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by

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ABSTRACT

Chang, B.D., Balch, T., Bennett, A.T., Buchan, C.M., Jacobi, C.A., Losier, R.J., Lyons, T.A., Page, F.H., Parker, E.V., TeKamp, C.M., and Bagnall, A.G. 2013. Spatially-intensive sediment surveys at two salmon farms in New Brunswick and Nova Scotia in September-October 2011. Can. Tech. Rep. Fish. Aquat. Sci. 3035: v + 32 p.

Spatially-intensive sediment surveys were conducted under two salmon farms, one in southwestern New Brunswick (NB) and one in Nova Scotia (NS) in September–October 2011. Provincial regulatory monitoring results for these farms were obtained for the same year. The purpose of this study was to examine the suitability of existing regulatory monitoring protocols, to compare protocols between the provinces, and to harmonize protocols based on sound scientific advice where possible. At the NB site, sulfide concentrations in Tier 2 equivalent monitoring were significantly higher than in Tier 1 monitoring. At the NS site, sulfide concentrations in Level II monitoring were significantly higher than in Level I monitoring. At the NB site, there were no significant differences in sulfide concentrations between "cage edge" stations and "between cage" stations. At the NB site, core samples collected by divers had significantly lower sulfide concentrations overall than grab samples taken using surface-deployed samplers at the same stations at the same times. At the NS site, there was no significant difference in sulfide concentrations when comparing subsamples taken using NS protocols (triplicate grab samples per station, one subsample taken from three locations within each grab sample) vs. NB protocols (one grab sample per station, three subsamples per grab sample). At the NB site, there was no significant difference in sulfide concentrations when comparing stations selected using the NB Tier 1 protocol vs. stations selected using the NS Level I protocol. Contour plots of sulfide concentrations derived from spatially-intensive surveys produced more accurate results than contour plots derived using regulatory monitoring; in NS, the number of monitoring stations is too small to produce accurate contours, while in NB, the many Tier 2 stations provide good spatial coverage under the cage array, but there are no stations outside the perimeter of the cage array. There was a negative relationship between sulfide concentration (log-transformed) and redox potential at both sites; the relationship showed high variability and appeared to be non-linear, with lower redox values than in previous studies in NB. At the NS site, there was a negative linear relationship between the sulfide concentration (log-transformed) and the Benthic Enrichment Index, with relatively low variability.

RÉSUMÉ

Chang, B.D., Balch, T., Bennett, A.T., Buchan, C.M., Jacobi, C.A., Losier, R.J., Lyons, T.A., Page, F.H., Parker, E.V., TeKamp, C.M., and Bagnall, A.G. 2013. Spatially-intensive sediment surveys at two salmon farms in New Brunswick and Nova Scotia in September-October 2011. Can. Tech. Rep. Fish. Aquat. Sci. 3035: v + 32 p.

Des relevés de sédiments spatialement intensifs ont été effectués sous deux exploitations salmonicoles de septembre à octobre 2011, une dans le sud-ouest du Nouveau-Brunswick (N.-B.) et une en Nouvelle-Écosse (N.-É.). Les résultats de la surveillance de réglementation provinciale pour ces exploitations ont été obtenus pour la même année. L'objectif de cette étude était d'examiner la pertinence des protocoles de surveillance réglementaire existants, de comparer les protocoles entre les provinces et d'harmoniser les protocoles fondés sur des avis scientifiques judicieux, si possible. Au site du Nouveau-Brunswick, les concentrations de sulfures de la surveillance de niveau 2 étaient beaucoup plus élevées que celles de la surveillance de niveau 1. Au site de la Nouvelle-Écosse, les concentrations de sulfures de la surveillance de niveau 2 étaient beaucoup plus élevées que celles de la surveillance de niveau 1. Au site du Nouveau-Brunswick, aucune différence importante n'a été décelée entre la concentration de sulfures pour les stations situées au bord des cages et celles situées entre les cages. Au site du Nouveau-Brunswick, les carottes recueillies par les plongeurs avaient des concentrations de sulfures beaucoup moins élevées en général que les échantillons ponctuels recueillis à l'aide d'un appareil déployé en surface aux mêmes stations, en même temps. Au site de la Nouvelle-Écosse, aucune différence importante n'a été décelée dans les concentrations de sulfures lorsque l'on compare les sous-échantillons prélevés en utilisant les protocoles de la Nouvelle-Écosse (3 échantillons ponctuels par station, 1 sous-échantillon prélevé à partir de 3 emplacements de chaque échantillon ponctuel) et les protocoles du Nouveau-Brunswick. (1 échantillon ponctuel par station, 3 sous-échantillons par échantillon ponctuel). Au site du Nouveau-Brunswick, aucune différence importante n'a été décelée dans les concentrations de sulfures lorsque l'on compare les stations choisies en utilisant le protocole de niveau 1 du Nouveau-Brunswick et les stations choisies en utilisant le protocole de niveau 1 de la Nouvelle-Écosse. Des tracés de contours des concentrations de sulfures provenant des relevés spatialement intensifs ont produit des résultats plus exacts que les tracés de contours provenant de la surveillance réglementaire. En Nouvelle-Écosse, il n'y a pas suffisamment de stations de surveillance pour produire des tracés exacts, tandis qu'au Nouveau-Brunswick, les nombreuses stations de niveau 2 fournissent une bonne couverture spatiale sous l'ensemble des cages, mais il n'y a aucune station à l'extérieur du périmètre de l'ensemble des cages. Il y avait une relation négative entre la concentration de sulfures (transformée en logarithmes) et le potentiel de redox aux 2 sites. La relation indiquait une grande variabilité et semblait être non linéaire avec des valeurs redox moins élevées que dans les études précédentes au Nouveau-Brunswick. Au site de la Nouvelle-Écosse, il y avait une relation négative linéaire entre la concentration de sulfures (transformée en logarithmes) et l'indice d'enrichissement benthique, avec une variabilité relativement faible.

INTRODUCTION

Marine finfish farms in New Brunswick and Nova Scotia must conduct annual environmental monitoring (NBDELG 2012a; NSDFA 2011a). Both provinces use the dissolved sulfide concentration in sediment pore water as the main indicator of environmental quality, based on research by Wildish et al. (1999, 2004). However, there are differences in the standard operating practices for monitoring in each province (NBDELG 2012b; NSDFA 2011b). The goals of this project were to examine the suitability of the existing monitoring protocols in each province, to compare the protocols between provinces, and ultimately to work towards harmonization.

ENVIRONMENTAL MONITORING OF FINFISH FARMS IN NEW BRUNSWICK

All approved finfish farms in New Brunswick (NB) must conduct annual Tier 1 monitoring between 1 August and 31 October (NBDELG 2012a). Tier 1 monitoring requires sediment sampling at a minimum of two stations per farm, plus an additional station for every 100 000 fish (or part thereof) on site above 200 000 fish (NBDELG 2012b). Tier 1 monitoring is conducted under the outer edges of selected cages located along the perimeter of the cage array (Fig. 1). Cage selection is based on fish biomass (the highest biomass cages are given priority), the cage array layout, water current patterns, and the direction of the shoreline. The classification of NB farms, based on the mean sulfide concentration in Tier 1 monitoring, is shown in Table 1. The oxidation-reduction (redox) potential is also measured, but is not used for site classification, but may be used to validate or confirm the sulfide results.

More intensive Tier 2 monitoring is required at farms where Tier 1 monitoring results in ratings of Hypoxic B or worse (mean sulfide concentration >3000 µM; NBDELG 2012a). Tier 2 monitoring requires sampling at many more stations (Fig. 2), including four stations around the circumference of each corner cage, plus stations under the outer edges of all other perimeter cages, as well as stations between all cages within the cage array; however, there are no stations outside the cage array (NBDELG 2012b). Tier 2 monitoring is to be conducted within 20 days of the Tier 1 monitoring.

Since 2011, Tier 1 and 2 monitoring in NB can be conducted by divers using core tubes (approximately 30 cm long by 5 cm in diameter) or using surface-deployed grab samplers (NBDELG 2012b). Using both sampling methods, sulfide and redox analyses are conducted on three subsamples per sampling station: when using divers, three core samples are taken within a 1 m^2 area in similar substrate at each station, and one 5-mL syringe subsample is collected from the top 2 cm of each core for analysis; when using surface-deployed grab samplers, one grab sample is taken per station, and three 5-mL subsamples are collected from the top 2 cm of each grab sample for analysis.

ENVIRONMENTAL MONITORING OF FINFISH FARMS IN NOVA SCOTIA

All finfish farms in Nova Scotia (NS) must conduct annual Level I monitoring, between 1 June and 30 September (NSDFA 2011a). Level I monitoring in NS requires sediment sampling at a minimum of three stations per farm, plus an additional station for every 150 000 fish (or part thereof) on site above 450 000 fish, as well as two reference stations located 100–300 m upstream and downstream of the site (Fig. 3; NSDFA 2011b). Samples can be collected by surface-deployed grab samplers or diver-retrieved cores. At each station, 3 samples are taken (3 cores or 3 grabs). From each core or grab sample, one 5-mL syringe subsample is taken from the top 2 cm at three points in the sample: 2 cm from the first point, 2 cm from a second point, and 1 cm from a third point. Each syringe subsample is analyzed for sulfide concentration, redox potential, percent water content (porosity), and percent organic matter (see below and NSDFA 2011b for further details). Values for redox potential, water content, and organic matter are used to calculate the Benthic Enrichment Index (BEI), which may be used to validate or confirm the sulfide results (see below). Sampling stations are situated at cage edges along a longitudinal axis running down the centre of the farm, beginning with stations at either end of the axis, as in Fig. 3. Any stations with sulfide concentrations >3000 µM must be re-sampled in subsequent Level I monitoring, until they return to oxic conditions. The classification of NS farms, based on the mean sulfide concentration in Level I monitoring (excluding the reference stations), is shown in Table 2.

Additional monitoring (Level II) must be conducted if Level I monitoring indicates Hypoxic B conditions or worse (≥50% of sampling stations with mean sulfide concentration >3000 µM). This includes stations at the edges of all cages adjacent to the station(s) which recorded elevated sulfide concentrations (>3000 µM) in the Level I monitoring, as well as at the 4 corner compensator buoys and at additional compensator buoys along the outer edge of the cage array (Fig. 3; NSDFA 2011b). Level II monitoring is to be conducted within 35 days of the Level I monitoring.

PROJECT DESCRIPTION

Spatially-intensive sediment sampling surveys were conducted at one salmon farm in the Bay of Fundy in southwestern New Brunswick (NB site) and at one salmon farm off the southern shore of Nova Scotia (NS site) during September–October 2011. The sulfide concentration and redox potential were measured in all samples at both sites. At the NS site, porosity and organic matter content were also measured at some stations. Results from provincial regulatory monitoring (see below) were obtained for both sites: Tier 1 monitoring at the NB site and Level I and II monitoring at the NS site. Tier 2 monitoring was not conducted at the NB site; however, the research survey included stations equivalent to Tier 2 monitoring.

Specific project goals were to examine:

1) How do sulfide concentrations compare between Tier 1 vs. Tier 2 equivalent monitoring at the NB site, and between Level I vs. Level II monitoring at the NS site?

2) How do sulfide concentrations at “cage edge” stations compare to concentrations at “between cage” stations (at the NB site)?

3) How do sulfide concentrations compare between core samples collected by divers vs. samples collected using surface-deployed grab samplers at the same times and stations (at the NB site)?

4) How do the sulfide concentrations compare between stations selected according NB Tier 1 protocols vs. stations selected using NS Level I protocols (at the NB site)?

5) How do sulfide concentrations compare between triplicate subsamples (per station) collected using NB protocols (triplicate subsamples from one grab sample per station) vs. NS protocols (triplicate grab samples per station, one subsample per grab sample) (at the NS site)?

6) How do contour plots of sulfide concentration data compare using data from the provincial monitoring programs vs. spatially-intensive research surveys (at both sites)?

7) What are the relationships between the sediment sulfide concentration and the redox potential and other parameters?

