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Analysis of results from the Environmental Management Program Tier 1 monitoring of salmon farms in southwestern New Brunswick, Bay of Fundy: Relationships between sediment sulfide concentration and selected parameters, 2002–2008

by

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ABSTRACT

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The Environmental Management Program (EMP) for fish farms in the southwestern New Brunswick area of the Bay of Fundy requires monitoring of the sulfide concentration in benthic sediments under all approved farms during 1 August to 31 October each year; this annual monitoring is designated “Tier 1”. Sediment sulfide data from the Tier 1 monitoring were obtained for each farm monitored during 2002–2008. Data were also obtained on several parameters related to the monitoring and farm operations: date of monitoring, farm age, farm lease area, average water depth in the farm lease, average current speed (model prediction) at the farm, year-class of fish on site, number of fish on site, and biomass of fish on site. Data were unavailable for the numbers and biomass of fish at many farms, especially during 2002–2004. There were no significant correlations between the sediment sulfide concentration and the date of Tier 1 monitoring, farm lease area, and average water depth in most years. There were significant correlations between the sediment sulfide concentration and farm age, average current speed, number of fish on site, and biomass of fish on site in most years, but with considerable variation. Further analyses will be performed on the data to examine these relationships. Data on sediment sulfide concentrations at fallowed farms indicated that 82% had Oxic A environmental ratings and 93% were Oxic (A or B); of the 9 farms with poorer ratings, 6 had been fallow for <4 months. A history of the EMP monitoring program is included as an appendix.

RÉSUMÉ

Chang, B.D. and Page, F.H. 2011. Analysis of results from the Environmental Management Program Tier 1 monitoring of salmon farms in southwestern New Brunswick, Bay of Fundy: Relationships between sediment sulfide concentration and selected parameters, 2002–2008. Can. Tech. Rep. Fish. Aquat. Sci. 2936: v + 77 p.

Le Programme de gestion environnementale des fermes piscicoles de la région du sud-ouest du Nouveau-Brunswick de la baie de Fundy exige le contrôle annuel, du 1er août au 31 octobre, de la concentration des sulfures des sédiments sous toutes les fermes approuvées. Ce contrôle annuel est désigné « niveau 1 ». Nous avons obtenu des données sur les concentrations de sulfure des sédiments issues du contrôle de niveau 1 pour chaque ferme contrôlée de 2002 à 2008. Nous avons aussi obtenu des données sur plusieurs paramètres liés au contrôle et à l’exploitation de ces fermes : date du contrôle, âge de la ferme, superficie de la concession piscicole, profondeur moyenne de l’eau dans la concession, vitesse moyenne du courant (prédiction par modèle) à la ferme, classe d’âge des poissons sur les lieux, nombre de poisons sur les lieux et biomasse de poissons sur les lieux. Des données sur le nombre et la biomasse de poissons à de nombreuses fermes n’étaient pas disponibles, en particulier pour la période allant de 2002 à 2004. La plupart des années, il n’y avait aucune corrélation significative entre, d’une part, la concentration de sulfure des sédiments et, d’autre part, la date du contrôle de niveau 1, la superficie de la

concession piscicole et la profondeur moyenne de l’eau. Par contre, la plupart des années, il y avait des corrélations significatives entre, d’une part, la concentration de sulfure des sédiments et, d’autre part, l’âge des fermes, la vitesse moyenne du courant, le nombre de poissons sur les lieux et la biomasse de poissons sur les lieux, mais ces corrélations variaient fortement. Nous effectuerons d’autres analyses des données pour corroborer ces relations. Les données sur les concentrations de sulfure dans les sédiments aux fermes en jachère indiquaient que 82 % d’entre elles avait une classification environnementale de niveau oxique A et 93 %, de niveau oxique (A ou B). Des neuf fermes de niveau de classification faible, six étaient en jachère depuis moins de quatre mois. Un historique du programme de contrôle du Programme de gestion environnementale est joint en annexe.

INTRODUCTION

The salmon farming industry in southwestern New Brunswick (SWNB) started in 1978. In 2009, there were more than 90 licensed finfish farms in the coastal waters of the SWNB area of the Bay of Fundy (Fig. 1), of which 60% were actively farming Atlantic salmon (*Salmo salar*) during at least part of the year. Salmon farms operating in 2009 were stocked with 60 000–700 000 fish per farm (average about 360 000). The total salmon production in SWNB in 2009 was 24 000 t (Statistics Canada 2010). There is also limited production of other fish species in SWNB: about 100 t of cod, halibut, and sturgeon were produced in 2009 (NBDAAF 2010). A few SWNB salmon farms are practicing integrated multi-trophic aquaculture (IMTA), growing mussels and kelp at salmon farms (Reid et al. 2011).

Salmon smolts are produced in freshwater hatcheries, and are transferred to marine farm sites at weights of 60–120 g (average about 85 g). Marine growout times in SWNB typically range from 20–30 months (average 24 months), with harvest sizes of 3.5–5.5 kg (average 4.5 kg). At the marine sites, farmed salmon are grown to market size in net cages suspended from floating collars. The most commonly used cages have circular plastic collars, 70–100 m in circumference (22–32 m diameter), with nets 8–12 m deep, holding 15 000–35 000 fish per cage. Cages are usually arranged in arrays of 1–3 rows, with about 10–20 m of water separating adjacent cages. In the early years of the SWNB industry, most farms held two or more year-classes on site at the same time. Starting in 2000, all farms were required to become single-year-class operations, based on a 2-year rotation cycle (NBDAFA 2000). This meant that farms could introduce new smolts every other year: farms were designated for stocking in either odd or even years. However, there was a provision to allow a limited holding over of market fish (up to 20% of the allowable production level) until September (of the second year), thus allowing a limited overlap between consecutive year-classes; approval of holdovers was subject to a review of fish health considerations. Also starting in 2000–2001, the industry was geographically organized within a framework of 22 Aquaculture Bay Management Areas (ABMAs; see Fig. 2). In most ABMAs, all farms in the same ABMA were required to stock in the same year (either odd or even years). Since 2006, farms have been required to operate on a 3-year rotation cycle, with mandatory fallowing of at least 4 months between successive year-classes. At the same time, a new ABMA framework was introduced, with far fewer ABMAs (Fig. 1). All farms in the same ABMA must stock in the same year (during the first year of the 3-year cycle). Also, all farms in the same ABMA must be fallowed for at least 2 simultaneous months prior to restocking any of the farms.

The first industry-wide environmental monitoring of SWNB marine fish farms was conducted in 1991. Since then, the SWNB monitoring program has evolved in response to research and monitoring results, as well as to changes in farm sizes, farm layouts, and cage technology. A history of environmental monitoring of marine finfish farms in SWNB is provided in the Appendix.

The current Environmental Management Program (EMP) for marine fish farms in SWNB is administered by the New Brunswick Department of Environment (NBDENV). The overall goal of the program is “to guide the long-term environmental sustainability of the marine finfish cage aquaculture industry in New Brunswick” and the primary purpose is “to accurately evaluate the condition of the marine sediments under the marine finfish cage aquaculture sites and provide a reliable indicator of compliance with the MEQO [Marine Environmental Quality Objective]" (NBDENV 2006). The MEQO with regard to organic enrichment of sediments under marine finfish aquaculture sites is Oxic conditions. From 2002−2005, the environmental indicators for achieving the MEQO were sediment redox (reduction-oxidation) potential (Eh, measured using a platinum electrode) and sulfide concentration (total S^{2-}, measured using a silver/sulfide electrode). Since 2006, sediment sulfide concentration alone has been used to determine environmental ratings of aquaculture sites (see Appendix). The use of sediment sulfide concentration as the indicator of benthic environmental quality in SWNB is based on the work of Hargrave et al. (1995, 1997) and Wildish et al. (1999, 2001a).

The EMP requires that each operating farm, and those fallowed but with current Approvals from NBDENV, conduct Tier 1 monitoring between 1 August and 31 October each year (see NBDENV 2007 and the Appendix for details). Samples are taken at selected cages at each farm. The number of cages sampled per farm depends on the number of fish present at the farm, with two cages sampled at farms holding 200 000 fish or less, plus an additional cage sampled for every 100 000 fish (or part thereof) above 200 000 fish. The cages to be sampled are selected based on water current patterns, fish biomass (higher biomass cages are given priority), and the direction of the shoreline; only cages located along the perimeter of the cage array are sampled.

Salmon farms in SWNB are located in relatively shallow, nearshore waters. Average depths within farm leases range from 6–40 m below normal lowest tide (average 14 m). Most farms are located over soft substrate, where sediment samples can usually be readily collected; however, some farms are located over rocky/cobble substrates where the collection of sediment samples may be difficult. The Tier 1 monitoring protocols introduced in 2006 require that at farms where the depth at the lease centre is <30.5 m (below mean low tide), three diver-deployed cores (approx. 30 cm long × 5 cm diameter) are collected in close proximity (usually within 1 m^2) under the outside edge of each sampled cage. Sediment sulfide concentrations are measured in 5-ml subsamples taken from the top 2 cm of each core (one subsample per core), for a total of three measurements per sampled cage. At deeper farms (>30.5 m depth), one surface-deployed grab is collected at the outer edge of each sampled cage. Sediment sulfide concentrations are measured in three 5-ml subsamples taken from the top 2 cm of each grab, for a total of three measurements per sampled cage. For approved farms holding no fish at the time of Tier 1 monitoring, two locations are to be sampled (total of 6 sediment samples), using locations from the most recent monitoring. Sampling protocols were slightly different prior to 2006. During 2002−2005, at farms <30.5 m depth, three cores were collected by diver at each selected cage, along a transect line extending from the outer cage edge toward the cage centre. At deeper farms, four replicate grab samples were collected at five locations: one at the centre of the cage array and one at each corner of the cage array (see Appendix for details).

Regulatory environmental ratings are assigned to each farm based on the average of all sediment sulfide measurements taken at each farm in the Tier 1 monitoring. The environmental ratings are thus based entirely on samples taken in the immediate vicinity of cages with higher biomasses (although not necessarily the highest biomasses, because only perimeter cages were sampled), which means that the ratings should represent areas of high intensity impacts at each farm, rather than the average conditions within the farm lease. This also means that the Tier 1 monitoring is designed to examine only localized (near-field) effects. A farm's environmental rating is determined according to the site classifications shown in Table 1. The environmental ratings do not involve comparisons to background or reference station levels. Data collected in SWNB away from operating farms and other pollution sources in 1994 (Hargrave et al. 1995, 1997), and data collected since 2000 at most new finfish farms prior to the start of operations, indicate that reference or background sediment sulfide concentrations in SWNB are generally <300 µM (Oxic A).

The EMP has required annual Tier 1 monitoring of sediment sulfide concentrations at all operating farms in SWNB since 2002. The purpose of this study was to look for relationships between the Tier 1 sediment sulfide concentrations and various parameters for which data could be obtained for most farms. The parameters selected were as follows:

- Tier 1 monitoring date
- Farm age
- Farm lease area
- Average water depth (within lease)
- Average predicted current speed
- Year-class of fish on site at the time of sediment monitoring
- Number of fish on site at the time of sediment monitoring
- Biomass of fish on site at the time of sediment monitoring

METHODS

Results from the Tier 1 monitoring from 2002–2008 were obtained from NBDENV. The monitoring data included the sediment sulfide concentration (total sulfides, S^{2-}, in µM) in individual samples and farm averages, and the date of monitoring. The date of monitoring in each year was converted to Julian date; the window for Tier 1 monitoring, 1 August to 31 October, converts to Julian days 213–304 (except 214–305 in leap years 2004 and 2008). Data were also obtained on the following farm parameters: farm age, lease area, average water depth within the lease, average predicted current speed at the site, and the year-class(es), number, and biomass of salmon on site at the time of Tier 1 monitoring. Farm age was estimated as the number of years between the current year and the farm's first year of operation (i.e., zero indicates monitoring during a farm's first year of operation), whether or not the farm was operating during the entire period. Lease areas were obtained from site boundary surveys. Water depths (relative to the normal lowest tide) were obtained from Canadian Hydrographic Service field sheets; the water depth at a farm was estimated as the arithmetic mean of all depth readings taken within a farm's lease boundaries.

The best measure of water current speeds at farms would have been data from current meter deployments; however, current meter data were not available at most of the farms in SWNB. Therefore to estimate current speeds at all farms, we used a three-dimensional, finite element particle tracking model (Greenberg et al. 2005) that was customized for the SWNB area. The model was run using boundary forcing by the principal lunar semidiurnal tidal constituent (M_2) alone. The model produced estimates of the initial speeds of 36 particles which were released from locations evenly spaced within a 200 × 200 m grid located near the centre of each farm. The model particles were released and maintained at a depth of 1 m below the water surface.

