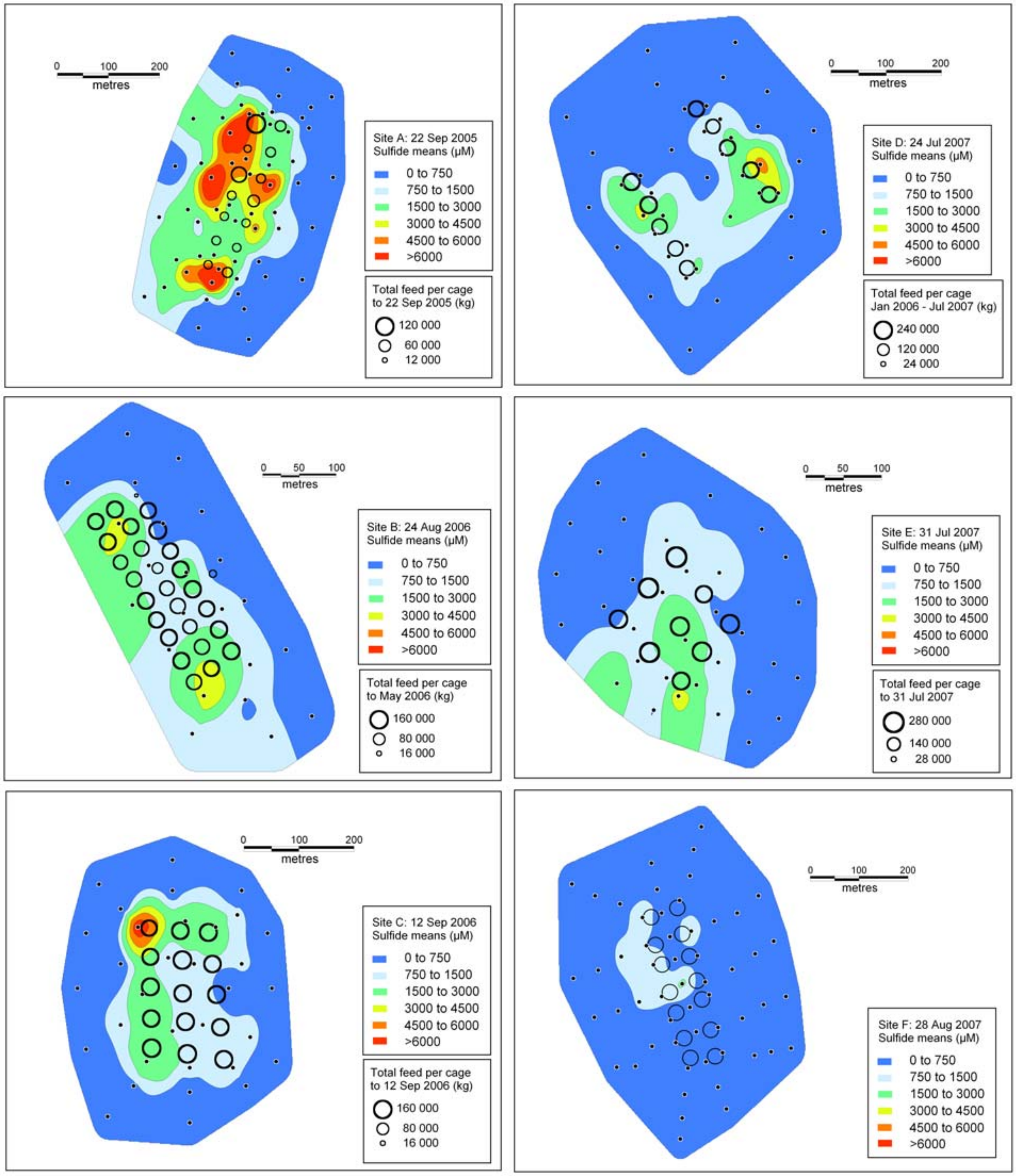

Fig. 3. Contour plots of mean sulfide values from spatially-intensive summer sampling surveys at six salmon farms in SWNB. Black dots indicate sampling locations. Circles represent approximate cage locations, with the circle sizes indicative of the amount of feed added per cage (see legend), except at site F (feed data not available).