METHODS

The NB farm had seventeen 100-m circumference cages in an array of 4 rows (Fig. 4). The farm was stocked with 555 000 Atlantic Salmon (*Salmo salar*) smolts in May 2009. A few fish were harvested in April–May 2011, but more than 90% of the biomass was harvested from late June to September 2011. Harvesting was completed on 22 September 2011. Tier 1 monitoring was conducted on 3 October 2011 by Sweeney International Marine Corp. (SIMCorp), following the NB protocols (NBDELG 2012b). Tier 1 monitoring was conducted at 5 stations (Fig. 4). One sediment sample was collected at each station using an Ekman grab sampler which collected approximately 0.023 m^2 of sediment (15 × 15 cm). From each grab sample, three 5-mL subsamples were taken from the top 2 cm of sediment. The subsamples were analyzed for sulfide concentration (total S^{2-}, in µM) and redox potential (mV_{NHE}) following the methods in NBDELG (2012b). Tier 2 monitoring was not required at this site.

A spatially-intensive sediment sampling survey (which included stations equivalent to Tier 2 stations, as well as additional stations within and outside the cage array) was conducted during 27 September–3 October 2011 (Fig. 4). The survey samples were collected using a surface-deployed Hunter-Simpson grab sampler which collected approximately 0.024 m^2 of sediment (16 × 15 cm) or an Ekman grab sampler which collected approximately 0.052 m^2 of sediment (23 × 23 cm). One grab sample was taken at each station. From each grab sample, three 5-mL subsamples were collected and analyzed for sulfide concentration and redox potential. For the three subsamples, sediment was taken from the top 2 cm of sediment at three points within the grab sample, using a cut-off 5-mL plastic syringe: 2 cm of sediment from one point, 2 cm from a second point, and 1 cm from a third point, as in the NS sampling protocol (NSDFA 2011b).

In addition, triplicate core samples (approximately 5-cm diameter × 30-cm long; taken within a 1 m^2 area in similar substrate) were collected by a diver at 8 “cage edge” stations at the NB site, at the same times that grab samples (using the Hunter-Simpson grab sampler) were taken at the same stations, to allow comparisons of sulfide data collected using the two sample collection techniques (Fig. 4). The diver-retrieved core sample data were not included in the other data analyses at the NB site.

The NS farm was actively growing Atlantic Salmon at the time of this study. This farm had an atypical configuration, with two 150-m circumference cages in one row, and another row of six 100-m circumference cages, with about 150 m of water separating the two rows (Fig. 5). The farm was stocked with 578 400 Atlantic salmon smolts in June–July 2010 and the harvest period was June–September 2012. Level I monitoring was conducted at 11 stations (including 2 reference stations) on 6 July 2011 and Level II monitoring was conducted at 10 stations on 23 August 2011 (Fig. 5). Level I and II monitoring was conducted by SIMCorp, using an Ekman grab sampler which collected approximately 0.052 m^2 of sediment (23 × 23 cm), following the NS sampling protocols (NSDFA 2011b). Three grab samples were collected per station. From each grab sample, one subsample was taken from the top 2 cm of sediment, as per the NS subsampling protocol (see above). Sulfide and redox potential analyses were conducted using similar methods as in NB (NSDFA 2011b). In addition, the NS protocols for Level I monitoring require analyses for sediment organic matter content and water content (porosity) to allow calculation of the Benthic Enrichment Index (BEI); see below for methods for calculating values of these parameters (see also NSDFA 2011b and Hargrave et al. 1994 for more details).

A spatially-intensive sediment sampling survey was conducted at the NS site during 12–15 September 2011 (Fig. 5) using the same grab samplers as in the NB survey. On 15 September 2011, the estimated biomass at this farm was 1 549 910 kg (151 880–224 260 kg per cage). At most of the NS survey stations, one grab sample was collected. At 12 of the NS survey stations, triplicate grab samples were taken (Fig. 5); this allowed comparison between monitoring using NS protocols (3 grabs per station, one sulfide measurement per grab sample) vs. NB protocols (one grab sample per location, three sulfide measurements per grab sample). Three subsamples were taken from each grab sample for sulfide and redox analysis (as required in the NB protocols). Subsamples were collected from the grab samples following the NS protocol (i.e. each subsample consisted of sediment from the top 2 cm at three points in the grab sample). The sediment organic matter content and water content were also measured in all subsamples from grab samples taken at the 12 research survey stations where triplicate grab samples were taken (see NBDFA 2011b for analytical methods).

The percent organic matter (POM) was calculated as:

$$\text{POM} = [\text{sediment organic content (g)}] / [\text{sediment dry weight (g)}] \times 100$$

The percent water content (PWC) was calculated as:

$$\text{PWC} = [\text{dried sediment weight (g)}] / [\text{wet sediment weight (g)}] \times 100$$

The Benthic Enrichment Index (BEI) was calculated as:

$$\text{BEI} = [\{(100 - \text{PWC}) / 100\} \times 10^4 \times \{(\text{POM}/100)/12\}] \times [\text{Redox } (\text{mV}_{\text{NHE}})]$$

At the NB site, the following sulfide concentration comparisons were made:

- Tier 1 vs. research survey stations equivalent to Tier 2 monitoring
- Tier 1 vs. research survey stations at Tier 1 locations
- all “cage edge” stations vs. all “between cage” stations
- station means at paired “cage edge” vs. “between cage” stations in close proximity
- research survey stations selected using NB Tier 1 protocols vs. stations selected using NS Level I protocols.

At the NS site, the following sulfide concentration comparisons were made:

- Level I vs. Level II
- Level I vs. research survey stations at Level I locations
- At 12 research survey stations where triplicate grabs were taken: samples taken using the NS sampling protocols (three grab samples per station, one sulfide measurement per grab sample) vs. samples taken using the NB protocols (one grab sample per station, three sulfide measurements per grab sample); for the statistical comparisons, NS protocol samples were selected by randomly choosing one of the three sulfide measurements from each of the three grab samples at each station; the NB protocol samples were selected by randomly choosing one of the three grab samples at each station, and using all three sulfide measurements from that grab sample.

Statistical comparisons were made using non-parametric tests, because the datasets usually deviated from normality and because of the small sample sizes (especially for Tier 1, Level I, and Level II data). Most comparisons were made using data from all samples (i.e. triplicate subsamples at each station) using the Mann-Whitney U test. Comparisons of means of triplicate subsamples at paired “cage edge” and adjacent “between cage” research survey stations at the NB site were made using the Wilcoxin paired sample signed-rank test. This test was also used to compare station means in core samples (collected by divers) vs. grab samples (collected using surface-deployed samplers) at the same locations at the NB site, and to compare the use of NS sampling protocols (3 grab samples per station, one sulfide measurement per grab sample) vs. NB protocols (one grab sample per station, 3 sulfide measurements per grab sample) at the NS site. All tests were 2-tailed, with $\propto$=0.05. Tests were done using the University of California Statistics Online Computational Resource (http://www.socr.ucla.edu/SOCR.html).

Contour plots were created using MapInfo Professional (version 8.0) and MapInfo Vertical Mapper (version 3.0). The interpolation technique was Natural Neighbor (simple); this technique appeared to be a reasonable choice for the distributions of sediment sampling points, based on recommendations in the software (MapInfo Corporation 2005). Default values (calculated by the contouring software) were used for Cell Size and Aggregation Distance. The Surface Solution Type used was Smoothed, without overshoot (the default choice). Calculations of the seafloor areas within the contour intervals assumed a flat bathymetry.

RESULTS

TIER 1 AND TIER 2 SULFIDE CONCENTRATIONS (NB SITE)

There was considerable variability among the triplicate samples at many stations. Standard deviations (SDs) per station averaged 165−206 in the different sampling events, with maximum values 232−3060 (Table 3). Coefficients of variation (CVs) per station averaged 35−44%, with maximum values 55−173% (Table 3).

The sulfide concentrations in Tier 1 monitoring were significantly lower than the concentrations in the Tier 2 equivalent stations in the research survey at the NB site (Table 4). In the research survey data, the overall mean (all stations) was slightly lower than the mean at the Tier 2 equivalent stations (Table 3); of the 168 survey stations, 70 (42%) were located within the cage array (i.e. at cage edges or between cages).

Comparison of the sulfide concentration in Tier 1 monitoring vs. the concentration in research survey samples collected at approximately the same locations indicated a significantly lower concentration for Tier 1 monitoring (Table 5). The sampling dates for the two sets of data overlapped: Tier 1 monitoring was conducted on 3 October 2011, while research survey samples at (or near) the same 5 stations were collected on 27 September 2011 (3 stations) and 3 October 2011 (2 stations). The sampling stations for the two sets of data were not in exactly the same locations: the average distance between the Tier 1 stations and the corresponding research survey stations was 8.0 m (range: 6.1−10.7 m).

LEVEL I AND LEVEL II SULFIDE CONCENTRATIONS (NS SITE)

There was considerable variability among the triplicate samples at many stations. SDs per station averaged 806−2010 in the different sampling events, with maximum values 2231−9760 (Table 3). CVs per station averaged 30−32%, with maximum values 58−111% (Table 3).

Comparison of the sulfide concentration in Level I monitoring (excluding the 2 reference stations) vs. Level II monitoring indicated a significant difference, with a higher mean concentration in Level II (Table 4). The lower mean concentration in Level I was mainly due to low (oxic) concentrations at three stations which were located >40 m from the nearest cage. The overall mean for the research survey was considerably lower than the Level I and II means (Table 3); of the 114 survey stations, only 23 (20%) were located within the two cage arrays (i.e. at cage edges or between cages).

Comparison of the sulfide concentrations in Level I monitoring (excluding the 2 reference stations) vs. the concentrations at the closest research survey stations indicated no significant difference (Table 5). The two sets of data were collected on different dates: Level I on 6 July 2011 and the research survey on 12−15 September 2011. The sampling stations for the two sets of data were not in exactly the same locations: the average distance between the Level I stations and the corresponding research survey stations was 9.9 m (range: 0−25 m).

SULFIDE CONCENTRATIONS AT "CAGE EDGE" VS. "BETWEEN CAGE" STATIONS (NB SITE)

Comparison of the sulfide concentrations in all "cage edge" vs. all "between cage" research survey samples (at the NB site) indicated no significant difference (Table 6). Paired comparison of the mean sulfide concentration at "cage edge" vs. adjacent "between cage" research survey stations (see Fig. 6) also indicated no significant difference (Table 6).

At the NS site, there was only one station equivalent to a "between cage" station at the NB site, due to the unusual layout at the NS site: there were two rows of cages, with a large gap between the rows, and it was not possible to collect samples between the cages in the row of six 100-m cages. Therefore, there were insufficient data to make comparisons between "cage edge" and "between cage" stations at the NS site.

SULFIDE CONCENTRATIONS IN CORE (DIVER-RETRIEVED) VS. GRAB (SURFACE-DEPLOYED) SAMPLES (NB SITE)

At all but one of the 8 research survey stations at the NB site where concurrent core and grab samples were taken (Fig. 4), the mean sulfide concentration was higher in the grab samples (Table 7). Overall, there was a significant difference between the sulfide concentrations of the diver core and grab samples ($p=0.04$). At 6 of the 8 sampling stations, the sulfide concentrations were in the oxic categories for both sampling methods.

SULFIDE CONCENTRATIONS PER STATION USING NB VS. NB SAMPLING PROTOCOLS (NS SITE)

There was no significant difference in the sulfide concentration between sampling conducted using the NS protocols (3 grab samples per station, one syringe subsample per grab sample) vs. samples collected using the NB protocols (1 grab sample per station, three subsamples per grab sample) at the 12 research survey stations at the NS site (Fig. 5) where triplicate grab samples were taken ($p=0.75$ for comparison of paired station means; Table 8).

SULFIDE CONCENTRATIONS IN STATIONS SELECTED USING NS LEVEL I PROTOCOLS VS. NB TIER 1 PROTOCOLS (NB SITE)

There were 5 Tier 1 stations at the NB site. The NS Level I protocols would require 4 stations (plus 2 reference stations) at this site (based on stocking of 555 000 fish), as shown in Fig. 4. The mean sulfide concentration in the survey stations equivalent to NB Tier 1 monitoring was 1 044 µM and for the stations equivalent to NS Level I monitoring was 917 µM (excluding the reference stations). There was no significant difference between sulfide concentrations from the two datasets ($p=0.77$).