Particle releases were repeated twelve times, at hourly intervals, in order to represent releases throughout one tidal cycle (12.4 h), for a total of 432 particles released from each farm (except slightly fewer at some farms which had lease areas too small to contain a 200 × 200 m grid). The average current speed at a farm was calculated as the arithmetic mean of the initial speeds of all 432 particles released from that farm.

Data on the year-class(es), number of fish, and biomass of fish on site at the time of Tier 1 monitoring were found in the Tier 1 monitoring reports or in production plans submitted by the farms to NBDENV, or were obtained from the farm operators. The data on the numbers and biomass of fish were estimates made by the farm operators for the date of monitoring or, in a few cases, were interpolations we made from data for dates within one year before and after the monitoring date.

Relationships among pairs of farm parameters, and between selected parameters and sediment sulfide concentrations, were examined. Spearman’s rank correlation coefficients (McDonald 2009) were calculated (α=0.05) where there were more than five data pairs. Comparisons of sediment sulfide concentrations among year-class categories were made using Kruskal-Wallis tests (α=0.05; McDonald 2009).

There were 130 cases during 2002–2008 of Tier 1 monitoring at fallowed farms (farms having no fish on site at the time of monitoring). In 120 of these cases, estimates of the length of the fallow time (in months) between harvesting and monitoring were obtained from farm production plans. In these cases, we examined the relationship between the length of the fallow period and the sediment sulfide concentration.

RESULTS

NUMBER OF FARMS CONDUCTING TIER 1 MONITORING

The number of licensed fish farms in SWNB increased from 91–95 during 2002–2008 (Table 2). However, the number of salmon farms conducting Tier 1 monitoring declined from 91 in 2003 to 63 in 2008. Licensed farms that were not monitored were not actively farming. Most of the monitored farms had farmed salmon on site at the time of monitoring – either smolts (fish transferred from hatcheries in the same year as the monitoring) or pre-markets (fish transferred from hatcheries in the previous year or earlier) – although several farms in each year had no fish on site at the time of monitoring (i.e., they had harvested all fish and had not yet restocked with smolts). Analyses were conducted only on farms approved for growing salmon: most of these farms grew only salmon, but we also included a few farms that were growing primarily salmon, but also had some non-salmon finfish species on site (1–3 farms per year during 2002–2007), and up to five farms per year practicing IMTA. Not included in our analyses were farms that were licensed exclusively for non-salmon species; the number of such farms grew from 1–10 during 2002–2008 (Table 2), although not all of these were active.

AVAILABILITY OF DATA ON SELECTED PARAMETERS

Data on sediment sulfide concentration, date of Tier 1 monitoring, farm age, farm lease area, average water depth, predicted current speed, and year-class(es) of salmon on site were obtained for almost all monitored farms in each year (Table 2). Tier 1 monitoring at a few farms occurred after 31 October: two farms in 2006, three farms in 2007, and one farm in 2008 were monitored in early November. These late monitoring events were probably due to weather-related delays. During 2002–2008, most salmon farms in SWNB held only one year-class of fish at the time of Tier 1 monitoring: either smolts (transferred to marine cages in the same year as monitoring) or older fish (pre-markets; transferred to cages in the year prior to monitoring, or earlier). Only a few farms held both smolts and older year-classes at the time of Tier 1 monitoring: three farms in 2002; two in 2003, 2004, and 2006; one in 2005 and 2007; and none in 2008. Estimates of the number of salmon present at the time of Tier 1 monitoring were available for 89–94% of farms for 2005–2008, but for only 22–51% in 2002–2004 (Table 2). Estimates of the biomass of salmon present at the time of Tier 1 monitoring were available for 77–89% of farms in 2005–2008, but for only 18–44% in 2002–2004 (Table 2).

SEDIMENT SULFIDE CONCENTRATION (TIER 1 MONITORING)

Table 3 shows the average sediment sulfide concentration per farm per year, from the Tier 1 monitoring database. The majority of farms in each year achieved Oxic ratings based on the classifications in Table 1: the percentage of farms receiving Oxic A ratings ranged from 33–81%, and the percentage receiving Oxic (A or B) ratings ranged from 58–88% (Fig. 2). The percentage of farms receiving Hypoxic ratings in each year ranged from 10–38%. Very few farms (0–4% in any year) received Anoxic ratings. The percentage of farms receiving non-Oxic (i.e. Hypoxic or Anoxic) ratings fell from 29–42% in 2002–2005, to 12–24% in 2006–2008.

The geographic distribution of the environmental ratings for salmon farms monitored during 2002–2008 is shown in Fig. 3 and 4. Oxic ratings were the majority in most areas in most years, except as noted below.

Environmental ratings within the current ABMA 1 varied within subareas. In northern Passamaquoddy Bay, Hypoxic ratings dominated in all years, except in 2008, when Oxic ratings dominated; in 2008, all of the farms in this subarea were empty at the time of Tier 1 monitoring. Anoxic ratings were found at one farm in northern Passamaquoddy Bay in each of the years 2002, 2006, and 2007 (although it was a different farm in each year). In southern Passamaquoddy Bay, ratings were mostly Oxic in all years. Along the northeastern shore of Deer Island and in the northern part of Campobello Island, Hypoxic or Anoxic ratings were common, but other parts of Deer and Campobello Islands had mostly Oxic ratings.

In the Letang area (current ABMA 2a), Hypoxic ratings predominated during 2002–2004. Ratings were mostly Oxic in 2005, when half of the farms were empty at the time of monitoring. There was a mix of Oxic, Hypoxic, and Anoxic ratings in 2006; mostly Oxic ratings in 2007; and a mix of Hypoxic and Oxic ratings in 2008.

In the eastern mainland area (current ABMA 3a), ratings were mostly Oxic, except at two farms in Beaver Harbour, at the western extreme of this area, where Hypoxic ratings occurred in five of the seven years.

In the eastern Grand Manan Island area (current ABMA 2b), ratings were mostly Oxic, except in 2005, when there was one Anoxic rating and several Hypoxic ratings, and in 2008, when there were several Hypoxic ratings. Most of the Hypoxic ratings and the one Anoxic rating were in the northern part of ABMA 2b. In the southern Grand Manan Island area (current ABMA 3b), ratings were mostly Oxic, with a few Hypoxic A ratings.

GEOGRAPHIC DISTRIBUTION OF SELECTED FARM PARAMETERS

The geographic distributions of selected parameters at approved farms (as of 2008) are shown in Fig. 5.

Farm age

The oldest farms (>20 years) were mostly in ABMA 2a and the southern part of ABMA 1. The youngest farms (<5 years) were in ABMA 3a and the northern part of ABMA 1.

Farm lease area

The largest farms (>30 ha) were found in ABMAs 3a, 3b, and the northern part of 1. The smallest farms (<10 ha) were in ABMAs 2a, 3b, and the southern part of 1.

Average water depth

The deepest farms (>30 m depth) were in ABMA 3a and the northern part of ABMA 1. Farms were found in shallow waters (<10 m depth) in all ABMAs.

Average predicted current speed

Low average predicted current speeds (<10 cm s^{-1}) were found in all ABMAs. The highest average predicted speeds were found in the southern Deer Island area (in the southern part of ABMA 1).

Number of salmon stocked

The farms that stocked the smallest numbers of salmon smolts (<200 000 fish) were mostly in ABMAs 1 and 2a. Farms stocking >500 000 fish were found in all ABMAs (except 4–6).

CORRELATIONS AMONG SELECTED FARM PARAMETERS

Significant correlations were observed among some pairs of farm parameters, but with considerable variation in most cases (Table 4, Fig. 6). The strongest relationship was the positive correlation between the number of salmon stocked and the farm lease area. There were also significant positive correlations between the number of salmon stocked and the average water depth, and between the farm lease area and the average water depth. There were significant negative correlations between the number of salmon stocked and the farm age, between the farm lease area and the farm age, and between the average water depth and the farm age. Correlations between the average predicted current speed and each of the other parameters were not significant (Table 4, Fig. 6).

Correlations between the number and biomass of salmon smolts on site at the time of Tier 1 monitoring were not significant ($p \geq 0.08$) in 2003, 2005, 2006, and 2007; however, significant correlations were found in 2004 and 2008 ($p < 0.05$; Table 5, Fig. 7). Correlations between the number and biomass of pre-market salmon on site at the time of Tier 1 monitoring were significant in all years during 2004–2008 ($p \leq 0.02$; Table 5, Fig. 7).

CORRELATIONS BETWEEN SELECTED PARAMETERS AND THE SEDIMENT SULFIDE CONCENTRATION

Date of monitoring

There were no significant correlations between the date of Tier 1 monitoring and the sediment sulfide concentration in any of the years during 2002–2008 (Table 6, Fig. 8).

Farm age

There were significant positive correlations between the farm age and the sediment sulfide concentration in all years, except 2008 (Table 6, Fig. 9). The relationships were strongest at farms ≤15 years old; many farms >20 years old had relatively low sediment sulfide concentrations. Farms <5 years old generally had low sediment sulfide concentrations, mostly in the Oxic rating (<1 500 µM). There was one farm which had a high sediment sulfide concentration (>4 000 µM) in 2008, although it was only one year old and had no fish on site at the time of monitoring; this farm had been stocked in the fall of 2007 with pre-market salmon (2006 year-class) transferred from another farm, and was harvested about one month prior to the 2008 monitoring.

Farm lease area

Significant correlations between the farm lease area and the sediment sulfide concentration were observed in only two years, 2002 and 2008; both of these were negative correlations (Table 6, Fig. 10).

Average water depth

There were no significant correlations between the average water depth and the sediment sulfide concentration, except in 2006 (Table 6, Fig. 11). The highest sediment sulfide concentrations occurred at shallower farms (≤15 m depth), but many shallow farms had low sediment sulfide concentrations, while most farms located in deeper waters (>20 m depth) had Oxic ratings (<1 500 µM S^{2-}).

Average predicted current speed

Significant negative correlations between the average predicted current speed and the sediment sulfide concentration were observed in all years (Table 6, Fig. 12). Farms with average predicted current speeds >20 cm s^{-1} had Oxic (<1 500 µM S^{2-}) ratings. The highest sediment sulfide concentrations were found at farms with low average current speeds (<10 cm s^{-1}), but many farms with low average current speeds had low sediment sulfide concentrations.

Year-class of salmon on site

There were significant differences in sediment sulfide concentrations between farms holding no fish, farms holding smolts, and farms holding pre-market fish at the time of Tier 1 monitoring, in every year from 2002–2008 (Kruskal-Wallis tests, $p<0.01$ in each year). Oxic sediment sulfide concentrations were common in all three year-class categories, but higher sulfide concentrations were more common at farms holding salmon, with the highest concentrations at farms holding pre-market fish (Fig. 13). However, there were a few instances of relatively high sulfide concentrations at farms holding no salmon. There were not enough multi-year-class farms in the database to show clear trends at such farms.

Number of salmon on site

There were significant positive correlations between the number of salmon on site at the time of Tier 1 monitoring and the sediment sulfide concentration in each year during 2005–2008, but not during 2002–2004 (Table 6, Fig. 14). As noted in Table 2, data on the number of salmon on site at the time of monitoring were obtained for ≥89% of farms during 2005–2008, but for ≤51% of farms in 2002–2004. The relationships were strongest at farms holding small to intermediate numbers of salmon. Farms holding no salmon at the time monitoring usually had low sediment sulfide concentrations, but there were some exceptions. Farms holding the largest numbers of salmon had relatively low sediment sulfide concentrations.

Biomass of salmon on site

There were significant positive correlations between the biomass of salmon on site at the time of Tier 1 monitoring and the sediment sulfide concentration in all years during 2004–2008, but not in 2002 and 2003 (Table 6, Fig. 15). As noted in Table 2, data on the biomass of salmon on site at the time of monitoring were obtained for ≥77% farms during 2005–2008, but for ≤44% of farms in 2002–2004. The relationships were strongest at farms holding small to intermediate biomasses of salmon. Farms holding zero biomass of salmon usually had low sediment sulfide concentrations, but a few farms holding zero biomass of salmon had relatively high sediment sulfide concentrations. Farms holding the highest biomasses of salmon had relatively low sediment sulfide concentrations.

SEDIMENT SULFIDE CONCENTRATION AT FALLOWED FARMS IN RELATION TO THE LENGTH OF THE FALLOW PERIOD

There were 130 cases of Tier 1 monitoring at fallowed farms (i.e., farms holding no salmon at the time of monitoring) during 2002–2008. These 130 cases represented 79 farms (36 farms were monitored more than once while fallowed during these years). Estimates of the length of the fallow period (number of months between harvesting and monitoring) were available for 120 of these cases (Table 7, Fig. 16). All but 24 of the 130 fallowed cases had Oxic A ratings (<750 µM S^{2-}). Of these 24 cases, 23 had estimates of the length of the fallow period. Of these 23 cases, 14 had been fallowed <4 months, 8 had been fallowed 4–12 months, and one had been fallowed 21 months (Table 8, Fig. 16).