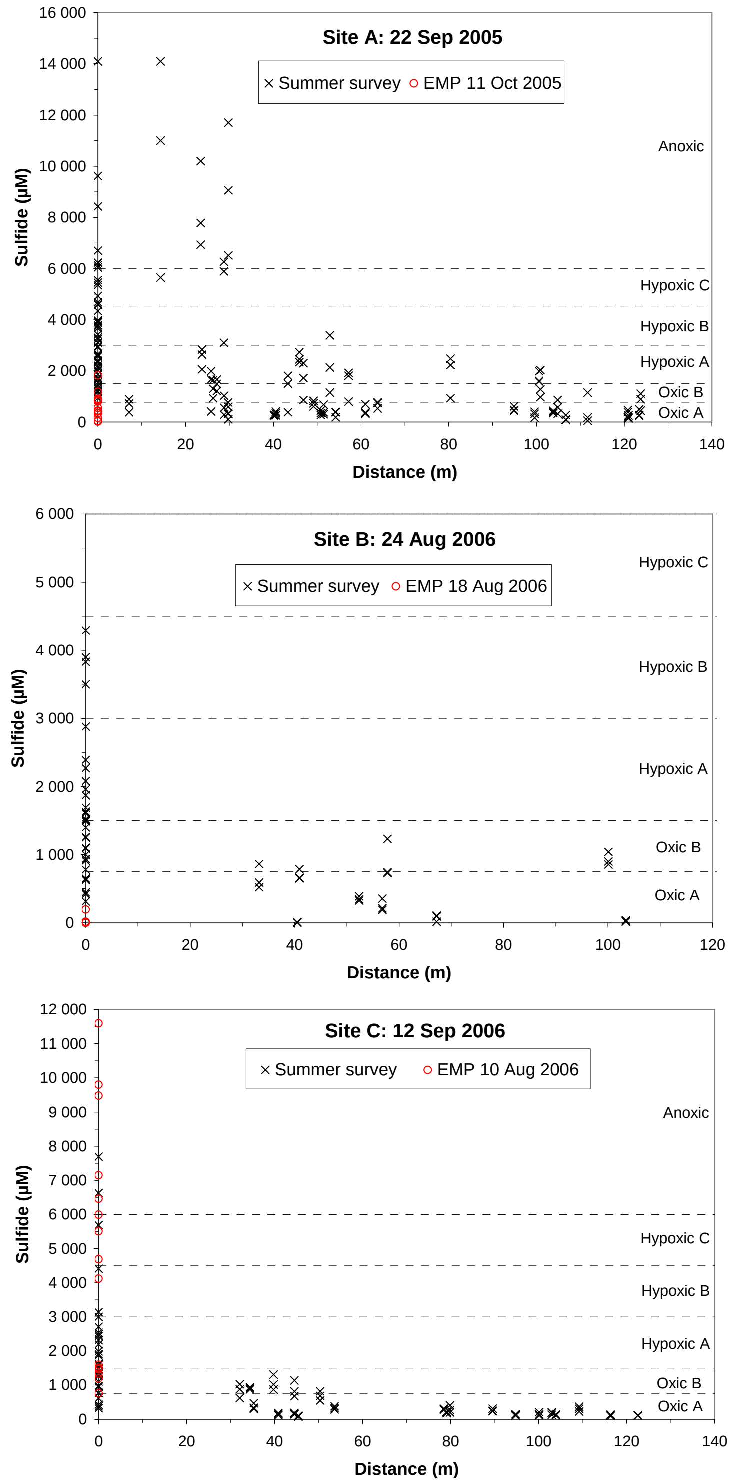

Fig. 4. Sulfide levels vs. distance from the edge of the cage array for individual samples collected in spatially-intensive summer sampling surveys at six salmon farms in SWNB. Also shown are individual sulfide values from EMP Tier 1 monitoring in the same year (red circles). Samples taken at the cage edge or within the cage array were given a distance value of 0 m.