CONTOUR PLOTS OF SULFIDE CONCENTRATION DATA

Contour plots of the sulfide concentration data are shown in Fig. 6 to 9. Calculated seafloor areas within the contour intervals are shown in Table 9.

NB site: The contoured area derived using all research survey samples (Fig. 6) had very large areas of oxic sediments (96% of the total), including large oxic areas outside the cage array. The small area with Hypoxic B or worse conditions (1 200 m^2; 1% of the total contoured area) extended outside the cage array. There were no anoxic areas. The contoured area derived using just the stations equivalent to Tier 2 monitoring (i.e. excluding stations outside the cage array, and some extra stations collected inside the array; see Fig. 7) was still mostly oxic (91%); the area with Hypoxic B or worse conditions (600 m^2) was only 1% of the total (Table 9). The mean sulfide concentration in the Tier 2 equivalent stations ranged from 105−5 343 µM. There were no fish in the 17 cages on site at the time of monitoring (there were also 3 mussel cages); harvesting had been completed 5 d prior to the start of the research survey (11 d prior to Tier 1 monitoring). The maximum biomasses per cage during 2011 ranged from 120 400–244 700 kg (dates of maxima per cage were between mid-April to mid-June; data obtained from the farm operator). The highest sulfide concentrations were in the shallower (northern) portion of the farm.

NS site: The contoured area derived using all research stations (Fig. 8) indicated elevated impacts (including anoxic conditions) under both cage rows and extending slightly beyond the cage rows. The contour plot using Level I and II data was considerably different (Fig. 9), with elevated impacts under and between the cage rows; this contour plot appeared to overestimate the impacted area (see Table 9), due to the small number of sampling stations, especially the lack of stations between the two rows of cages.

COMPARISONS AMONG PARAMETERS

Sulfide concentration vs. redox potential (both sites)

There was a negative relationship between the sulfide concentration (log-transformed) and the redox potential at both sites, but there was considerable variability and the relationship appeared to be non-linear (Fig. 10). The r^2 values for linear relationships were: at the NB site, 0.56 for research survey data; at the NS site, 0.40 for research survey data and 0.69 for regulatory monitoring (Level I and II) data.

Sulfide concentration vs. other parameters (NS site)

There was a positive relationship between the sulfide concentration (log-transformed) and the percent organic matter (POM) at the NS site (Fig. 11). The variability in POM values increased as the sulfide concentration increased, and r^2 values were low (0.42 for research survey data and 0.33 for Level I monitoring data).

There was also a positive relationship between the sulfide concentration (log-transformed) and the percent water content (PWC) at the NS site (Fig. 12). The variability in PWC values increased as the sulfide concentration increased, and r^2 values were low (0.36 for research survey data and 0.27 for Level I monitoring data).

There was also a positive relationship between the sulfide concentration (log-transformed) and the Benthic Enrichment Index (BEI) at the NS site (Fig. 13), with relatively good fit ($r^2 = 0.70$ for both research survey data and Level I monitoring data).

DISCUSSION AND CONCLUSIONS

COMPARISONS OF SULFIDE CONCENTRATION BETWEEN TIERS OR LEVELS OF MONITORING

At the NB site, the mean sulfide concentration in Tier 2 equivalent monitoring (from the research survey) was significantly higher than the mean concentration in Tier 1 monitoring, although both means were low (oxic). The low sulfide concentrations were probably related to the absence of fish at the time of monitoring. The significantly higher sulfide concentration in the Tier 2 equivalent monitoring at this site is unlike findings at most NB farms which conducted Tier 2 monitoring during 2007–2011: Tier 2 results were significantly lower than Tier 1 results in 11 of 14 cases (Chang et al. 2013).

The significant difference between Tier 1 monitoring and corresponding locations in the research survey at the NB site was also surprising, especially given the absence of temporal differences in the two sampling events (the dates of Tier 1 monitoring and the research survey overlapped). This suggests small-scale spatial variations in sulfide concentrations (since the two sets of data were not collected in exactly the same locations, due to cage movement caused by tides), as has been reported previously (Chang et al. 2011, 2013). Another possible factor is that different individuals and organizations were involved in collecting and analyzing the two sets of samples, so there may have been some differences in methodologies, even though the same protocols (NBDELG 2012b) were followed in both cases.

At the NS site, the mean sulfide concentration in Level II monitoring was significantly higher than the mean in Level I monitoring (excluding reference stations), although this was mainly due to low concentrations at some Level I stations which were located distant from the cages. Sulfide concentrations were in the Hypoxic B category for both Levels.

COMPARISON OF SULFIDE CONCENTRATION IN “CAGE EDGE” VS. “BETWEEN CAGES” STATIONS

There was no significant difference between sulfide concentrations in research survey grab samples taken at all “cage edge” stations compared to samples taken at all “between cage” stations at the NB site. When comparing paired samples of “cage edge” stations and adjacent “between cage” stations, there also was no significant difference. The lack of significant differences between “cage edge” and “between cage” stations was also found at most Tier 2 monitoring events in NB during 2007–2011 (Chang et al. 2013). Except where currents are strong, most wastes would be expected to fall directly under cages, so sulfide concentrations might be expected to be higher at "cage edge" than at "between cage" stations. The lack of a difference at the NB site in this study is probably related to cage movement over the tidal cycle. Other studies have observed that fish cages in southwestern NB can move horizontally in the order of 10–40 m over a tidal cycle (S. Smedbol, unpublished data; Hanke 2010), so the location where a "cage edge" sample is taken may be situated "between cages" at other stages of the tide, and "between cage" locations may at times be situated under cages.

In areas where there is less tidal influence, such as in NS, significant differences between "cage edge" and "between cage" stations might be expected, because there would be less movement of cages over the tidal cycle. The mean tidal range near the NS study site is 1.6 m, compared to 5.9 m at the NB site. Unfortunately, due to the unusual configuration of the NS site, there was only one "between cage" station, so there was not sufficient data to compare "cage edge" and "between cage" stations.

COMPARISON OF SULFIDE CONCENTRATIONS IN CORE (DIVER-RETRIEVED) VS. GRAB (SURFACE-DEPLOYED) SAMPLES

In all but one of the research survey stations (at the NB site) where sampling was conducted using diver-retrieved cores and surface-deployed grabs at the same time, the sulfide concentration was higher in the surface-deployed grab samples, and overall, the grab samples had significantly higher sulfide concentrations than the diver core samples. No explanation for this difference can be offered at this time. The majority of the stations had sulfide concentrations in the oxic categories for both sampling types. It is recommended that additional sampling be conducted using both methods at other farms, including more locations with elevated sulfide concentrations.

COMPARISON OF SULFIDE CONCENTRATION PER STATION USING NB VS. NS SAMPLING PROTOCOLS

Using research survey data from 12 stations at the NS site, there was no significant difference in the sulfide concentration (per station) between samples collected using the NS protocols (triplicate grab samples per station, one sulfide measurement per grab sample) vs. NB protocols (one grab sample per station, three sulfide measurements per grab sample). Note, however, that this was not an exact comparison of the NS vs. NB sampling protocols, because the NS protocols for taking syringe subsamples were used in both cases: the NS protocol stipulates that each 5-mL syringe sample must be taken from the top 2 cm of sediments at 3 points in the grab sample, while the NB protocol only stipulates that each syringe sample must be taken from the top 2-cm of sediment.

COMPARISON OF SULFIDE CONCENTRATION USING STATIONS SELECTED USING NB TIER 1 PROTOCOLS VS. NS LEVEL I PROTOCOLS

Using the research survey data from the NB site, there was no significant difference in the sulfide concentration between stations selected using NB Tier 1 protocols vs. stations selected using NS Level I protocols (excluding the 2 reference stations). Because of the atypical configuration of the NS site, similar comparisons were not done for that site.

CONTOUR AREAS FOR MEAN SULFIDE CONCENTRATION PER STATION

At the NB site, when using all research survey stations (including stations located outside the cage array), it was found that elevated benthic impacts extended slightly outside the cage array. Therefore, the existing Tier 2 monitoring design, which only includes stations within the perimeter of the cage array, would have missed some areas of elevated benthic impacts at this site. In this case, the area of elevated impacts (Hypoxic B to Anoxic) estimated using only Tier 2 monitoring stations was half of that estimated using all sampling data. In another study, elevated impacts were also found to extend outside the cage array at some NB salmon farms where spatially-intensive sediment sampling was conducted (Chang et al. 2011).

At the NS site, contours produced using Level I and II data were imprecise, overestimating the seafloor area with elevated impacts. This was due to the small number of stations, especially the lack of stations between the two cage rows, which, at this site, were widely separated. As a result, the contours produced using Level I and II data suggested elevated sulfide concentrations between the cage rows, while contours based on the research samples (which included stations between the rows of cages) showed that concentrations were actually low between the cage rows.

RELATIONSHIPS BETWEEN SULFIDE CONCENTRATION AND OXIDATION-REDUCTION (REDOX) POTENTIAL AND OTHER PARAMETERS

The relationship between sediment sulfide concentration (log-transformed) and oxidation-reduction (redox) potential showed a negative relationship, which appeared to be non-linear, similar to equation 1 in Hargrave (2010), rather than linear as in equation 2 (Hargrave 2010; see Fig. 14). However, the redox values in the present study appeared to be slightly lower (for equivalent sulfide concentrations) than the data used in the Hargrave (2010) equations. The data in this study mostly fell within the values for the relationship between sulfide concentration and redox potential observed in Tier 2 monitoring at NB farms during 2007–2011 (Fig. 15).

The relationship between sulfide concentration and percent organic matter showed a poor fit at the NS site, as did the relationship between sulfide concentration and water content. However, the relationship between sulfide concentration and the Benthic Enrichment Index (which is calculated from the redox potential, percent organic matter, and water content) showed a relatively good fit. Data from additional sites is required to confirm this finding.

GENERAL CONSIDERATIONS

Conclusions derived from this study are constrained by some of the limitations of the data. In particular, only two farms were studied (one in each provincial jurisdiction), and both were somewhat atypical, compared to most monitored farms. The NB farm, while having a fairly typical grid layout, had no fish on site when the research survey was conducted, as harvesting had been completed just before the study commenced. The NS farm was active at the time of sampling, but had an unusual layout, with two sizes of cages, and a separation of 150 m between the two rows of cages.

ACKNOWLEDGEMENTS

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Table 1. Site classifications based on mean sediment sulfide concentration (total S^{2-}) in annual monitoring of finfish farms in New Brunswick (based on NBDELG (2012a).

Site classification	Mean sediment sulfide (total S^{2-})	Effects on marine sediments
Oxic A	<750 µM	Low effects
Oxic B	750−1 499 µM	Low effects
Hypoxic A	1 500−2 999 µM	May be causing adverse effects
Hypoxic B	3 000−4 499 µM	Likely causing adverse effects
Hypoxic C	4 500−5 999 µM	Causing adverse effects
Anoxic	>6 000 µM	Causing severe damage

Table 2. Site classifications based on sediment sulfide concentration (total S^{2-}) in annual monitoring of finfish farms in Nova Scotia (based on NSDFA 2011a).

Site classification	Sediment sulfide (total S^{2-}) (Level I excluding reference stations)	Effects on marine sediments
Oxic	≥50% of stations with means <1 500 µM	Low effects
Hypoxic A	≥50% of stations with means >1 500 µM and <3 000 µM	Likely causing adverse effects near some cage structure
Hypoxic B	≥50% of stations with means >3 000 µM and <70% with means >6 000 µM	Likely causing adverse effects near some cages
Anoxic	≥70% of stations with means >6 000 µM	Causing adverse effects to large portions of site

Table 3. Mean sulfide concentrations per site, with mean, minimum, and maximum standard deviations (SD) per station and coefficients of variation (CV) per station in regulatory monitoring and research surveys at one salmon farm in New Brunswick (NB) and one salmon farm in Nova Scotia (NS). Single grab samples were taken at each station, except triplicate grab samples were taken at 12 NS stations. Triplicate subsamples were taken from each grab sample for geochemical analyses. NS Level I excludes two reference stations. SDs and CVs were calculated for all subsamples taken at each station. n = number of sampling stations; CV(%) = SD/mean × 100.