DISCUSSION

The annual monitoring program for SWNB salmon farms uses sediment sulfide concentration as the indicator of benthic impacts. Other studies have shown that macrofaunal diversity shows a general decline with increasing sediment sulfide concentrations (Brooks and Mahnken 2003; Hargrave et al. 2008; Hargrave 2010), including some research done at salmon farms in SWNB (Wildish et al. 2001a; Chang et al. 2011a). In our study we looked for relationships between the sediment sulfide concentration under salmon farms and various parameters related to the annual monitoring and farm operations in SWNB. We were able to obtain data on several monitoring and farm parameters for more than three-quarters of approved salmon farms during 2005–2008, but data for some parameters were unavailable at many farms in earlier years.

Research conducted in other parts of the world has also examined the relationships between indicators of organic enrichment at salmon farms with various parameters associated with farms and monitoring programs. At Scottish salmon farms, Mayor et al. (2010) found that the abundance of benthic macrofauna and the sediment organic carbon concentration were influenced by a significant, but weak, interaction between farm size (maximum permitted biomass) and current speed. In addition, the concentration of total organic matter in the sediment was influenced by an interaction between distance from the cage and water depth. However, the authors noted that the production and fate of organic waste at fish farms is complex: in isolation, current speed, water depth, and farm size were not necessarily good predictors of benthic impacts. In Norway, Carroll et al. (2003) found that environmental classification (based on sediment organic carbon concentration) was not significantly correlated with water depth, farm age, feeding levels, or average current speed; however, the implementation of fallowing did have a significant effect. Lumb (1989) found relationships between seabed type, water depth, the amount of water movement, and the intensity of organic enrichment at Scottish salmon farms. Models such as DEPOMOD (Cromey et al. 2002) predict that organic matter deposition rates will increase with increasing feeding rates and decreasing water currents and depths.

In our study, we found significant positive correlations between the number of salmon on site (at the time of monitoring) and the sediment sulfide concentration, and between the biomass of salmon on site and the sediment sulfide concentration; however, there was considerable variation in these relationships. The correlations between sediment sulfide concentration and the numbers/biomass of salmon appeared to be strongest when the numbers/biomass were at low to intermediate levels; the relationships appeared to disappear at higher numbers/biomass, and sediment sulfide concentrations were quite low at the farms with the highest numbers/biomass (Fig. 14 and 15). Similar findings were reported at salmon farms in British Columbia (Brooks 2001; Brooks and Mahnken 2003), where it was found that sediment sulfide concentrations increased during early stages of farm production, when biomass and feeding rates were low, but that benthic effects did not increase linearly with increasing production. A strong relationship between biomass of fish on site and sediment sulfide concentration might be expected if farms with higher biomasses were stocked at higher densities. However, in SWNB farms generally stock fish at similar densities, regardless of farm size. Farms holding more fish generally have more cages, spread over a larger area, compared to farms holding fewer fish; hence the positive relationship that was observed between the number of fish stocked and the lease area. As a result, the waste deposition at farms holding higher numbers of salmon will be spread over a larger area, but not necessarily result in an increase in the intensity of impact at the most highly impacted locations (unless there are overlaps of the zones of impacts of adjacent cages). This may explain the lack of a stronger relationship between biomass and sediment sulfide concentration: the Tier 1 monitoring only measures the intensity of impact, not the area of impact. Nevertheless, the presence of significant (albeit weak) correlations between fish numbers/biomass and sediment sulfide concentrations indicates that reducing the fish numbers/biomass may help to reduce sediment sulfide concentrations at highly impacted farms. The best predictor of benthic impacts would likely be the actual amount of waste (feces and uneaten feed) that reaches the seafloor in the vicinity of fish farms and remains there. The amounts of feces and uneaten feed produced are related to feeding practices (Islam 2005; Mente et al. 2006), including the type of feed, the method and frequency of feeding, and the feed conversion ratio, but such data were not available for most farms in our study.

We found significant negative correlations between the average predicted current speed and the sediment sulfide concentration in all years. In an earlier study at some Scottish and Irish salmon farms, Black et al. (1996) found a negative correlation between average current speed and hydrogen sulfide concentration in the water immediately above the seafloor beneath salmon farms. Lumb (1989) also reported a relationship between the amount of water movement and organic enrichment at Scottish salmon farms, while Carroll et al. (2003) found that current speed was not significantly correlated with sediment environmental classification at Norwegian salmon farms.

We found significant positive correlations between the farm age and the sediment sulfide concentration in most years, although the relationship did not appear to apply to older farms (>20 years of age). In Norway, Carroll et al. (2003) found that farm age was not significantly correlated with sediment environmental classification.

The date of Tier 1 monitoring (within the August–October monitoring period) was not significantly correlated with the Tier 1 monitoring sediment sulfide concentration in any year (Table 6, Fig. 8). However, in another study in SWNB (Page et al. 2011), sediment sulfide concentrations showed a general increase during September–October at two farms holding fish that had been stocked the previous fall (fish biomass and feeding rates increased during the sampling period); while in the following year, the sediment sulfide concentration decreased during August–October while harvesting was occurring (fish biomass and feeding rates decreased during the sampling period). Tier 1 monitoring included farms where biomass and feeding rates were increasing during August–October, as well as farms where harvesting was occurring during this period and, hence, biomass and feeding rates were decreasing.

There was no significant correlation between the farm lease area and the sediment sulfide concentration in most years (Table 6, Fig. 10). Although farms that were larger in lease area generally stocked more fish, the fish were usually distributed among more cages over a larger area, thus spreading out the waste, rather than intensifying the waste deposition at the most impacted locations which are sampled in the Tier 1 monitoring. There was also no significant correlation between the average water depth and the sediment sulfide concentrations in most years (Table 6, Fig. 11). However, deeper farms usually had low sediment sulfide concentrations, as might be expected, since at deeper sites, the wastes take longer to reach the seafloor, and therefore will be more widely dispersed by currents. At shallow farms, wastes will not be as widely dispersed, and greater impacts might be expected; however, this may be countered by the fact that the farms stocking the fewest number of fish were located in shallow waters.

There were geographic variations in the distribution of environmental ratings (Fig. 3, 4). Anoxic and Hypoxic ratings were most commonly observed in northern Passamaquoddy Bay and northern Campobello Island (in ABMA 1), where predicted average current speeds are low, and in the Letang area (ABMA 2a), which is dominated by older farms, with relatively low current speeds. Several Hypoxic ratings, and one Anoxic rating were also observed in eastern Grand Manan Island (ABMA 2b), where current speeds and water depths are low. In the Maces Bay area (ABMA 3a), environmental ratings were mostly Oxic; most farms in this area were newer, larger (in farm lease area and number of smolts stocked), in relatively deep waters, with moderate current speeds. However, the two farms in Beaver Harbour (at the western extreme of ABMA 3a) frequently had Hypoxic ratings; these two farms were older, in shallow waters, with very low current speeds.

An interannual trend in environmental ratings was observed: fewer farms have received Hypoxic and Anoxic ratings since 2006. One probable reason for the improvement in environmental ratings was the implementation of a Performance Based Standards (PBS) approach to the regulation of marine environmental quality in 2006 (NBDENV 2006). Under the PBS approach, strong justification must be provided to maintain or increase the numbers of fish stocked at farms with Hypoxic B ratings or worse, and if environmental impacts increase, progressively more rigorous mitigation and remediation measures are required.

Another probable factor the interannual trend was the introduction of the new ABMA framework in 2006. Farms operating within the new ABMA framework must be fallowed at least 4 months between successive year-classes. This fallow period should allow benthic conditions to recover (at least partially), before the next year-class is introduced. As noted above, Carroll et al. (2003) found that implementation of fallowing had a significant effect on sediment environmental classification at Norwegian salmon farms. In our study, most fallowed farms received an Oxic A rating if monitored >4 months after harvesting, although elevated sediment sulfide concentrations (Hypoxic B) occurred at two fallowed farms 7–8 months after harvesting, and slightly elevated sediment sulfide concentrations (Oxic B) were found at one fallowed farm 21 months after harvesting. Other studies have indicated that chemical remediation of sediments at salmon farms often occurs within 6 months or less after harvesting (Brooks 2001 and Brooks et al. 2003, in British Columbia; MacLeod et al. 2004, 2006, in Tasmania), but that at heavily impacted farms, Anoxic sediments can persist for one year or more after fish have been removed (Lumb 1989, in Scotland; Wildish et al. 2001b, in SWNB; Brooks et al. 2004, in British Columbia). These studies also indicate that biological recovery of sediments under salmon farms requires considerably more time than chemical recovery.

Changes in husbandry practices at farms may be another factor in the apparent improvement in environmental ratings at SWNB salmon farms. In the past, net cleaning was often conducted on site, resulting in the deposition of biofouling material on the seafloor. The EMP version 2.0 (NBDENV 2006) recommends that nets be taken on shore for cleaning; only lightly fouled nets can be cleaned on site. There have also been developments in salmon feeds and feeding practices, which have led to improvements in the feed conversion efficiency (Tacon 2005), which should mean lower feed wastage rates. On the other hand, the trend toward increasing the numbers (and biomass) of fish on farms could increase the risk of causing higher impacts.

An underlying concern in our analyses is the accuracy of the data. There are uncertainties related to the data collected by the Tier 1 monitoring program; specifically, how accurately does the sediment sulfide data reflect actual conditions under farms, especially given the small number of sample locations per farm (as few as two) and the sometimes wide variation in sediment sulfide concentrations among subsamples taken from the same sample location (see also Chang et al. 2011a). As indicated previously, the Tier 1 monitoring does not measure the overall impact on the seafloor in the vicinity of farms; rather, it measures the intensity of impact at the locations where high impacts would be expected (i.e., at cages holding higher biomasses of fish). There are also probable errors in the data for some of the parameters examined. The numbers and biomass of fish on site at the time of monitoring are based on estimates provided by the farm operators; hence the accuracy of these estimates can vary depending on the methods used by different farms to derive these estimates. The current speeds used were based on a model, since actual current data were not available for most of the monitored farms. Furthermore, the model was run using only the principal tidal constituent (M_2); it did not include other tidal components or winds, although the M_2 is the dominant tidal constituent in SWNB.

As in the Mayor et al. (2010) study, we can conclude that the sediment conditions under salmon farms in SWNB are a result of a complex interaction among several factors, and no one parameter can be used as a predictor of benthic conditions. However, our results indicate that older farms, with low current speeds and high numbers/biomass of fish have an increased risk of causing high sediment sulfide concentrations and receiving poor environmental ratings. On the other hand, the date of monitoring (within the August-October monitoring window), the farm lease area, and the water depth did not significantly influence the sediment sulfide concentration in most years. Further data analyses will be conducted to examine the relationships (or lack thereof) between the various parameters and the sediment sulfide concentration.

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Table 1. Environmental ratings in use since 2006 in the New Brunswick Department of Environment's Environmental Management Program for finfish farms in southwestern New Brunswick (NBDENV 2006a). Ratings are based on the average sediment sulfide concentration (total S^{2-}) of all samples collected at each farm during Tier 1 monitoring.

Environmental rating	Sediment sulfide (total S^{2-}) (µM)	Effects on marine sediments
Oxic A	<750	Low effects
Oxic B	750–1 500	Low effects
Hypoxic A	1 500–3 000	May be causing adverse effects
Hypoxic B	3 000–4 500	Likely causing adverse effects
Hypoxic C	4 500–6 000	Causing adverse effects
Anoxic	>6 000	Causing severe damage

Table 2. Summary of data obtained at salmon farms in SWNB, 2002–2008: Tier 1 monitoring results and other parameters. The number of licensed salmon farms includes some farms that were licensed for both salmon and non-salmon species; the number of licensed non-salmon farms includes farms growing only non-salmon species.

	2002	2003	2004	2005	2006	2007	2008
Number of licensed finfish farms	91	94	94	94	94	94	95
Number of licensed salmon farms	90	92	91	91	88	87	85
Number of monitored salmon farms	90	91	87	73	71	69	63
Number of licensed non-salmon farms	1	2	3	3	7	7	10
Number of monitored non-salmon farms	1	2	3	3	6	5	6
<u>Data obtained: % of Tier 1 monitored salmon farms</u>							
Tier 1 sediment sulfide concentration	100	100	100	100	100	100	100
Date of Tier 1 monitoring	100	100	93	97	99	97	100
Farm age	100	100	100	100	100	100	100
Farm lease area	99	99	99	99	99	99	100
Average water depth in lease area	99	99	99	99	99	99	100
Average predicted current speed	99	99	99	99	99	99	100
Year-class of salmon at monitoring date	100	100	100	100	100	100	100
Number of salmon at monitoring date	22	36	51	89	93	94	92
Biomass of salmon at monitoring date	18	33	44	77	89	84	83

Table 3. Average sediment sulfide concentrations (total S^{2-}, in µM) in Tier 1 monitoring of benthic sediments at salmon farms in SWNB, 2002–2008. Environmental ratings are based on the classification system used since 2006 (Table 1). Values in regular font are Oxic; numbers in italics are Hypoxic; and numbers in bold italics are Anoxic. Blank cells were either not monitored (not active) or were not growing salmon. Aquaculture Bay Management Areas (ABMAs) are those implemented in 2006 (Fig. 1). Farms in the former ABMA 4 are included within ABMA 1. Data obtained from the New Brunswick Department of Environment.