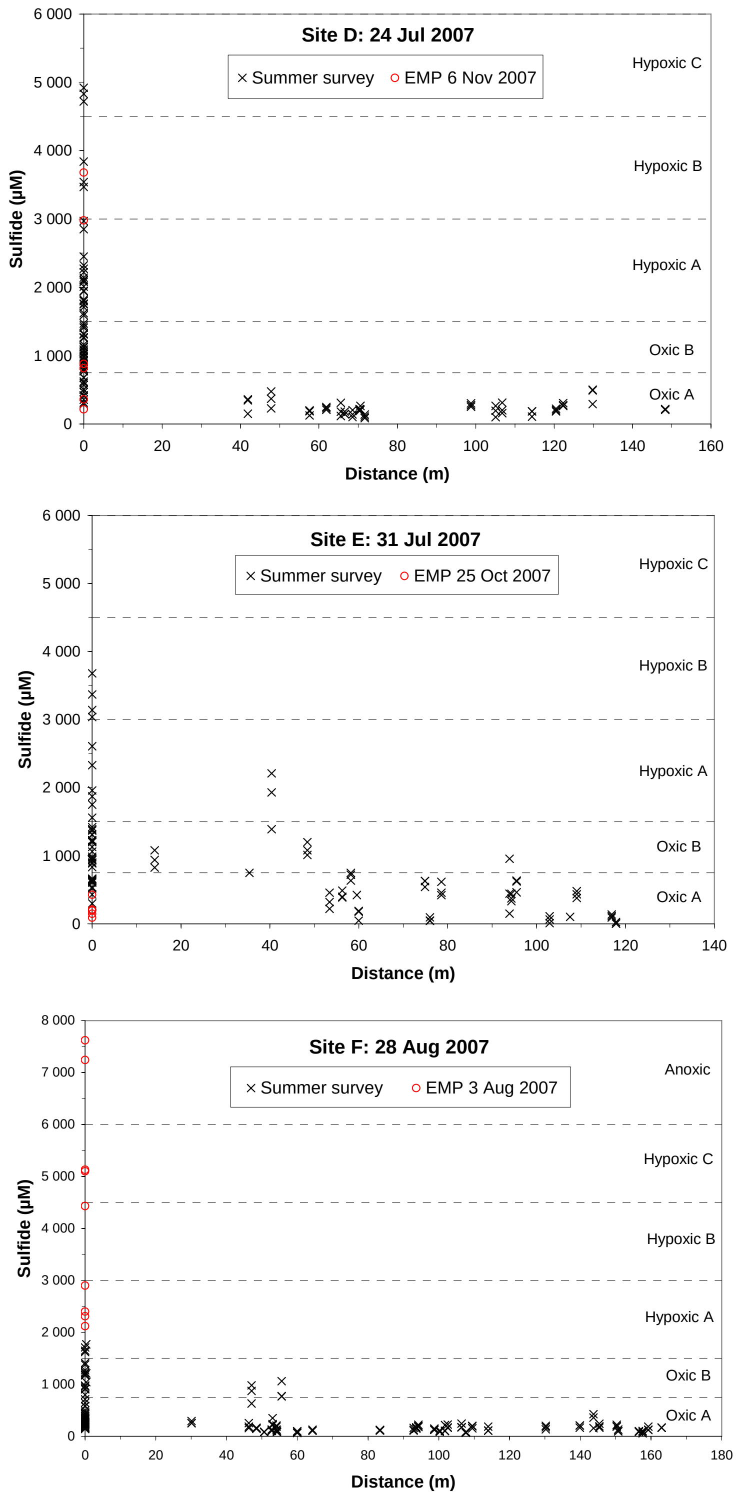

Fig. 4 (continued).