Site and sampling type	n	Site mean (μM)	SD per station Mean	SD per station Min.	SD per station Max.	CV (%) per station Mean	CV (%) per station Min.	CV (%) per station Max.
NB Tier 1	5	428	165	55	232	40.3	11.9	55.1
NB Tier 2 equivalent	50	836	269	10	3 060	34.9	2.2	87.1
NB research survey	168	619	206	0	3 060	43.5	2.2	173.2
NS Level I	9	5 122	1 125	186	2 231	30.2	11.7	77.8
NS Level II	10	7 450	2 010	450	5 205	31.9	6.6	57.8
NS research survey	114	2 720	806	9	9 760	31.7	1.8	110.7

Table 4. Comparisons of sediment sulfide concentrations for Tier 1 vs. Tier 2 equivalent monitoring at a salmon farm in New Brunswick (NB) and for Level I (excluding reference stations) vs. Level II monitoring at a salmon farm in Nova Scotia (NS). At the NB site, a research survey which included stations equivalent to Tier 2 monitoring was conducted; additional survey stations at locations not required in Tier 2 protocols are not included in this table. Comparisons were made using individual sample data (triplicate subsamples at each station). n = number of sampling stations; s = significant ($\propto$=0.05, 2-tailed).

Site	Tier 1 or Level I monitoring: Date	n	Mean sulfide (μM)	Tier 2 or Level II monitoring: Date	n	Mean sulfide (μM)	Prob.	Sig.
NB	03 Oct 11	5	428	27 Sep–03 Oct 11	50	836	0.03	s
NS	06 Jul 11	9	5 122	23 Aug 11	10	7 450	0.03	s

Table 5. Comparisons of sediment sulfide concentrations in regulatory monitoring (NB Tier 1 and NS Level I) with corresponding stations in research surveys conducted at one salmon farm in NB and one salmon farm in NS. Comparisons were made using individual samples (triplicate subsamples at each station). n = number of sampling stations; s = significant (∝=0.05, 2-tailed); ns = non-significant.

	Regulatory monitoring (Tier 1 or Level I)			Corresponding research survey stations				
Site	Date	n	Mean sulfide (µM)	Date	n	Mean sulfide (µM)	Prob.	Sig.
NB	03 Oct 11	5	428	27 Sep–03 Oct 11	5	1 044	0.03	s
NS	6 Jul 11	9	5 122	12–15 Sep 11	9	4 742	0.28	ns

Table 6. Comparisons of sediment sulfide concentrations at “cage edge” vs. “between cage” research survey stations at a salmon farm in NB. Data were collected between 27 September and 3 October 2011. Comparison of all “cage edge” vs. all “between cage” stations was made using individual sample data (triplicate subsamples at each station). A paired comparison of station means (for triplicate subsamples at each station) were made where there were “cage edge” stations and adjacent “between cage” stations in close proximity (see Fig. 6). n = number of sampling stations; ns = not significant (∝=0.05, 2-tailed).

	Cage edge stations		Between cage stations			
Data source	N	Mean sulfide (µM)	N	Mean sulfide (µM)	Prob.	Sig.
All stations	45	909	24	843	0.17	ns
Paired stations	26	923	26	922	0.29	ns

Table 7. Mean sediment sulfide concentrations in core samples collected by divers (3 cores per station, one sulfide measurement per core) vs. grab samples collected by surface-deployed samplers (one grab sample per station, 3 sulfide measurements per grab sample) at 8 research survey stations at a salmon farm in NB on 28 September 2011 (see Fig. 4). There was a significant overall difference between the means of core vs. grab samples ($p=0.04$, 2-tailed).

Sampling station	Mean sulfide (μM) Core samples (diver-retrieved)	Mean sulfide (μM) Grab samples (surface-deployed samplers)
M2-2	744	491
M3-2	123	249
T1	3 247	5 343
T6	431	1 037
T11	247	589
T18	281	2 600
T36	299	660
T60	387	587

Table 8. Mean sediment sulfide concentrations in research survey samples collected using NS protocols (3 grab samples per station, one sulfide measurement per grab sample) vs. NB protocols (one grab sample per station, 3 sulfide measurements per grab sample) at 12 stations at a salmon farm in NS on 12–14 September 2011 (see Fig. 6). There was no significant overall difference between the station means using the two sampling protocols ($p=0.75$, 2-tailed).

Sampling station	Mean sulfide (μM) NS protocols	Mean sulfide (μM) NB protocols
T3	294	270
T24	566	1 021
T29	3 967	1 197
T40	150	269
T51	8 510	7 437
T62	822	584
T67	1 041	1 713
T76	4 643	4 880
T82	3 423	2 470
T102	6 793	10 967
T106	17 140	19 800
T114	162	175

Table 9. Calculated seafloor areas within contour intervals, based on sediment sulfide data collected at a New Brunswick (NB) salmon farm (top) and a Nova Scotia (NS) salmon farm (bottom). Research survey sampling at the NB farm included Tier 2 equivalent stations at the outer edges of perimeter cages and within the cage array; additional research survey stations were located inside and outside the cage array (Fig. 4). Research survey sampling at the NS farm was conducted near and outside the cage rows (Fig. 5); Level I and II sample stations are also shown in Fig. 5. Contour plots are shown in Fig. 6 to 9.

Rating	Sulfide concentration (μM)	Seafloor area (m^2): New Brunswick farm	
		All survey stations	Tier 2 stations only
Oxic A	<750	179 900	27 000
Oxic B	750–1 500	23 200	13 000
Hypoxic A	1 500–3 000	6 900	3 400
Hypoxic B	3 000–4 500	1 000	300
Hypoxic C	4 500–6 000	200	300
Anoxic	>6 000	0	0
≥Hypoxic B (% of total)	>3 000	8 200 (1%)	600 (1%)

Rating	Sulfide concentration (μM)	Seafloor area (m^2): Nova Scotia farm	
		All survey stations	Level I & II monitoring
Oxic A	<750	129 900	32 800
Oxic B	750–1 500	54 000	17 500
Hypoxic A	1 500–3 000	19 700	24 600
Hypoxic B	3 000–4 500	7 800	24 700
Hypoxic C	4 500–6 000	6 800	15 700
Anoxic	>6 000	14 600	48 300
≥Hypoxic B (% of total)	>3 000	28 700 (13%)	88 700 (54%)

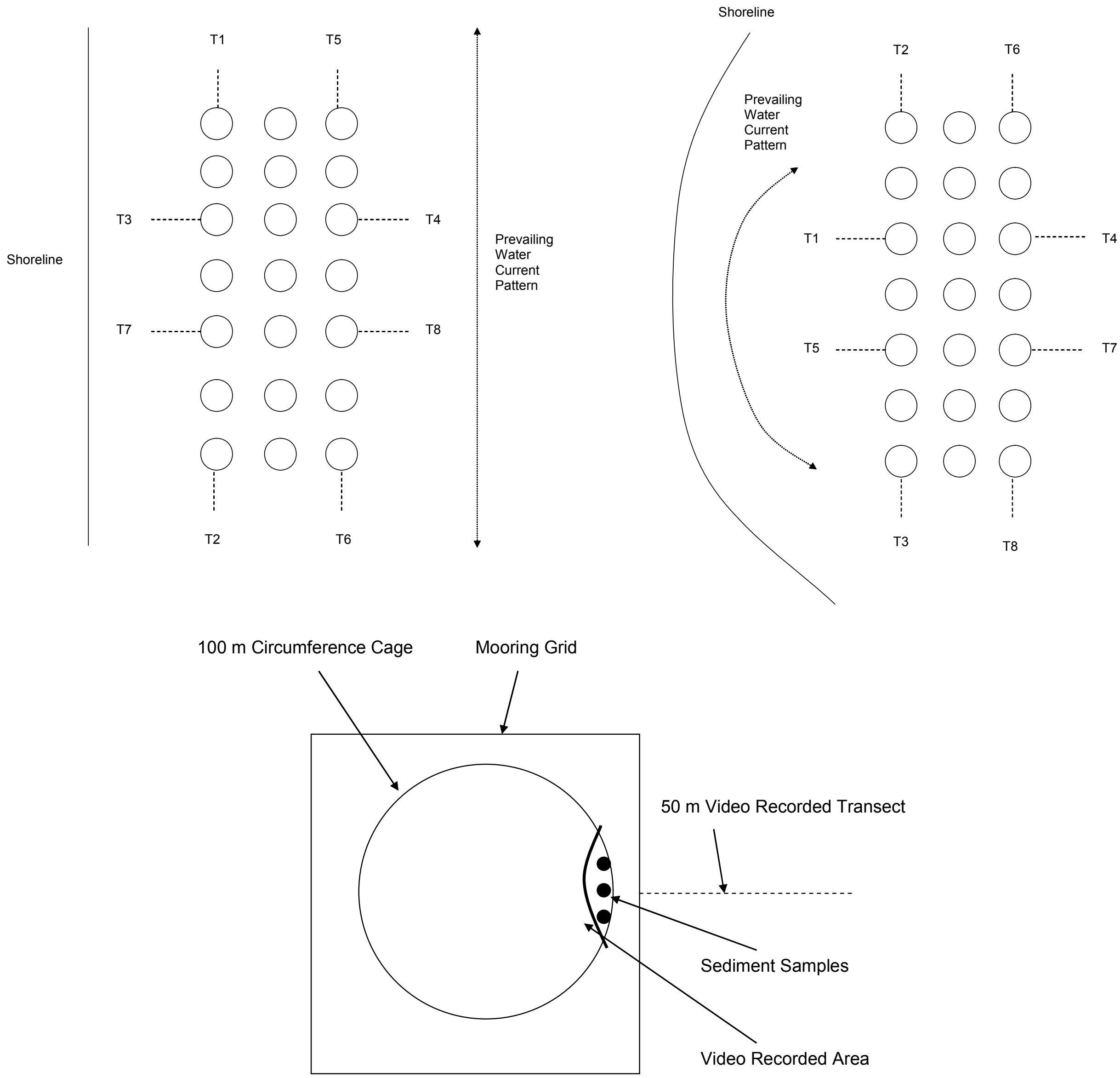


Fig. 1. Locations of transects and samples for Tier 1 monitoring of marine finfish farms in New Brunswick (from NBDELG 2012b). Top left: transect locations for sites with generally linear water current patterns and moderate or high current speeds. Top right: transect locations for sites with generally curving water current patterns or low current speeds. Bottom: close-up of a cage showing sampling stations where triplicate sediment samples were taken at the cage edge (within 1 m^2, in similar substrate types) for each transect.

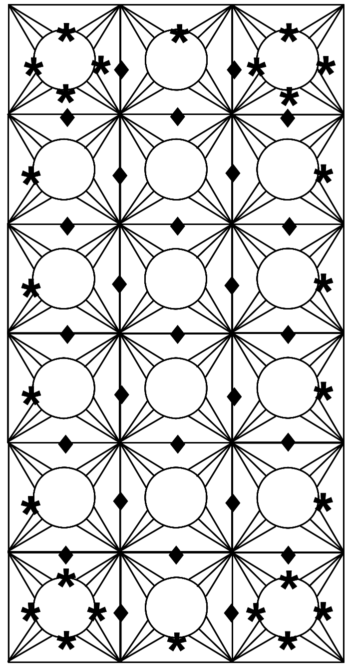


Fig. 2. Sampling stations for Tier 2 monitoring of marine finfish farms in New Brunswick (from NBDELG 2012b). Triplicate samples are taken at each station marked by ∗ (cage edges) and ♦ (between cages). Large circles represent cages.