ABMA	Farm	2002	2003	2004	2005	2006	2007	2008
1	42	*3 233*	*4 892*	1 241	*4 020*	191		
1	44	1 200	*2 843*	*2 172*	1 321	505	*1 683*	1 475
1	45	1 164	*2 264*	567	***6 603***	410	711	60
1	46	*2 435*	*4 922*	1 250	*3 821*	***6 697***	373	231
1	49	608	233	762		337	897	52
1	50	99	106	66				
1	51	389	951	774		603	551	28
1 (4)	52	430	1 201	729	222	47	92	58
1 (4)	53	1 481	*2 160*	469	1 216	1 413	*2 693*	203
1 (4)	54	770	1 362	673	190	800	349	826
1	55	1 242	280	541	7	321	148	338
1	56	1 058	714	494			456	626
1	57	160	650	1 033	735	186	476	105
1	59	1 117	*1 742*	1 022	*2 533*	*1 603*	437	
1	60	55	116	319				
1	61	*2 422*	*2 753*	*2 376*	*2 948*	*2 379*	*4 291*	140
1	64	*2 398*	***16 417***					
1	84	*4 610*	*3 245*	*2 147*				
1	168	753	270	609	126	132	468	308
1	179	234	336	408	1 022		83	66
1	181	***6 265***	*3 803*	1 165		*2 261*	*5 597*	268
1	186	1 044	***14 829***	*2 648*	*3 306*	481	226	*5 672*
1	206	994	*1 910*	925	*3 569*	173	148	1 429
1	214	233	*1 877*	1 384			476	121
1	215	926	1 134	1 182	***7 823***	387	816	110
1	222	494	958	1 203	1 483	430	541	78
1	228	700	659	607	*1 830*	*3 730*	*1 687*	407
1	251	918	1 293	*2 167*	*2 689*		384	91
1	255	919	797					
1	256	642	382	5	59		2	0
1	290	*4 153*	*4 587*	*1 954*	497	***7 017***		
1	320	284	808	1 052	812	433	258	
1	337	*2 145*	*2 841*	*2 924*		*5 270*		
1	342	*3 775*	*2 233*	311		*1 848*	***9 468***	623
1	370	960	1 418	479	*2 066*	855	606	197
1	377	1 260	779	1 079	*1 554*	573	638	161
1	411	51	723	1 031	631	50		
1	502							*4 095*
1	504							163

Table 3 (continued).

ABMA	Farm	2002	2003	2004	2005	2006	2007	2008
2a	14	*2 260*	*5 153*	*2 693*	*4 708*	*2 961*	727	
2a	16	*2 308*	*3 317*	1 255	1 097	350	235	672
2a	17	1 460	1 280	*1 728*	*2 020*	*2 948*	588	7
2a	18	*1 612*	*2 406*	992	989	1 090	380	
2a	20	*2 622*	*5 505*	*3 375*				
2a	22	*2 701*	*2 176*	1 136				
2a	23	*2 469*	*4 047*	*2 389*	1 160	73	137	
2a	24	702	564	1 087			22	228
2a	25	*3 570*	***6 812***	*5 721*	*1 626*	***6 158***	314	229
2a	26	1 215	*4 770*	1 391	783	233	262	*2 080*
2a	27	*3 475*	*4 760*	*3 959*	*1 583*	1 429	305	174
2a	28	*4 557*	*5 097*	*2 216*	885	675		
2a	29	*1 789*	*3 600*	*2 756*	*3 478*	546		
2a	30	*2 769*	*4 791*	*2 936*	1 432	362		
2a	32	864	*1 528*	*3 507*	1 153	*1 854*	1 488	*2 178*
2a	33	1 062	*1 670*	1 250				*1 870*
2a	34	*1 854*	1 191	*1 684*	292			
2a	35	*2 483*	*3 458*	*5 980*	1 434	227		
2a	36	*2 000*						470
2a	37	*1 697*	801	*4 107*	758	*4 846*	774	*5 227*
2a	95	*2 617*	*3 522*					
2a	159	710	659					
2a	276	1 382	*4 792*	1 441	1 006	*2 570*	200	754
2b	2	14	*1 819*	1 244	*5 214*	297	776	*3 839*
2b	172	379	975	725	*4 697*	12	208	*2 667*
2b	213	869	*3 119*	935	*2 812*	495	410	*2 295*
2b	282	141	650	492	187	137		
2b	282b		204	106	553	26		
2b	298	36	254	306	1 094	7	27	330
2b	300	21	581	372	*2 338*	16	70	338
2b	316	44	321	1 216	986	169	5	
2b	349	260	1 116	660	1 336		195	*2 520*
2b	350	591	1 366	989	*1 883*	260	539	892
2b	368	837	1 139	584	***11 121***	37	543	*1 700*
2b	381	16	187	635	651	12	1	

Table 3 (concluded).

ABMA	Farm	2002	2003	2004	2005	2006	2007	2008
3a	10	1 104	*4 273*	*1 684*	*2 577*	294	*3 252*	63
3a	12	*3 984*	*2 693*	*2 257*	1 352	81	59	62
3a	378	675	815	*1 706*	931	*2 192*	732	1 344
3a	400	188	533	1 066	1 049	1 283	120	605
3a	404	66	1 362	368	611	450	135	343
3a	412	209	829	1 205	1 104	339	*1 934*	25
3a	495		352	1 130	915	175	80	
3a	496					333	320	122
3a	501			28	100	135	0	159
3b	3	208	253	536	655	*2 906*	*287*	*2 644*
3b	202	481	236	*2 700*	743	1 463	65	*1 966*
3b	270	504	381	977	273	706	91	1 308
3b	292	531	318	1 075	751	1 460	252	*1 951*
3b	303	85	181	72	309	64	1	267
3b	403	95	33	131	120	481	1	0
3b	403b		77	182	128			
3b	408	78	195	540	106		9	52
3b	413	239	321	458	388	249	62	
3b	491	4	131	99	224	1 050	51	15
5	4	243	*2 594*	*4 456*	*2 938*	*5 682*	732	
6	38	698						
6	39	1 145	829					
6	40	1 212	1 394	1 181	647			

Number of farms per environmental rating class

Oxic A	39	31	31	24	45	56	42
Oxic B	25	22	31	24	9	5	7
Hypoxic A	*17*	*16*	*18*	*14*	*10*	*4*	*10*
Hypoxic B	*6*	*9*	*5*	*5*	*1*	*2*	*2*
Hypoxic C	*2*	*10*	*2*	*3*	*3*	*1*	*2*
Anoxic	***1***	***3***	***0***	***3***	***3***	***1***	***0***
Totals	**90**	**91**	**87**	**73**	**71**	**69**	**63**

Table 4. Spearman's rank correlation coefficients (r_s) for correlations among pairs of selected farm parameters (2-tailed tests), for the 68 fish farms in SWNB that stocked salmon during 2005–2008. For farms that stocked more than once during this period, the most recent stocking was used. Probabilities in bold italics are significant ($p<0.05$).

Correlation	n	r_s	p (α=0.05)
Number of salmon stocked (1000s) vs. farm age	68	-0.31	***<0.01***
Number of salmon stocked (1000s) vs. farm lease area	68	0.60	***<0.01***
Number of salmon stocked (1000s) vs. average water depth	68	0.27	***0.03***
Farm lease area vs. farm age	68	-0.56	***<0.01***
Farm lease area vs. average water depth	68	0.39	***<0.01***
Average water depth vs. farm age	68	-0.31	***0.01***
Average current speed vs. farm age	68	-0.13	0.28
Average current speed vs. farm lease area	68	0.10	0.42
Average current speed vs. average water depth	68	-0.09	0.47
Average current speed vs. number of salmon stocked (1000s)	68	-0.03	0.79

Table 5. Spearman's rank correlation coefficients (r_s) for correlations between the number of salmon and the biomass of salmon on site at the time of Tier 1 monitoring (1-tailed tests) for salmon farms in SWNB, 2002–2008. Probabilities in bold italics are significant ($p<0.05$). Smolts are salmon that were stocked in the year of monitoring; pre-markets are salmon that were stocked one or more years prior to the year of monitoring. Coefficients and probabilities were not calculated for smolts in 2002 and for pre-market salmon in 2002 and 2003, due to the scarcity of data.

Year-class type and monitoring year	n	r_s	p (α=0.05)
Smolts 2002	4	–	–
Smolts 2003	6	0.60	>0.10
Smolts 2004	8	0.67	***<0.05***
Smolts 2005	18	0.34	0.08
Smolts 2006	10	-0.16	>0.10
Smolts 2007	9	0.00	>0.10
Smolts 2008	10	0.69	***<0.02***
Pre-markets 2002	3	–	–
Pre-markets 2003	5	–	–
Pre-markets 2004	12	0.99	***<0.01***
Pre-markets 2005	21	0.59	***0.02***
Pre-markets 2006	22	0.82	***<0.01***
Pre-markets 2007	14	0.55	***0.02***
Pre-markets 2008	19	0.53	***0.01***

Table 6. Spearman's rank correlation coefficients (r_s) for correlations between selected parameters and the average sediment sulfide concentration from Tier 1 monitoring at salmon farms in SWNB, 2002-2008. Significance tests are 2-tailed. Probabilities in bold italics are significant (p<0.05).

Parameter	Year	n	r_s	p (α=0.05)
Date of monitoring	2002	90	-0.16	0.14
	2003	90	0.02	0.85
	2004	81	-0.03	0.81
	2005	71	-0.17	0.15
	2006	70	0.03	0.82
	2007	68	-0.13	0.28
	2008	63	-0.04	0.79
Farm age	2002	90	0.58	***<0.01***
	2003	90	0.55	***<0.01***
	2004	87	0.51	***<0.01***
	2005	73	0.36	***<0.01***
	2006	71	0.27	***0.02***
	2007	70	0.32	***<0.01***
	2008	63	-0.01	0.93
Farm lease area	2002	89	-0.26	***0.02***
	2003	89	-0.21	0.05
	2004	86	-0.19	0.08
	2005	72	-0.13	0.29
	2006	70	0.01	0.94
	2007	69	-0.14	0.24
	2008	63	-0.26	***0.02***
Average water depth	2002	89	0.02	0.82
	2003	89	-0.03	0.80
	2004	86	0.04	0.68
	2005	72	-0.16	0.17
	2006	70	0.33	***<0.01***
	2007	69	0.01	0.43
	2008	63	-0.10	0.43

Table 6 (concluded).

Parameter	Year	n	r_s	p (α=0.05)
Average predicted current speed	2002	89	-0.53	***<0.01***
	2003	89	-0.58	***<0.01***
	2004	86	-0.44	***<0.01***
	2005	72	-0.38	***<0.01***
	2006	70	-0.36	***<0.01***
	2007	69	-0.49	***<0.01***
	2008	63	-0.26	***0.04***
Number of salmon on site	2002	20	-0.04	0.87
	2003	33	-0.04	0.84
	2004	43	0.03	0.83
	2005	65	0.28	***0.02***
	2006	66	0.52	***<0.01***
	2007	65	0.34	***<0.01***
	2008	58	0.49	***<0.01***
Biomass of salmon on site	2002	16	0.45	0.08
	2003	30	0.04	0.82
	2004	38	0.47	***<0.01***
	2005	56	0.56	***<0.01***
	2006	63	0.57	***<0.01***
	2007	58	0.44	***<0.01***
	2008	54	0.48	***<0.01***

Table 7. Numbers of fallowed salmon farms (holding no fish) at which Tier 1 monitoring was conducted in 2002–2008. Also shown are the number of fallowed farms with sediment sulfide concentrations >750 µM and the mean, minimum, and maximum sediment sulfide concentrations at fallowed farms.

	2002	2003	2004	2005	2006	2007	2008	Total
No. of fallowed farms monitored:								
– total	4	11	13	15	30	34	23	130
– with estimate of months fallow	4	11	12	12	27	31	23	120
No. of fallowed monitored farms with >750 µM average S^{2-}:								
– total	1	7	5	6	1	3	1	24
– with estimate of months fallow	1	7	4	6	1	3	1	23
Sediment sulfide concentrations at fallowed farms (S^{2-}, µM):								
– Mean	477	1 289	727	794	354	313	326	509
– Minimum	99	106	66	7	7	0	0	0
– Maximum	1 145	3 803	1 954	3 478	3 730	1 934	4 095	4 095

Table 8. Numbers of fallowed salmon farms (farms holding no fish at the time of Tier 1 monitoring), by environmental rating and length of fallow period (number of months between harvesting and Tier 1 monitoring), 2002–2008. The 120 cases represent 73 farms (34 farms were monitored more than once while fallowed during these years).