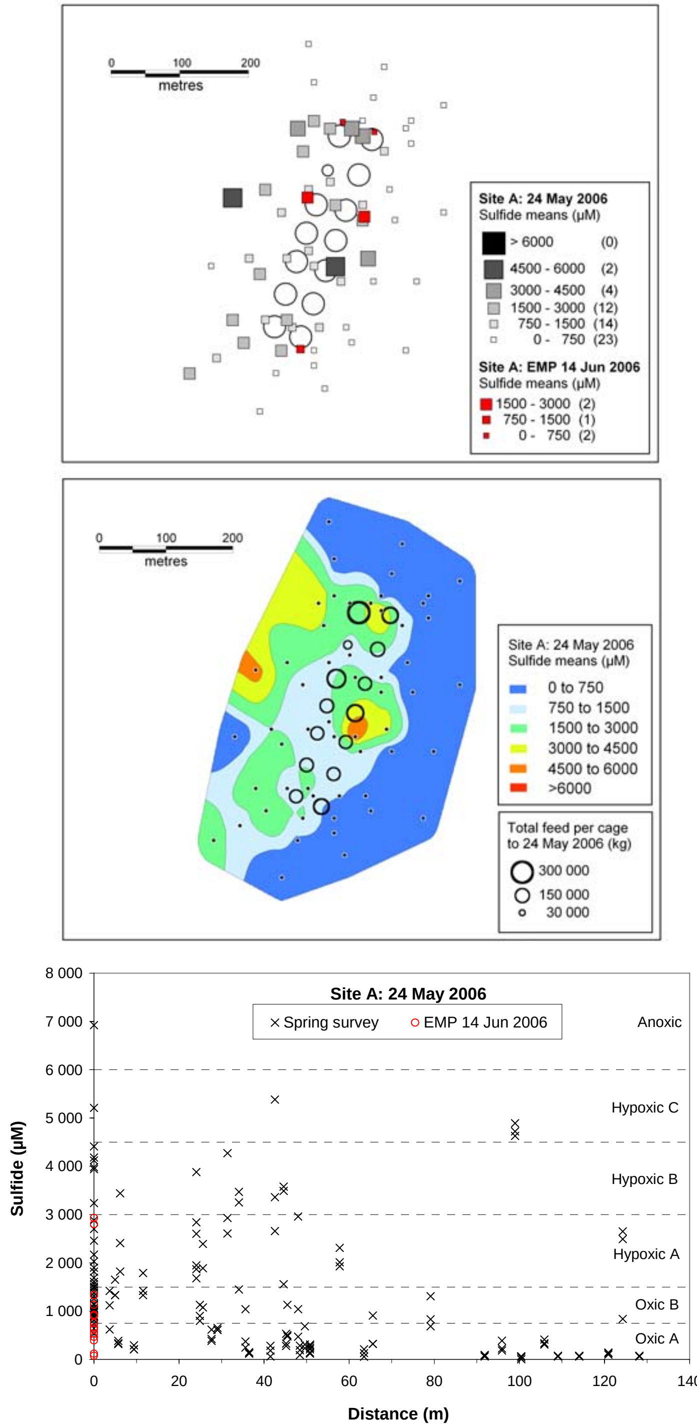

Fig. 5. Results from spatially-intensive benthic sulfide sampling at site A on 24 May 2006. Top: mean values for each sample location (black and grey squares), with mean values for EMP monitoring on 14 June 2006 (red squares; Tier 1 locations only). Middle: contour plot of sulfide values (black dots are sample locations); circles represent cages, with circle sizes indicative of the feeding rate (see legend). Bottom: graph of sulfide values (individual subsamples) vs. distance from the edge of the cage array; also shown are individual sample sulfide values from EMP monitoring (Tier 1 locations).