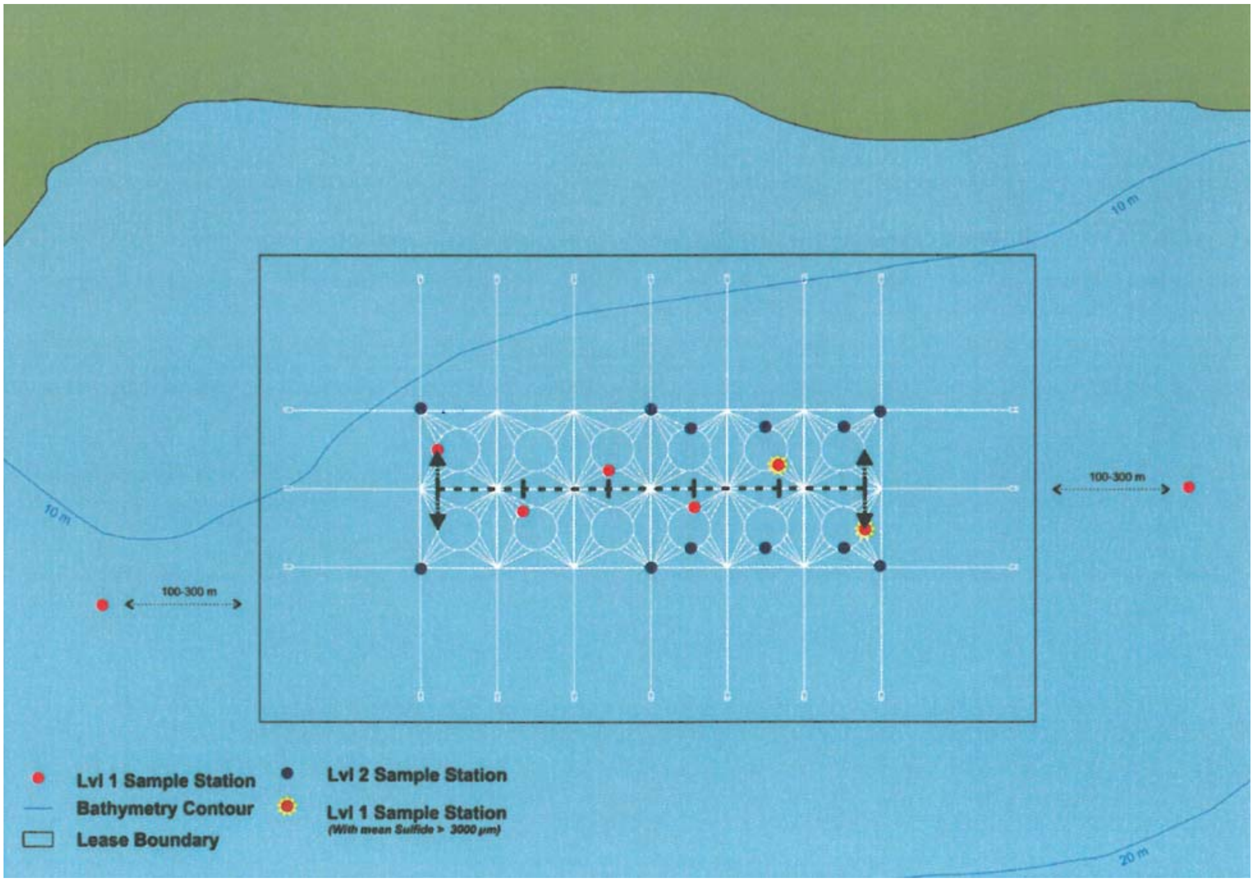


Fig. 3. Sampling stations for Level I and Level II monitoring of marine finfish farms in Nova Scotia (from NSDFA 2011b).

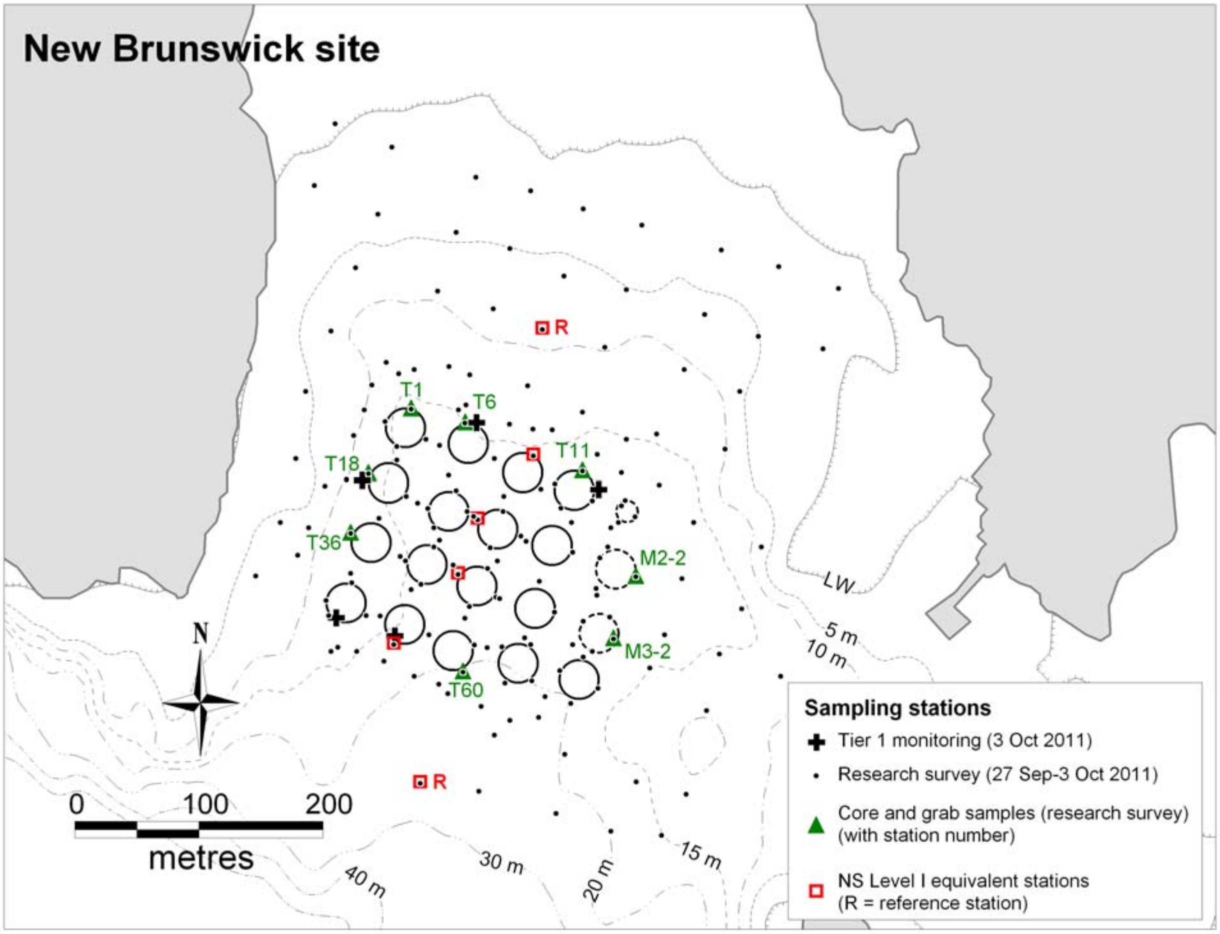


Fig. 4. Sampling stations at the New Brunswick salmon farm: Tier 1 monitoring (5 stations) and a spatially-intensive research survey (168 stations, of which 70 were within the cage array). Single grab samples were taken at each station. Triplicate subsamples were taken from each grab sample for geochemical analyses. At 8 research survey stations, diver-retrieved cores and surface-deployed grab samples were collected concurrently. Also shown are research survey stations equivalent to Nova Scotia (NS) Level I monitoring stations (6 stations, including 2 reference stations). Circles indicate cage sizes and approximate locations (seventeen 100-m circumference cages); dashed circles represent three mussel cages. The average depth under the survey area was approximately 16.4 m below chart datum (lowest normal tide).

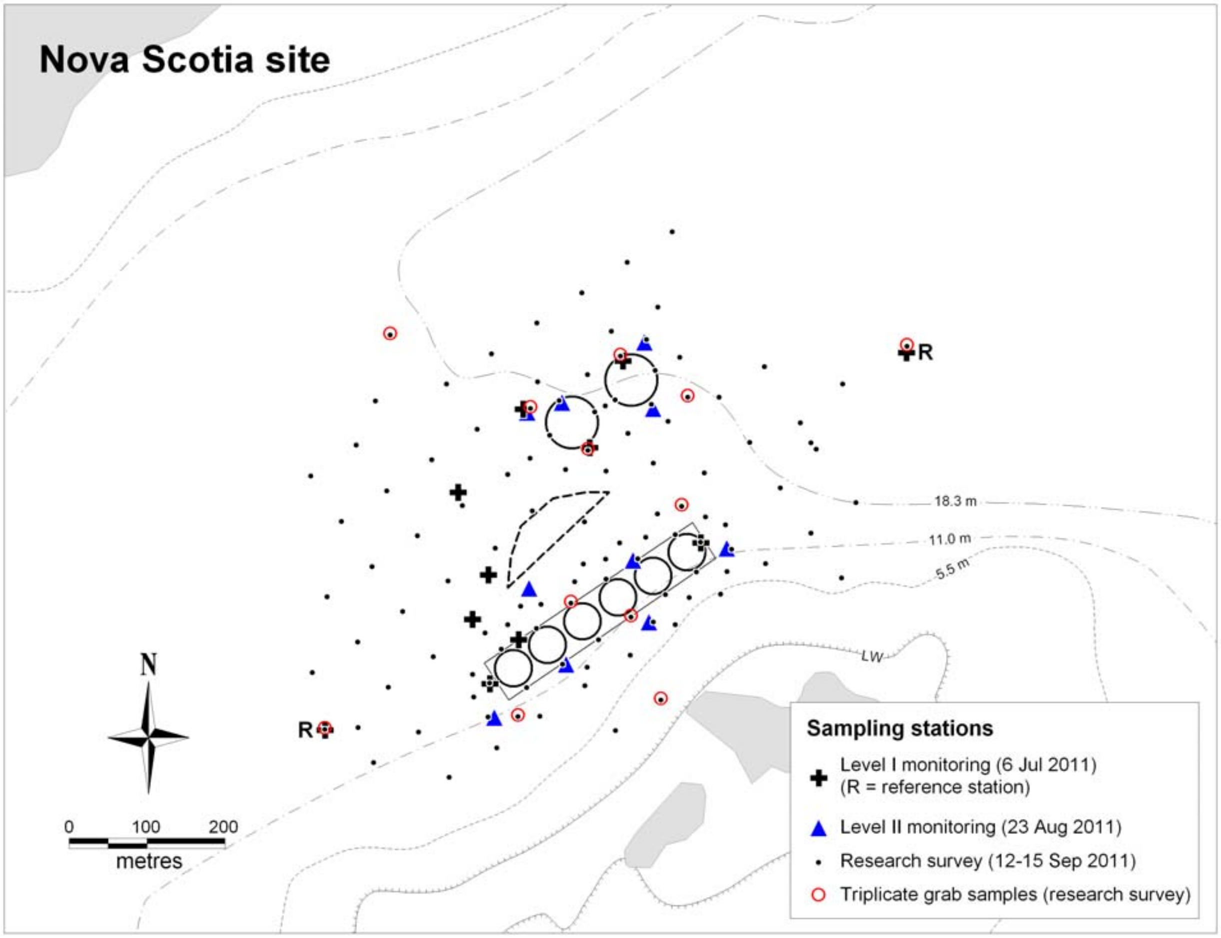


Fig. 5. Sampling stations at the Nova Scotia salmon farm: Level 1 monitoring (11 stations, including 2 reference stations), Level II monitoring (10 stations), and a spatially-intensive research survey (114 stations, of which 23 were within the two cage arrays). In the Level I and II monitoring, three grab samples were collected per station, and one subsample was taken from each grab sample for geochemical analyses. In the research survey, single grab samples were taken at each station, except triplicate grab samples were taken at 12 stations; triplicate subsamples were taken from each grab sample for geochemical analyses. Circles indicate sizes and approximate locations of cages (two 150-m circumference cages and six 100-m circumference cages); the dashed line indicates empty cage structures. The average depth under the survey area was approximately 15 m below chart datum (lowest normal tide).