No. of months fallowed	Environmental rating						
	Oxic A	Oxic B	Hypoxic A	Hypoxic B	Hypoxic C	Anoxic	Total
<4	31	8	3	3	0	0	45
4–12	35	5	1	2	0	0	43
>12	31	1	0	0	0	0	32
Total	97	14	4	5	0	0	120

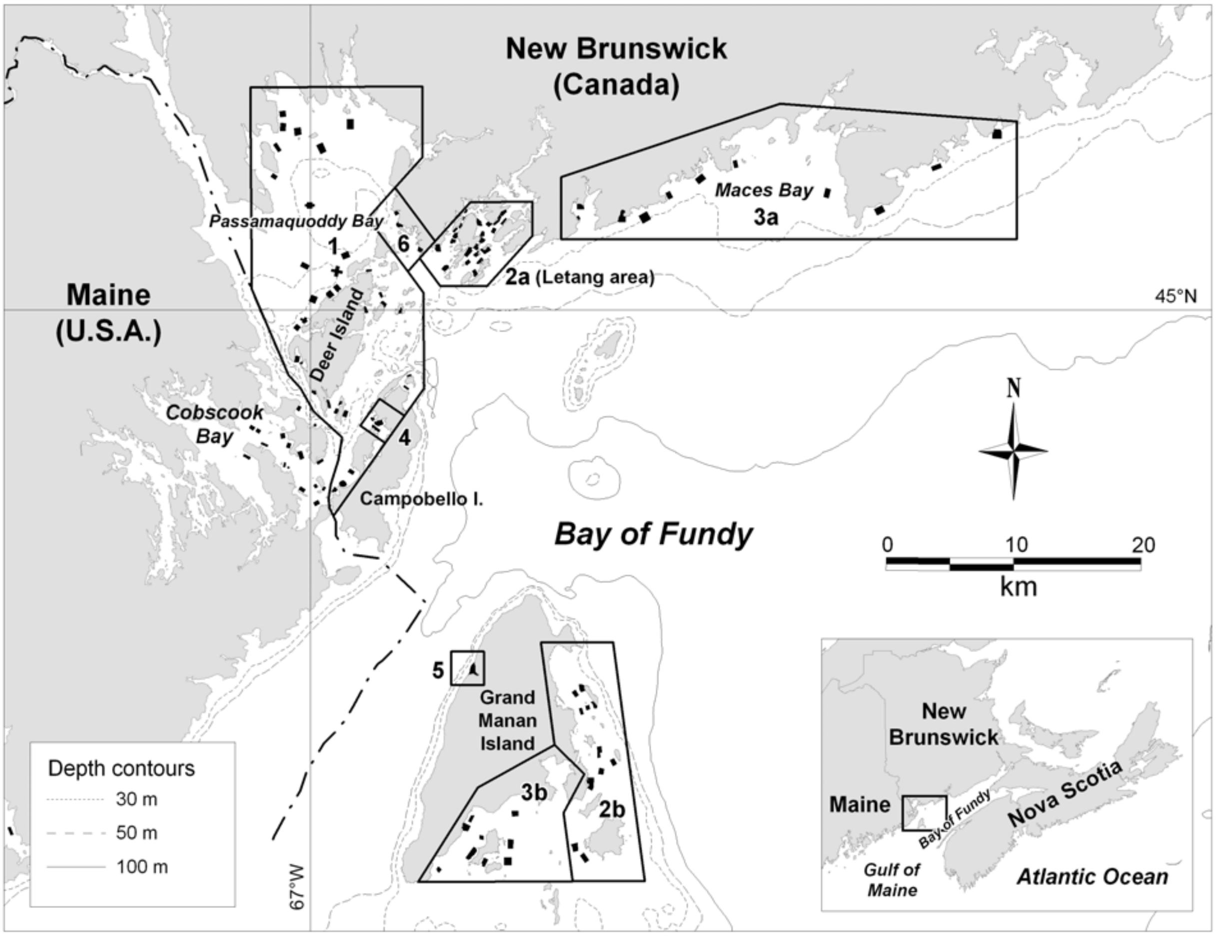


Fig. 1. Map of the SWNB portion of the Bay of Fundy, showing licensed fish farms in 2009 (small black polygons) and Aquaculture Bay Management Areas implemented in 2006 (black outlines). Farms in ABMA 1 were allowed to stock salmon in 2006, 2009, and 2012; farms in ABMAs 2a and 2b in 2007, 2010, and 2013; and farms in ABMAs 3a and 3b in 2008, 2011, and 2014. Stocking years were not specified for two small ABMAs: 4 (which is now part of ABMA 1) and 5. ABMA 6 was designated for non-salmonid species only. Also shown are finfish farm leases in Cobscook Bay, Maine.

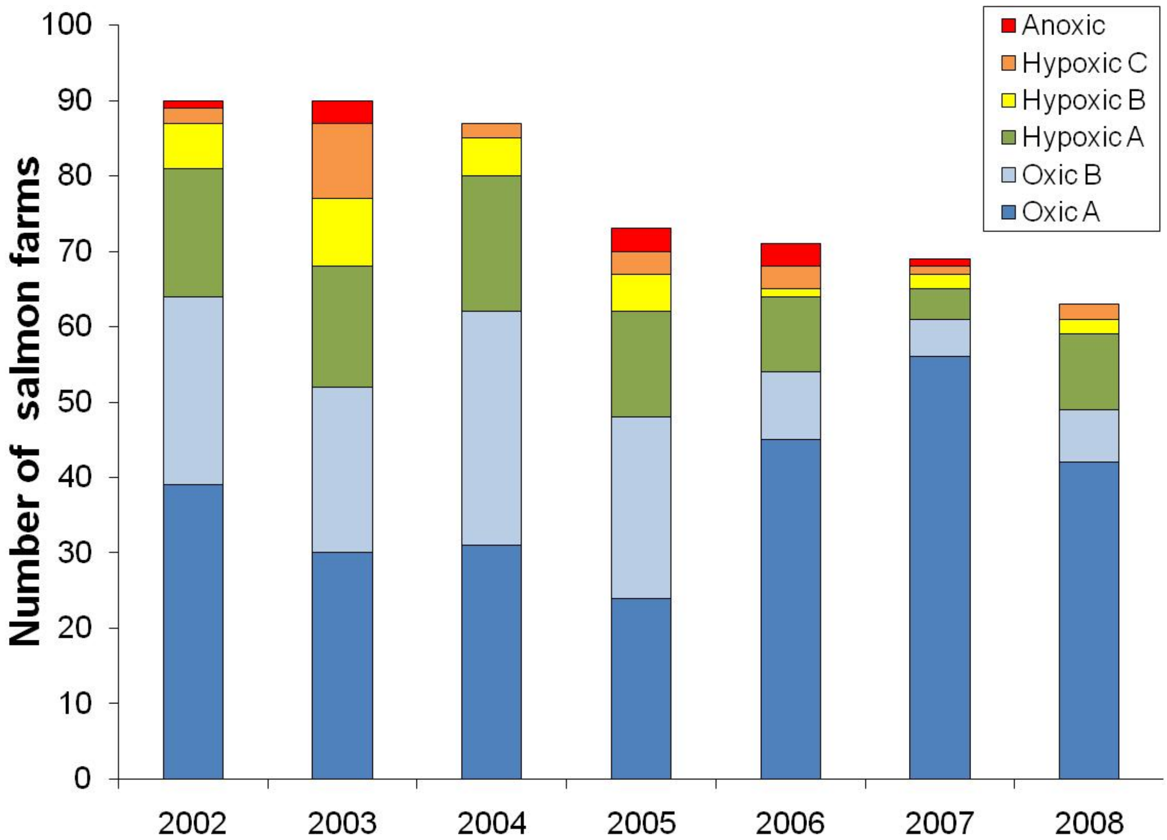


Fig. 2. Environmental ratings at salmon farms in SWNB by year, during 2002–2008. The ratings shown are based on sediment sulfide concentrations from Tier 1 monitoring (see Table 1).

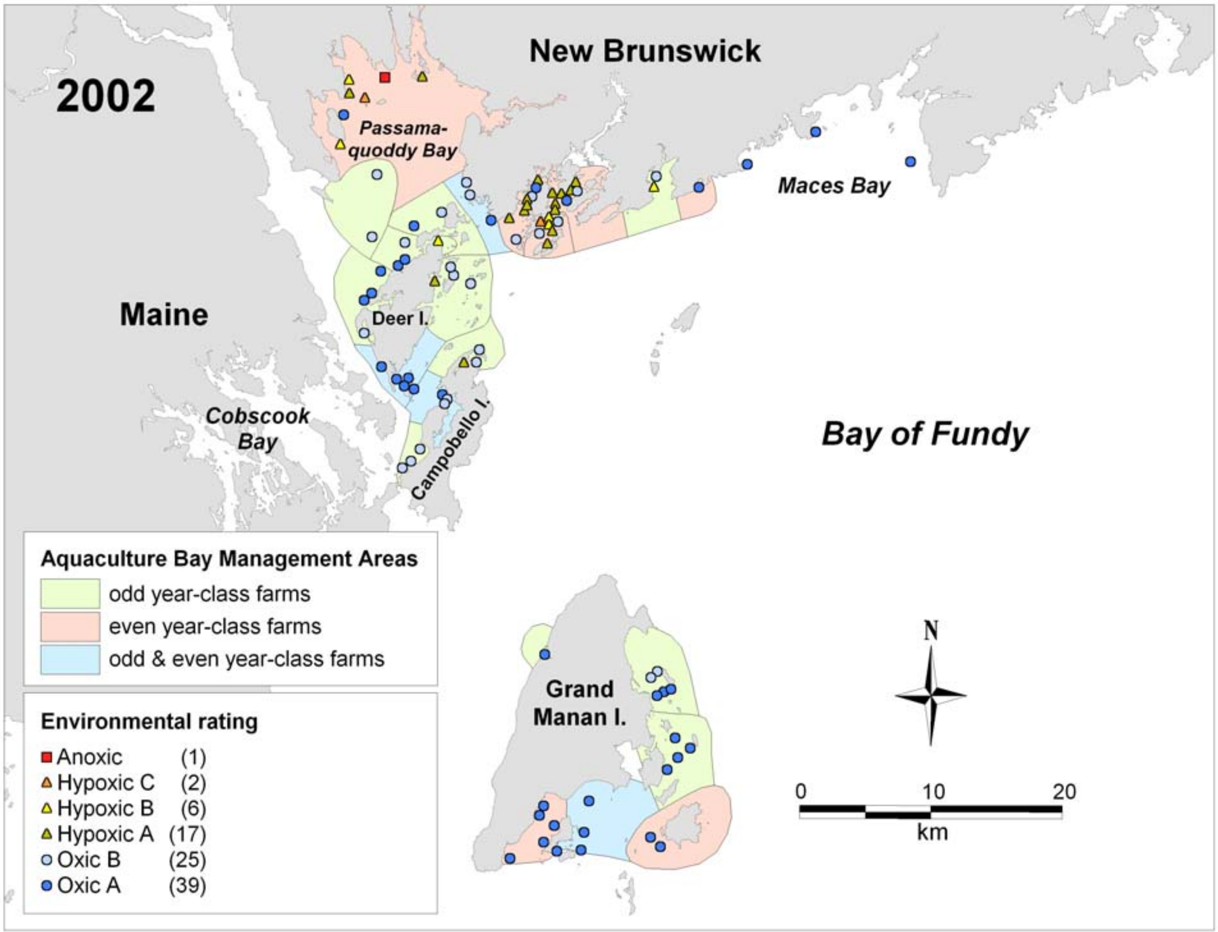


Fig. 3a. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2002. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas used in 2001–2005. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

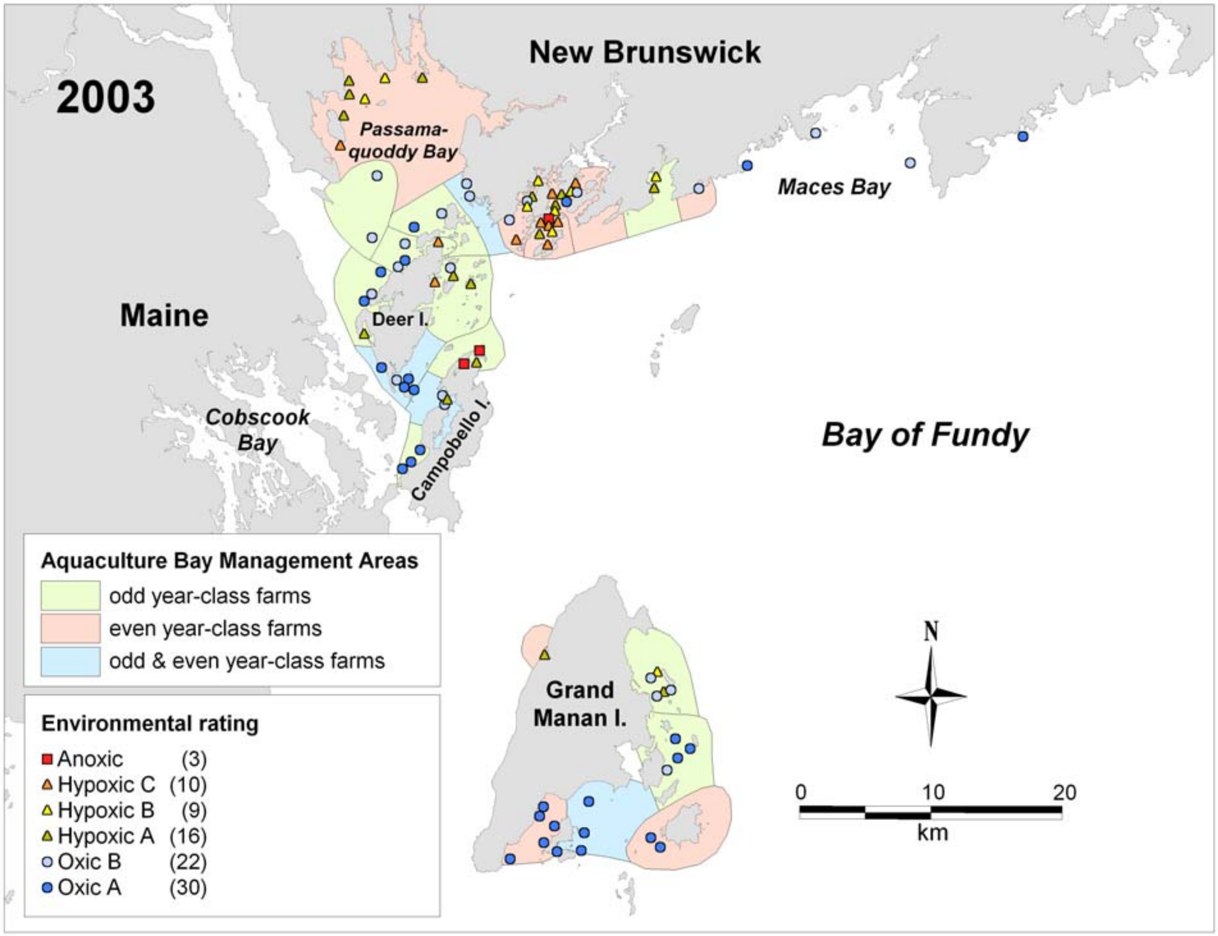


Fig. 3b. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2003. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas used in 2001–2005. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

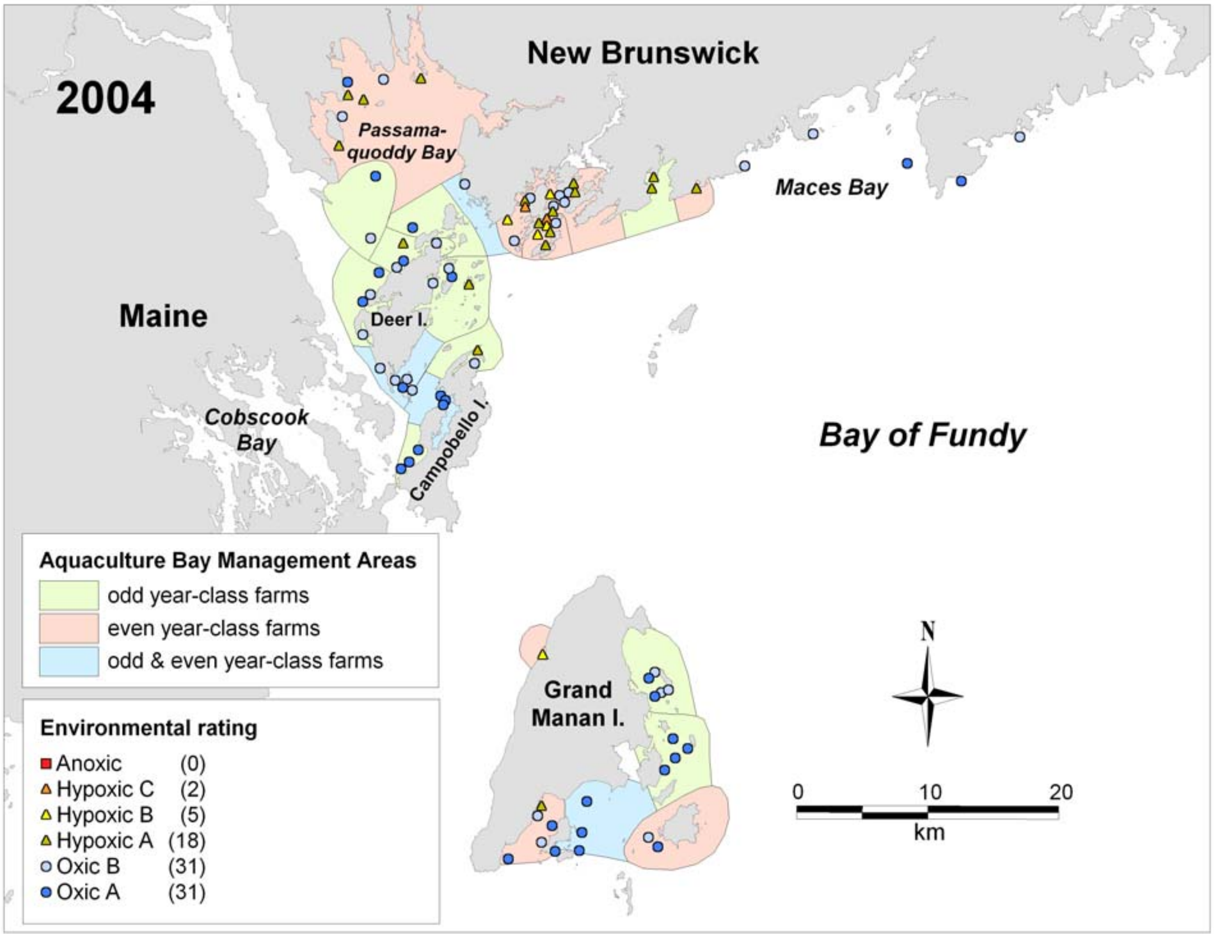


Fig. 3c. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2004. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas used in 2001–2005. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

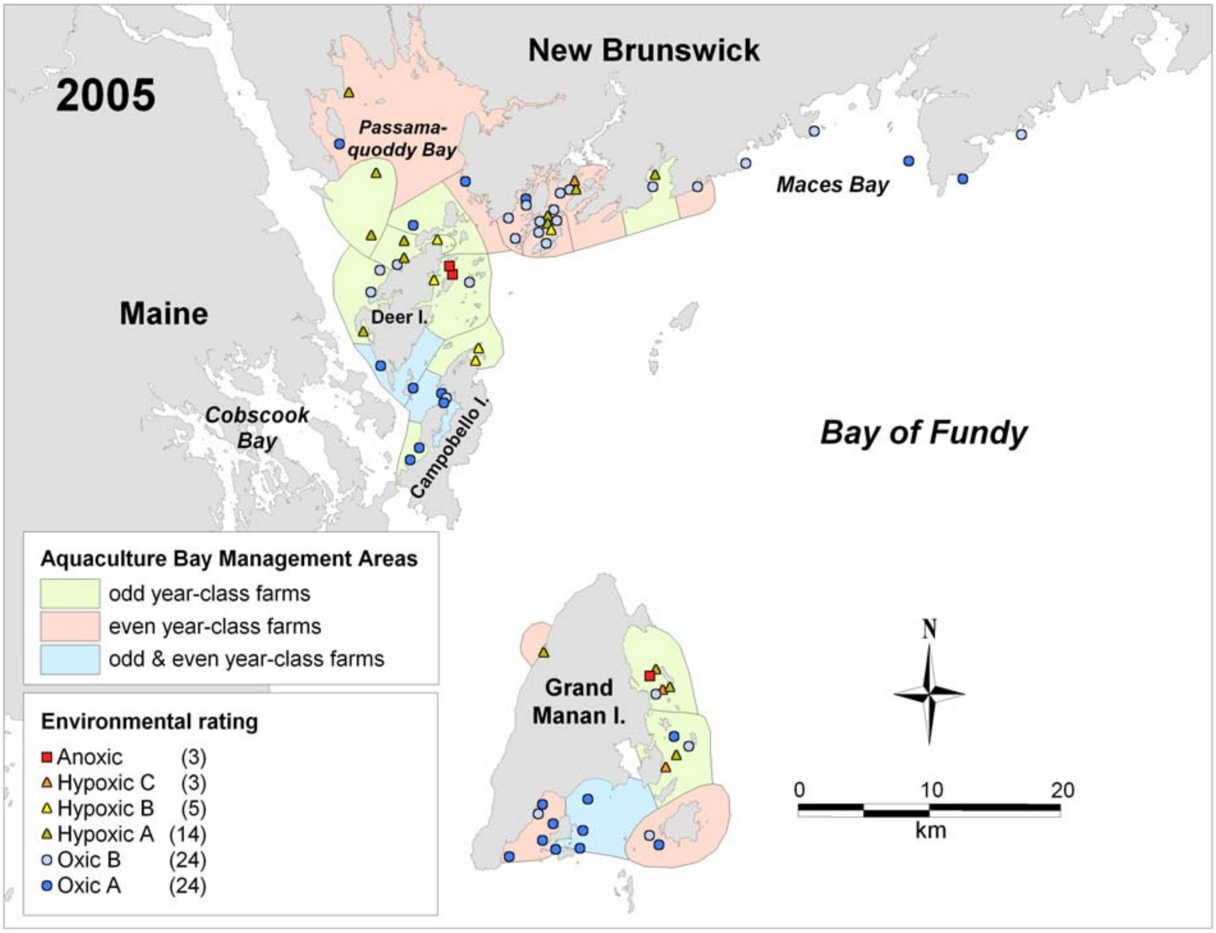


Fig. 3d. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2005. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas used in 2001–2005. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

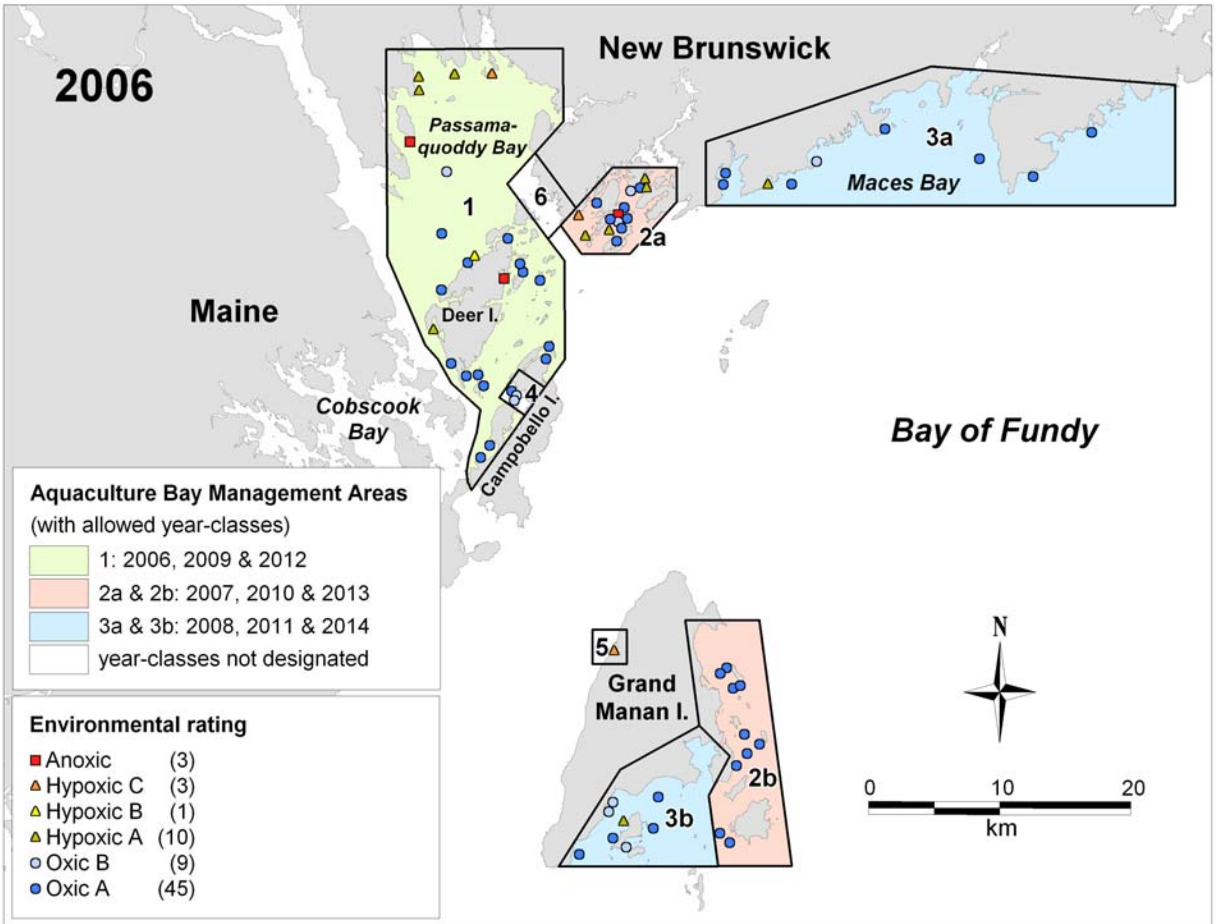


Fig. 3e. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2006. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas implemented in 2006. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