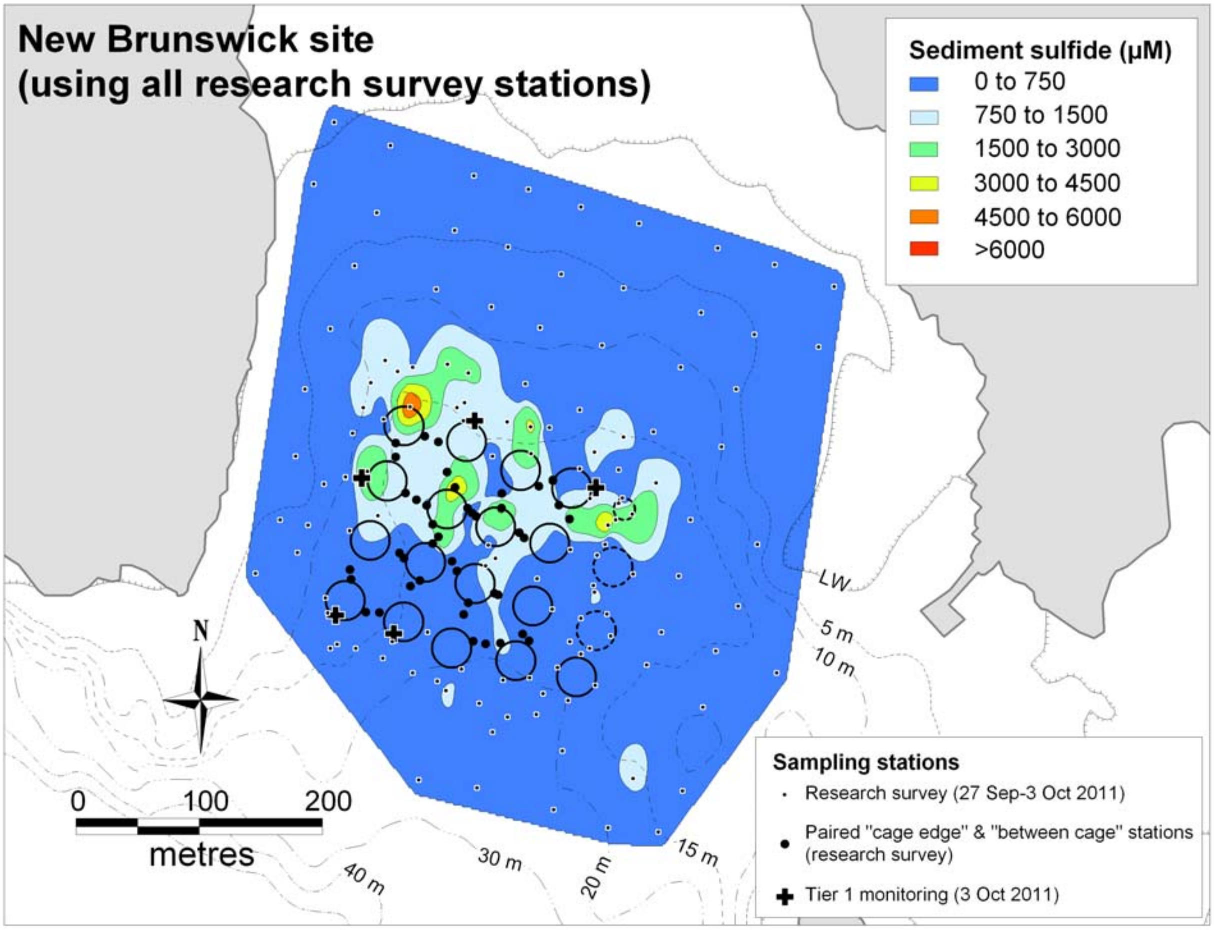


Fig. 6. Contour plot of sediment sulfide concentrations derived using all research survey data collected using surface-deployed grab samplers at the New Brunswick salmon farm, 27 September to 3 October 2011. Circles indicate cage sizes and approximate locations (seventeen 100-m circumference cages); dashed circles represent mussel cages. There were no fish on site at the time of monitoring.

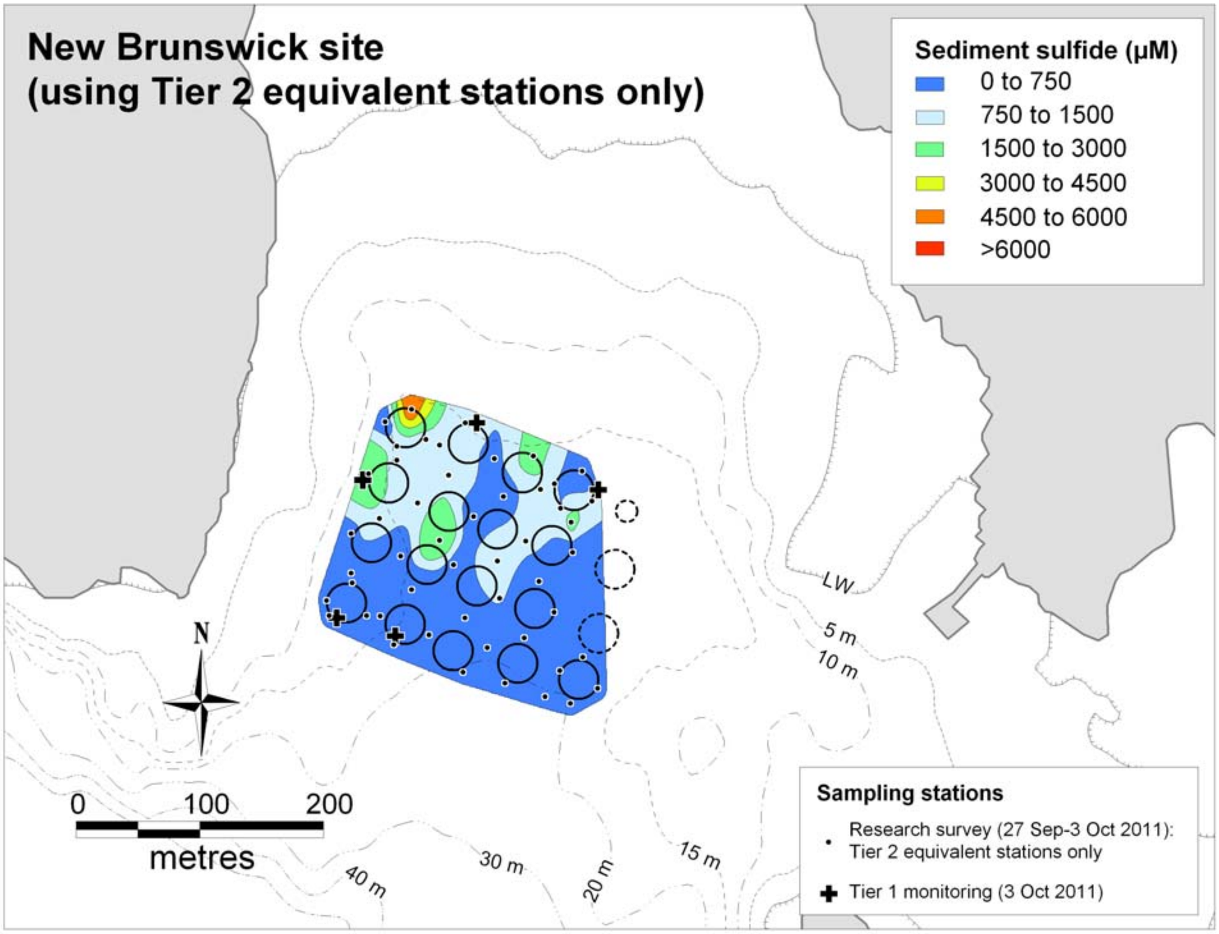


Fig. 7. Contour plot of sediment sulfide concentrations derived using research survey data collected using surface-deployed grab samplers at Tier 2 equivalent stations at the New Brunswick salmon farm, 27 September to 3 October 2011. Circles indicate cage sizes and approximate locations (seventeen 100-m circumference cages); dashed circles represent three mussel cages. There were no fish on site at the time of monitoring.

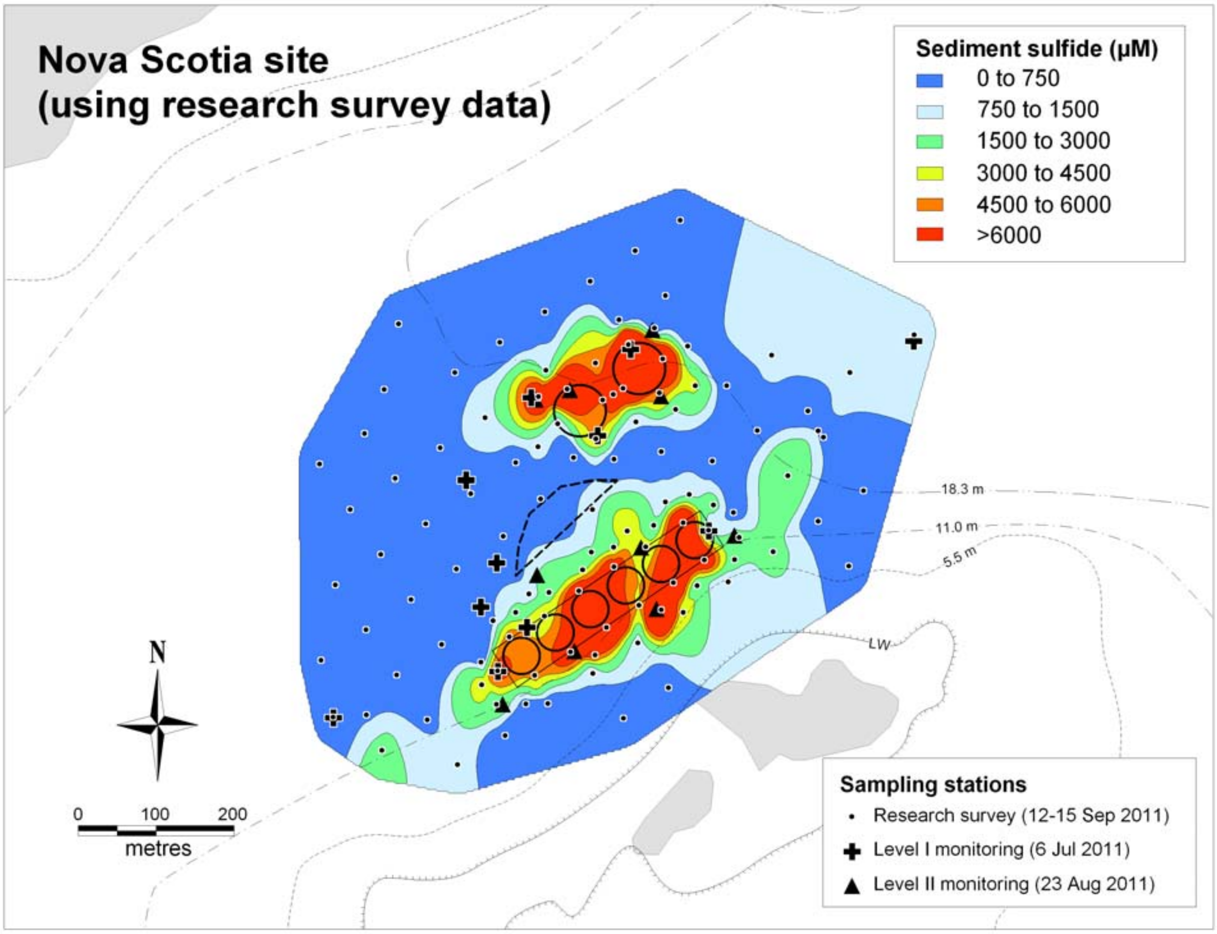


Fig. 8. Contour plot of sediment sulfide concentrations derived using research survey data collected using surface-deployed grab samplers at the Nova Scotia salmon farm, 12–15 September 2011. Circles indicate cage sizes and approximate locations (two 150-m circumference cages and six 100-m cages); the dashed line indicates empty cage structures. Also shown are 11 Level I monitoring stations (including 2 reference stations) and 10 Level II monitoring stations. On 15 September 2011, there was a total of 1 549 910 kg of salmon on site: 218 360–224 260 kg in each of the two larger cages and 151 880–213 230 kg in each of the 6 smaller cages.