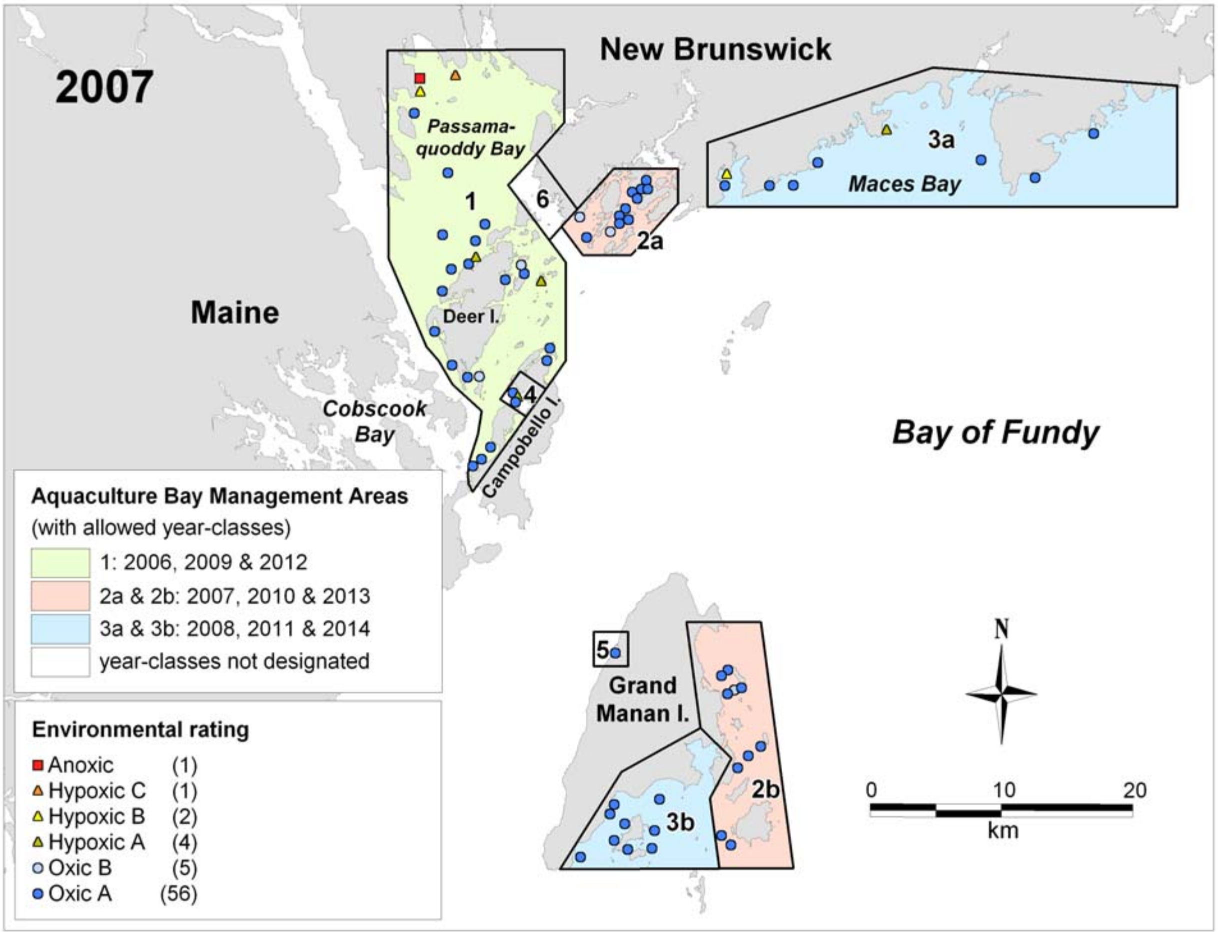


Fig. 3f. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2007. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas implemented in 2006. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

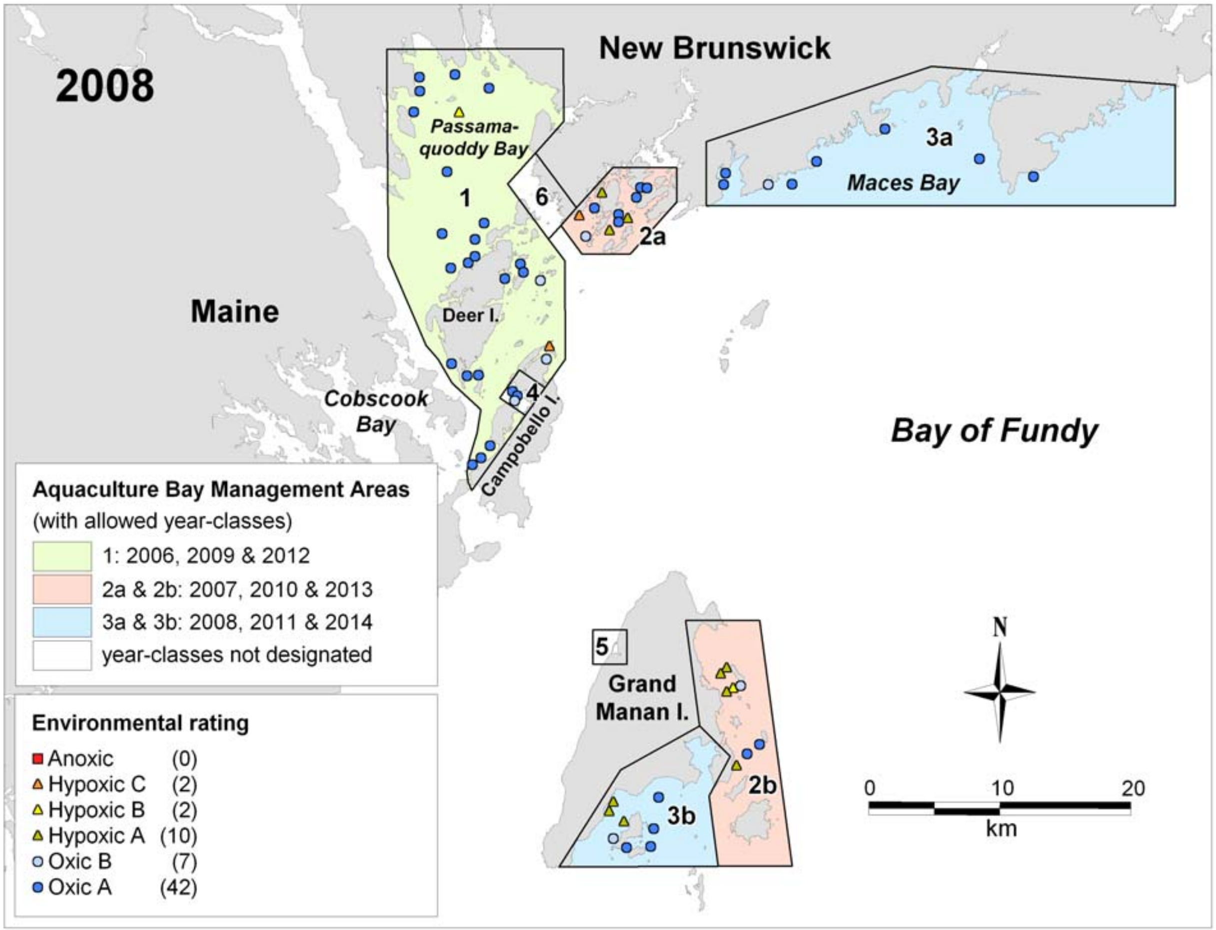


Fig. 3g. Map of the geographic distribution of environmental ratings from Tier 1 monitoring of salmon farms in SWNB in 2008. The ratings shown are based on sediment sulfide concentrations (see Table 1). Also shown are Aquaculture Bay Management Areas implemented in 2006. The numbers of farms in each environmental rating are shown in the legend (in parentheses). Non-salmonid farms are not included.

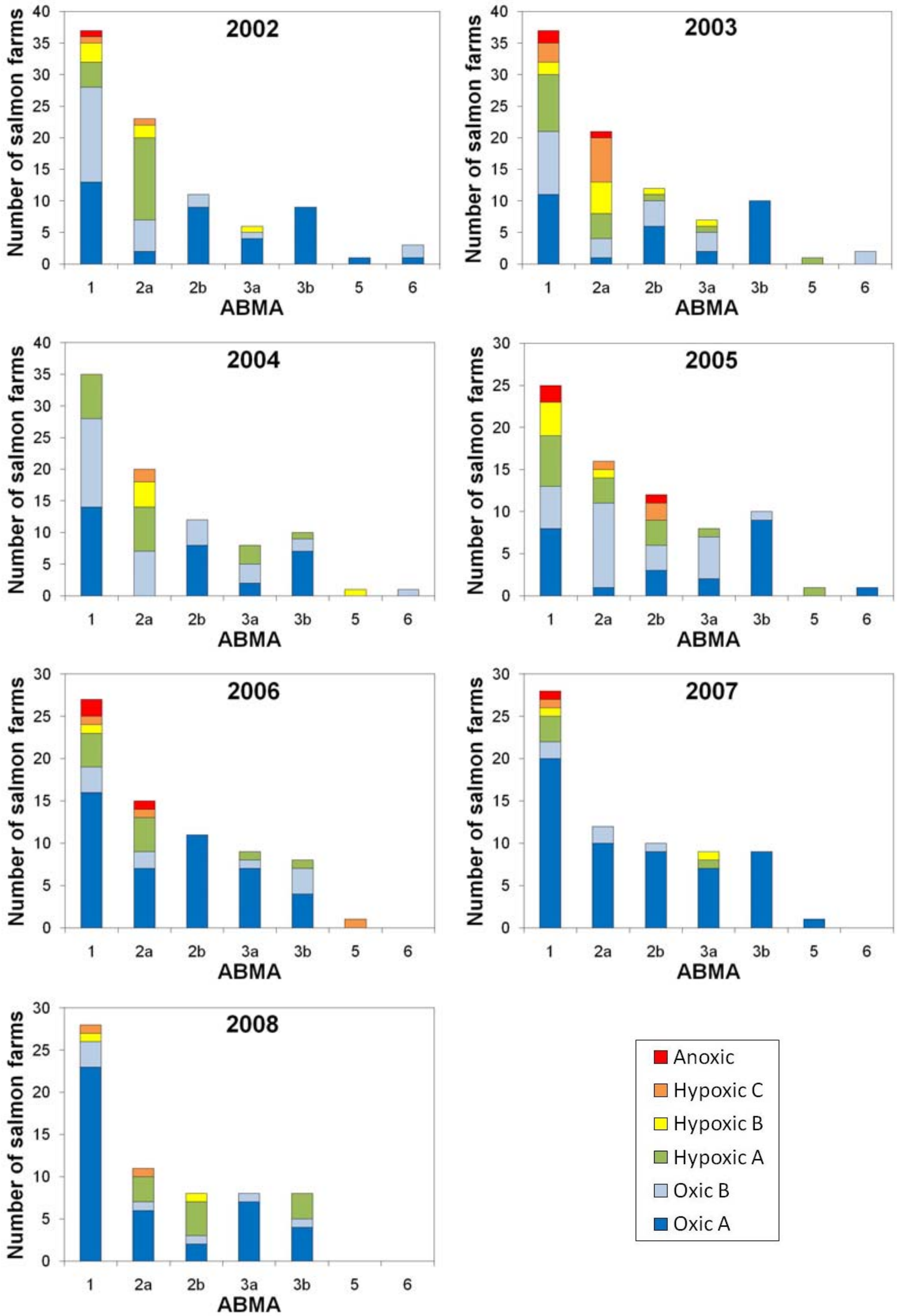


Fig. 4. Environmental ratings at salmon farms in SWNB by year and geographic subarea, during 2002–2008. The ratings shown are based on sediment sulfide concentrations (see Table 1). The geographic subareas are the Aquaculture Bay Management Areas (ABMAs) implemented in 2006; in the graphs, ABMA 1 includes ABMA 4 (which became part of ABMA 1 in 2010).