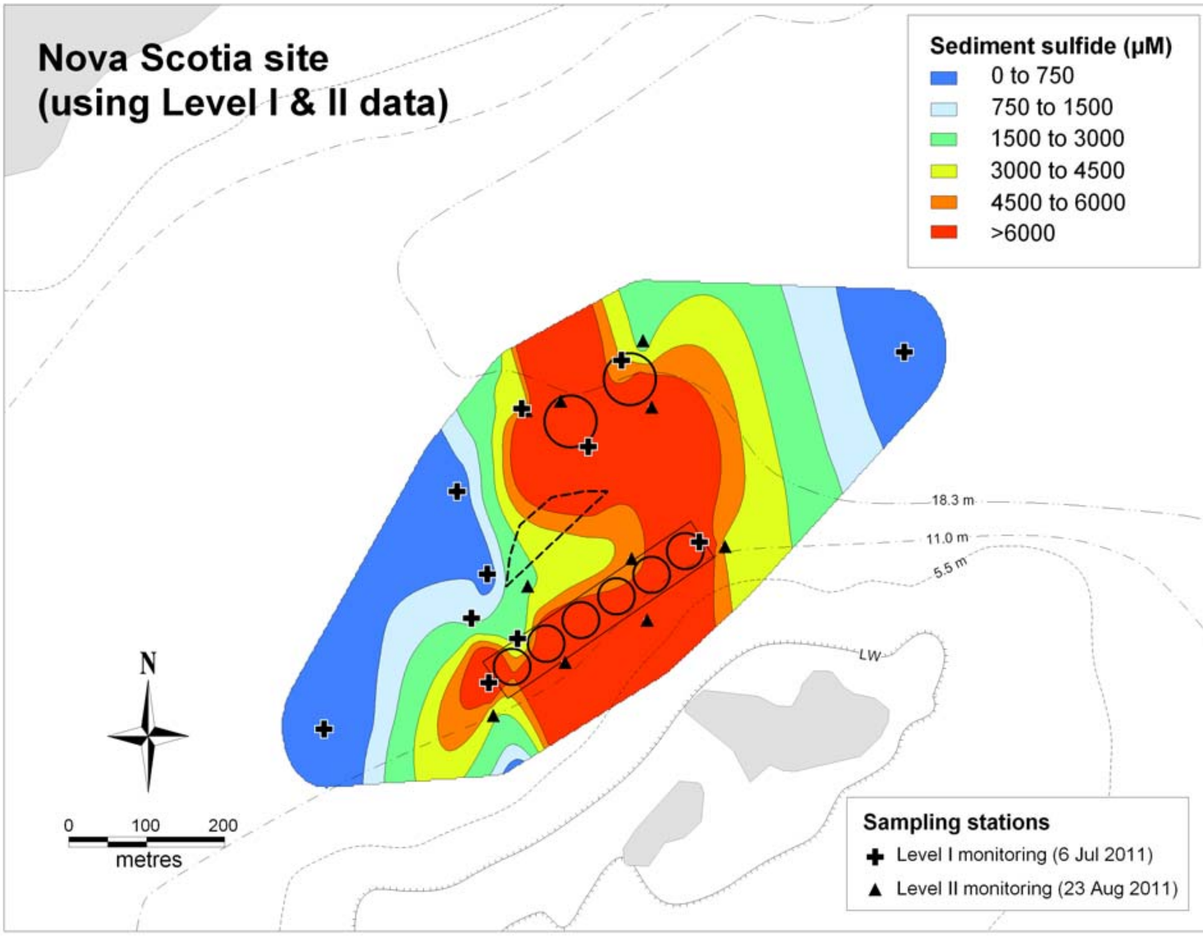
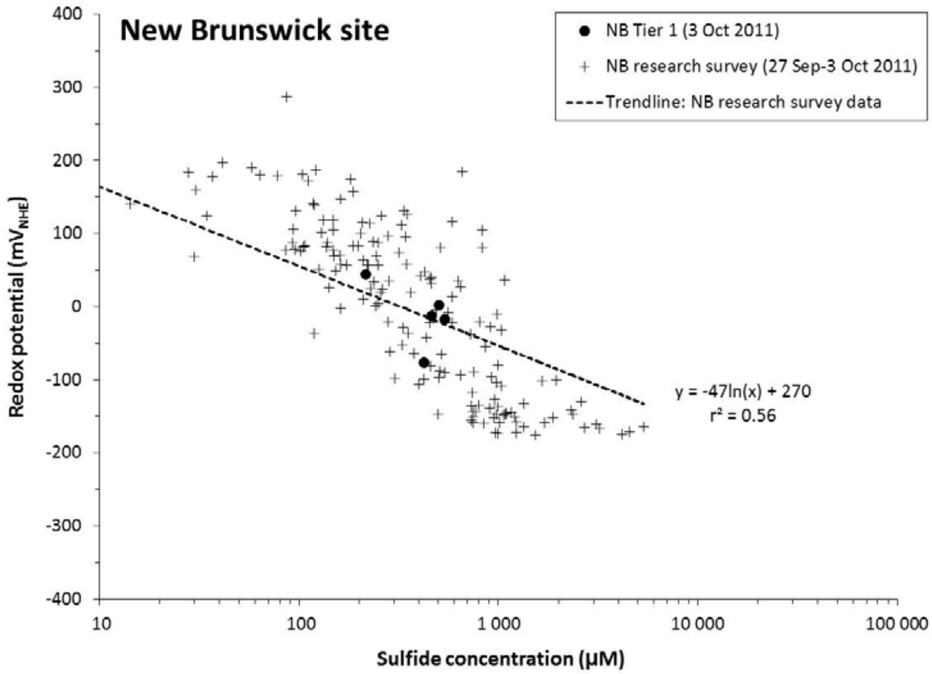


Fig. 9. Contour plot of sediment sulfide concentrations derived using Level I and II monitoring data collected using surface-deployed grab samplers at the Nova Scotia salmon farm. Circles indicate cage sizes and approximate locations (two 150-m circumference cages and six 100-m cages); the dashed line indicates empty cage structures. Level I monitoring was conducted on 6 July 2011 (11 stations, including 2 reference stations) and Level II monitoring was conducted on 23 August 2011 (10 stations).



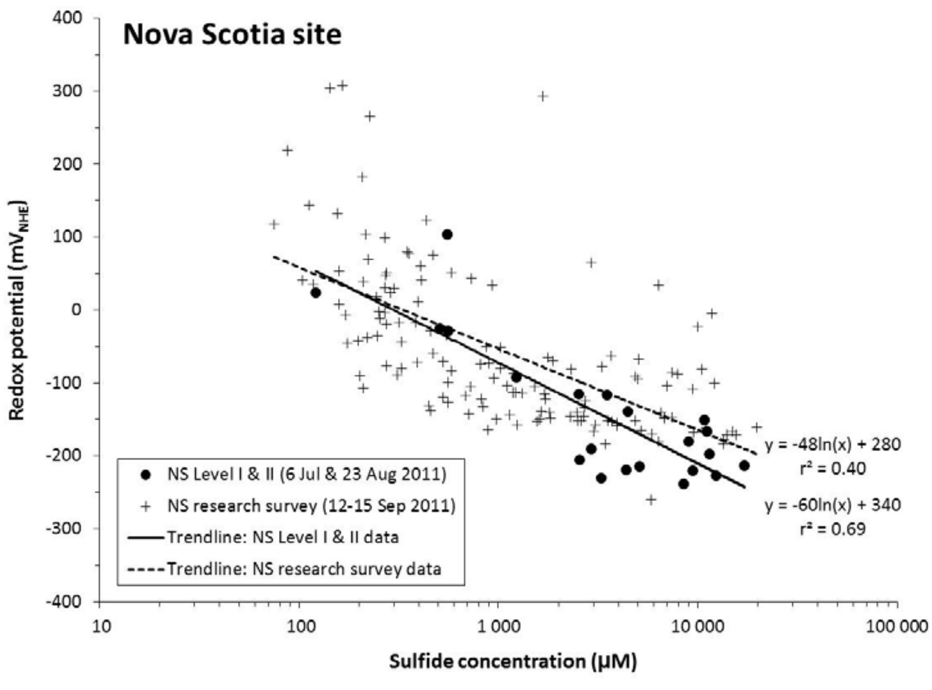


Fig. 10. Relationships between sediment sulfide concentration (log-transformed) and oxidation-reduction (redox) potential at a salmon farm in New Brunswick (NB, top) and a salmon farm in Nova Scotia (NS, bottom) in 2011. Values shown are means of triplicate subsamples per station. The NB research survey data excludes 11 points with sulfide concentrations <10 µM, which is the minimum sensitivity of the electrodes used to measure sulfide concentrations (Hargrave et al. 2008).

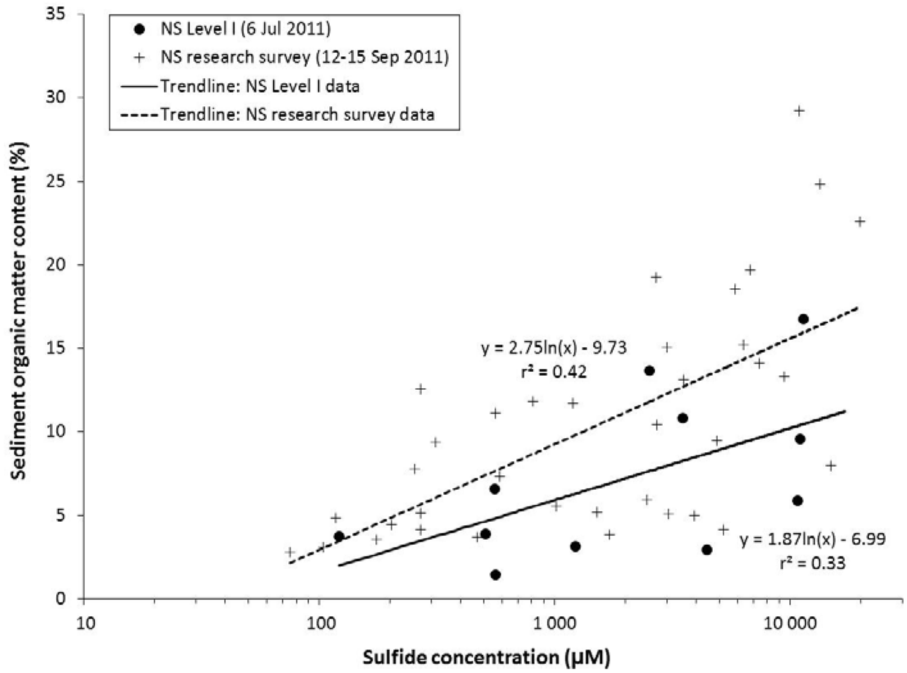


Fig. 11. Relationships between sediment sulfide concentration (log-transformed) and sediment organic matter content (%) at the Nova Scotia (NS) salmon farm in 2011. Values shown are means of triplicate subsamples per station.

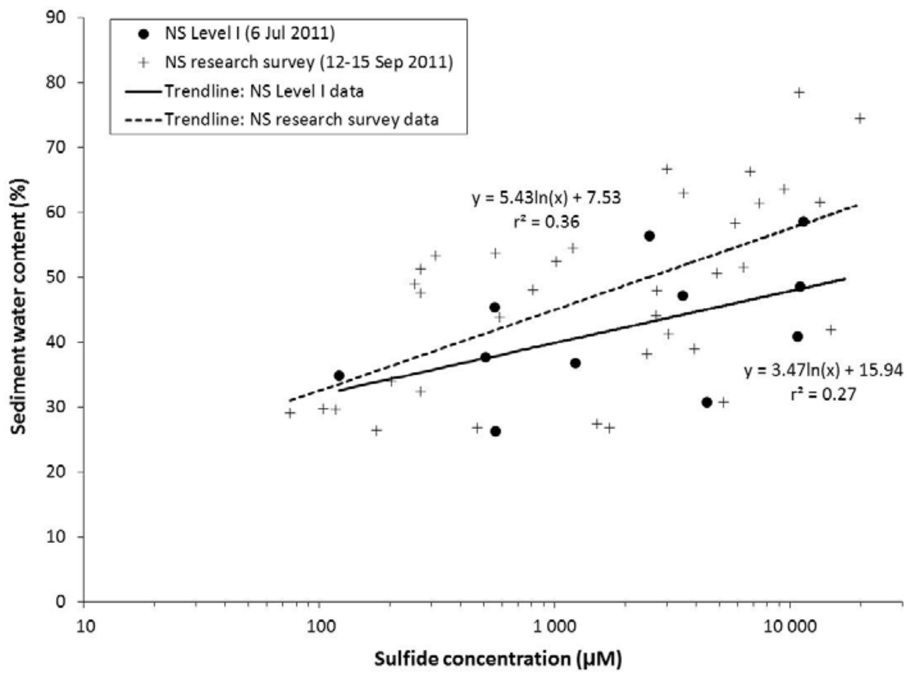


Fig. 12. Relationships between sediment sulfide concentration (log-transformed) and sediment water content (%) at the Nova Scotia (NS) salmon farm in 2011. Values shown are means of triplicate subsamples per station.

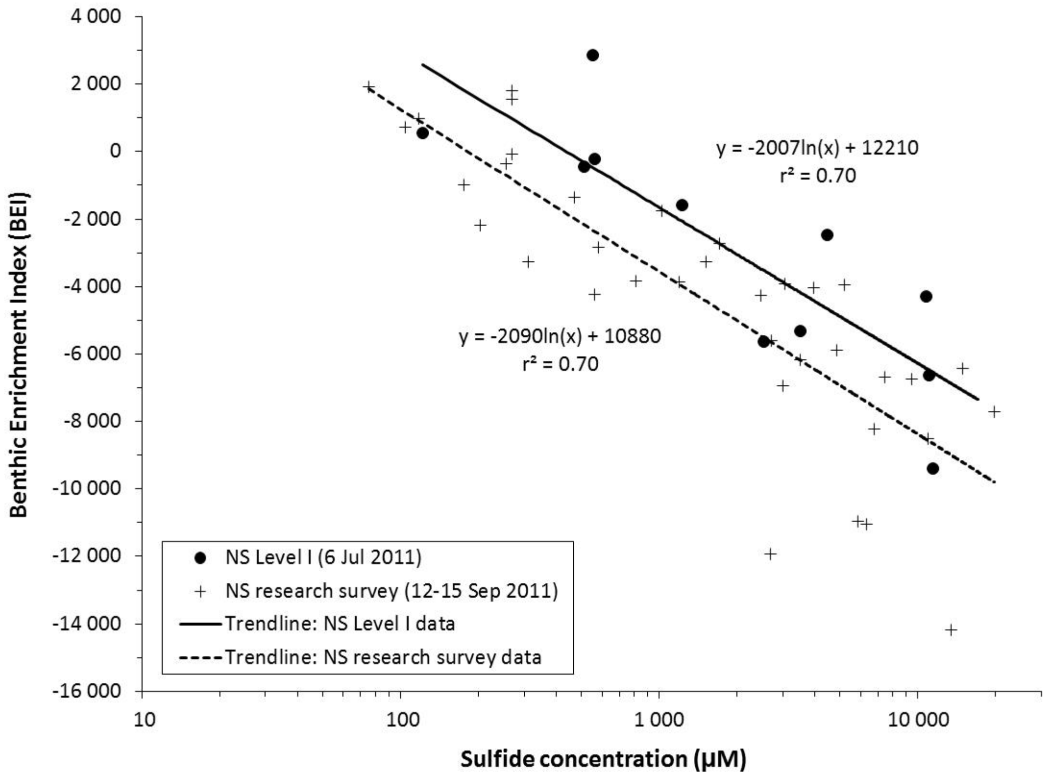


Fig. 13. Relationships between sediment sulfide concentration (log-transformed) and the Benthic Enrichment Index at the Nova Scotia (NS) salmon farm in 2011. Values shown are means of triplicate subsamples per station.

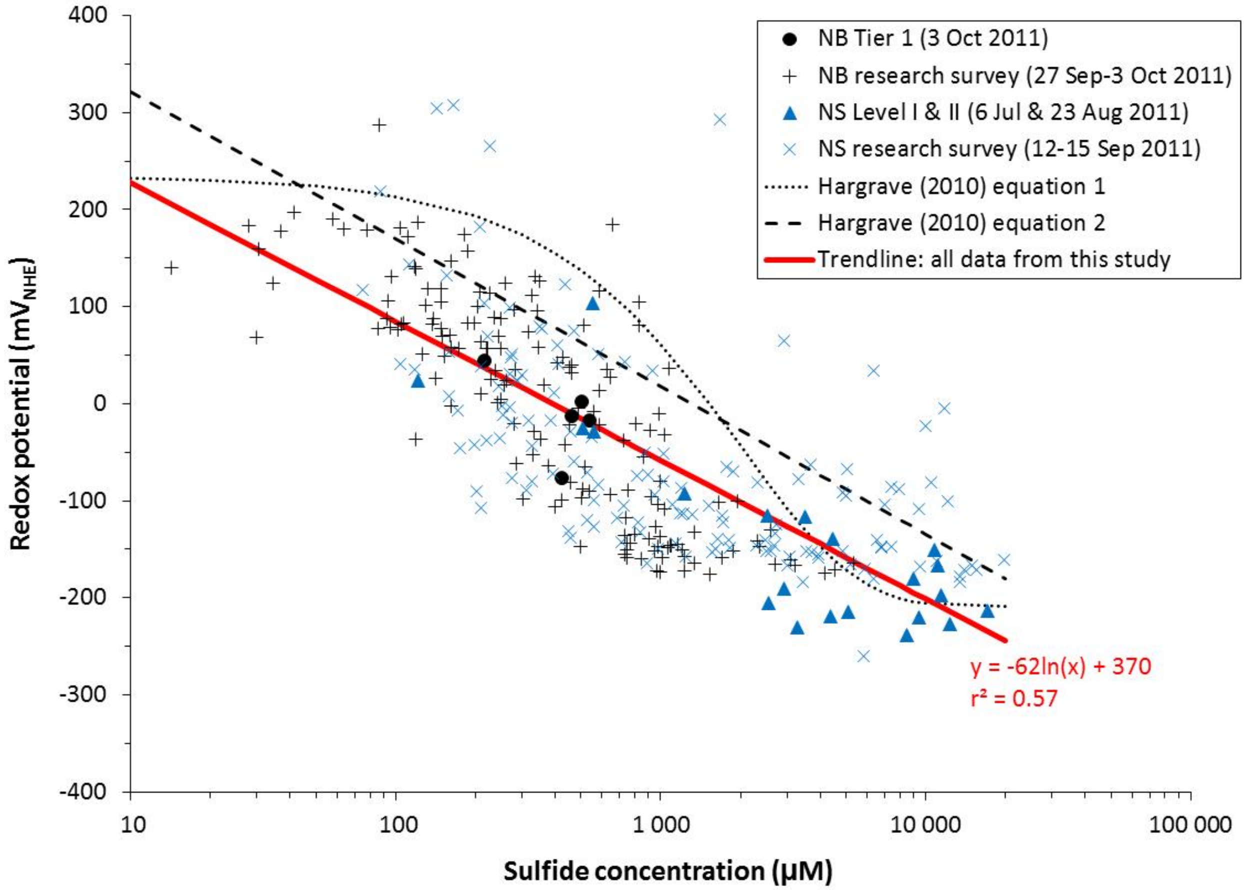


Fig. 14. Relationships between sediment sulfide concentration (log-transformed) and oxidation-reduction (redox) potential at a salmon farm in New Brunswick (NB) and a salmon farm in Nova Scotia (NS) in 2011. Values shown are means of triplicate subsamples per station. The red line is the linear relationship and equation for all data combined. Also shown are lines for relationships between these parameters from Hargrave (2010). The NB research survey data excludes 11 points with sulfide concentrations <10 µM, which is the minimum sensitivity of the electrodes used to measure sulfide concentrations (Hargrave et al. 2008).

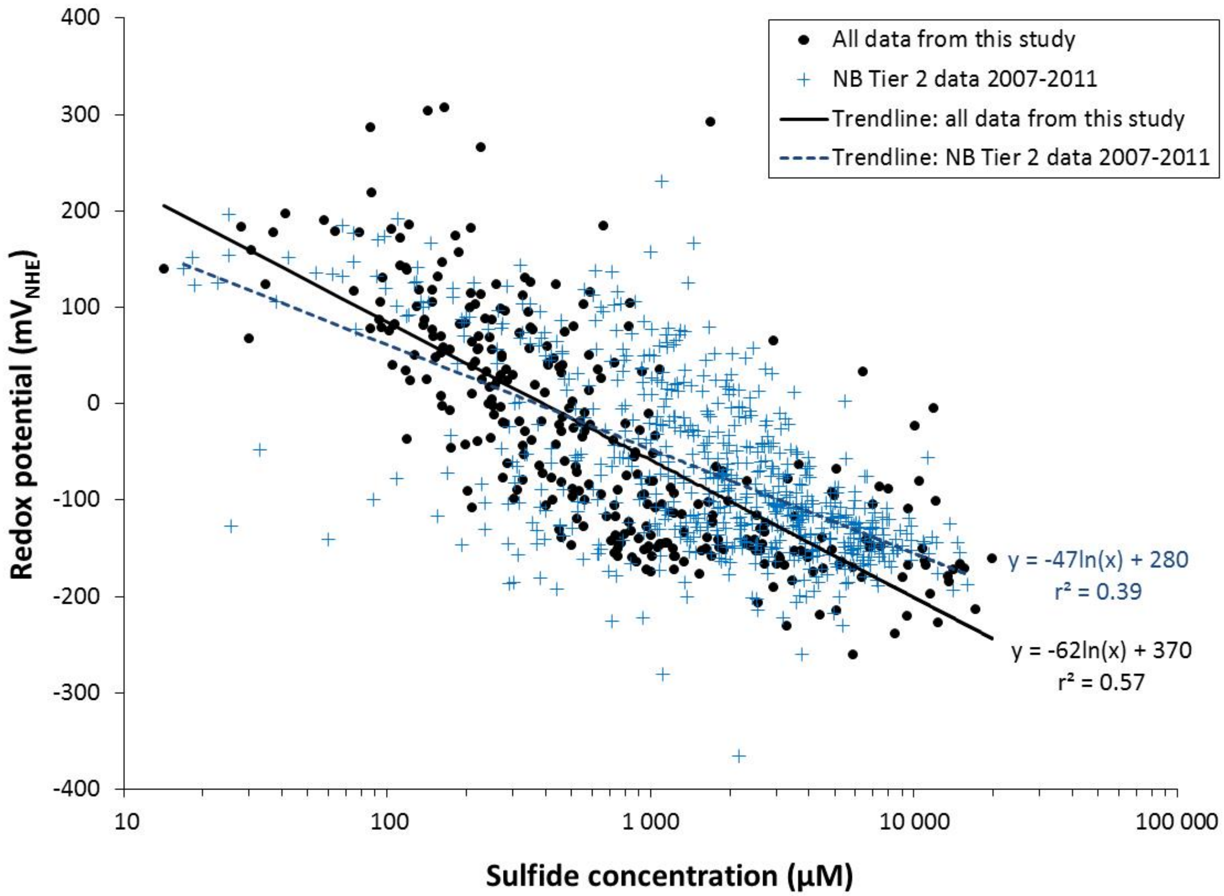


Fig. 15. Relationships between sediment sulfide concentration (log-transformed) and oxidation-reduction (redox) potential in the current study (all station means; see Fig. 14), compared to similar data from New Brunswick (NB) Tier 2 monitoring (all station means from 2007–2011; see Chang et al. 2013).