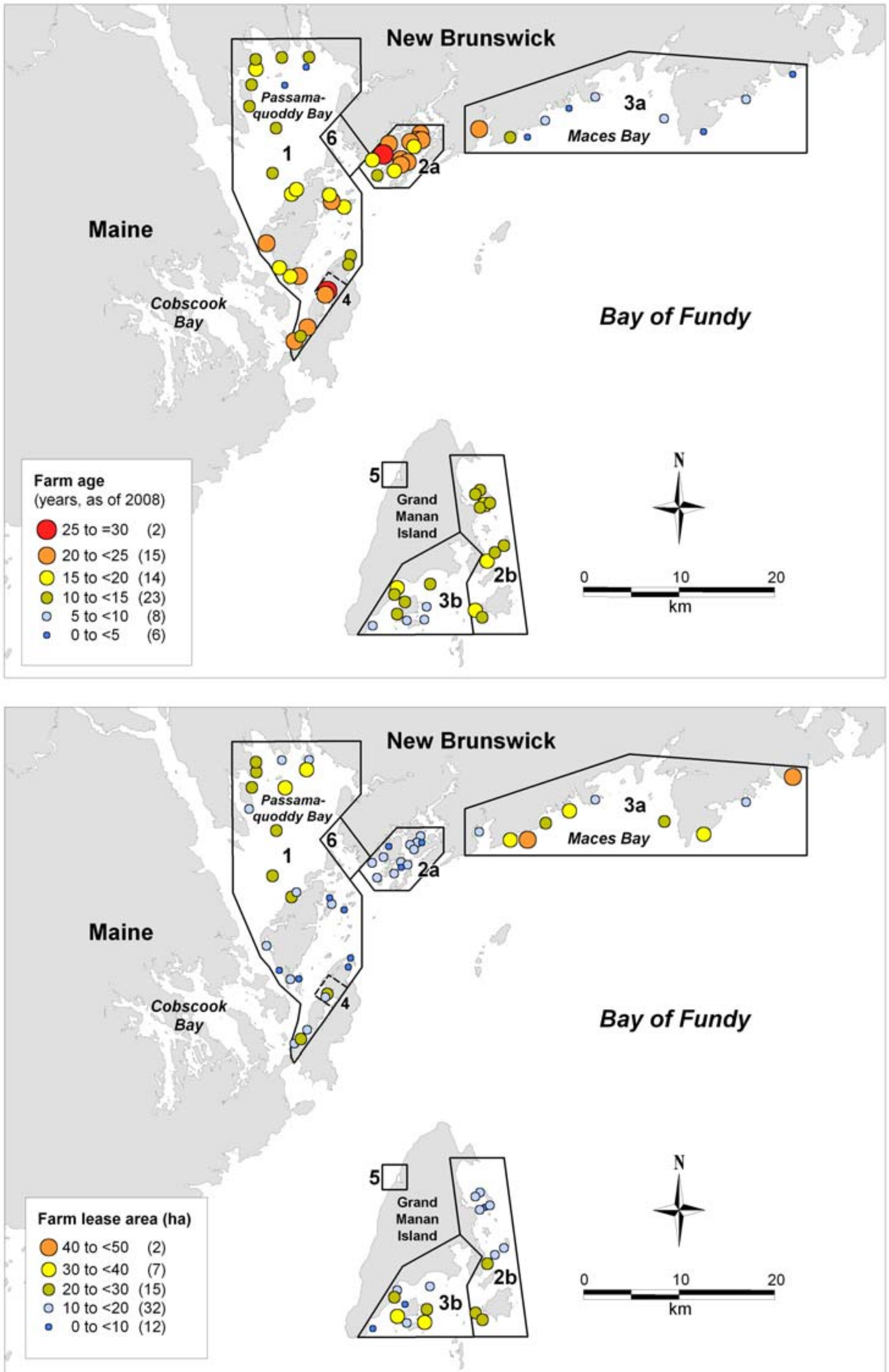
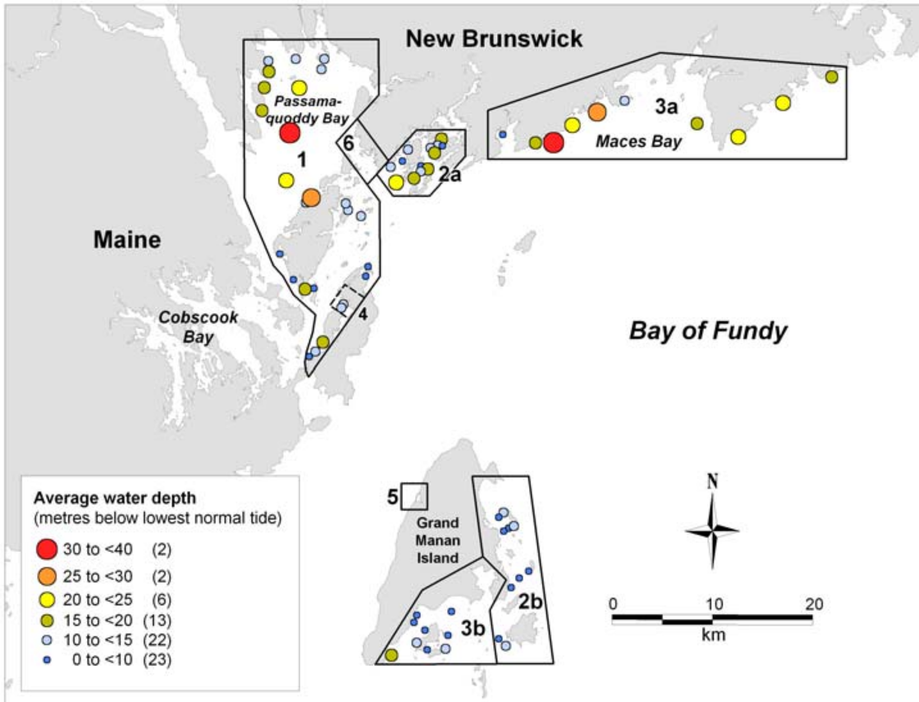


Fig. 5. Distribution of selected farm parameters among farms in SWNB that stocked salmon during 2005–2008. Lines indicate boundaries of Aquaculture Bay Management Areas. Top: farm age as of 2008. Bottom: farm lease area.



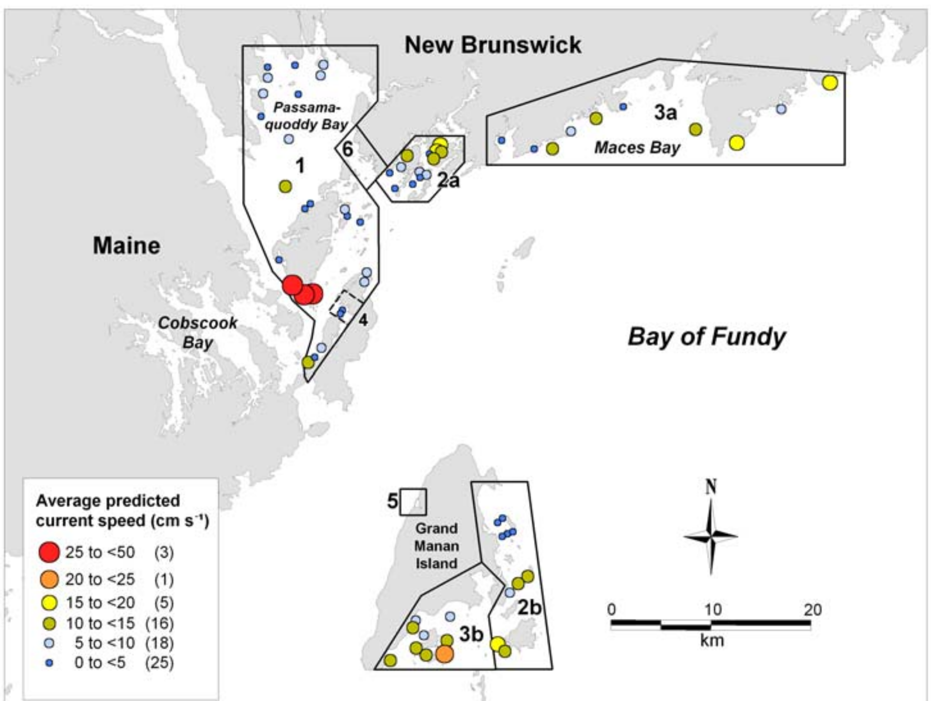


Fig. 5 (continued). Top: average water depth of farm lease. Bottom: average predicted current speed at farm.

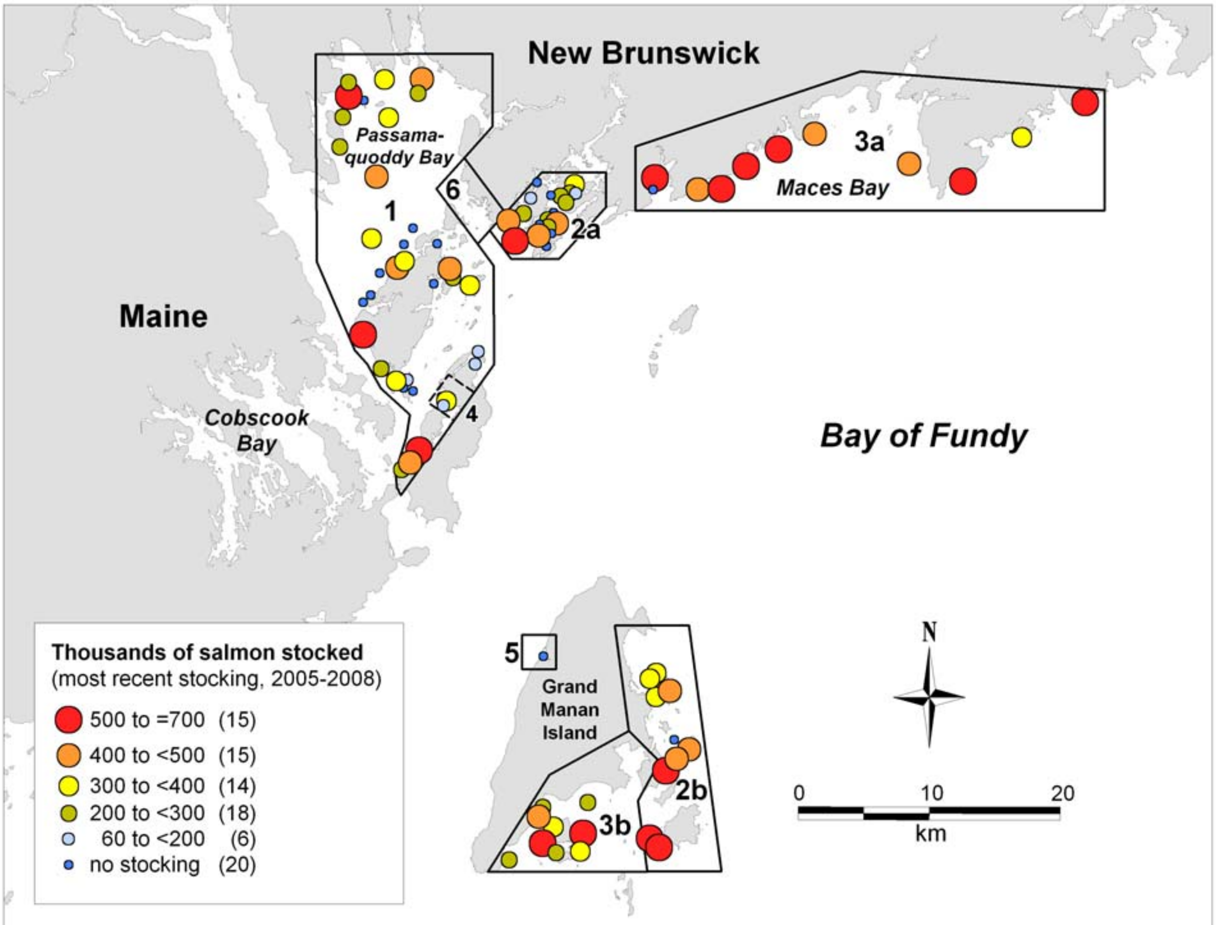


Fig. 5 (concluded). Number of salmon smolts stocked per farm during 2005–2008. For farms that stocked more than once during this period, the most recent stocking is shown. Also shown are licensed salmon farms that did not stock during this period.

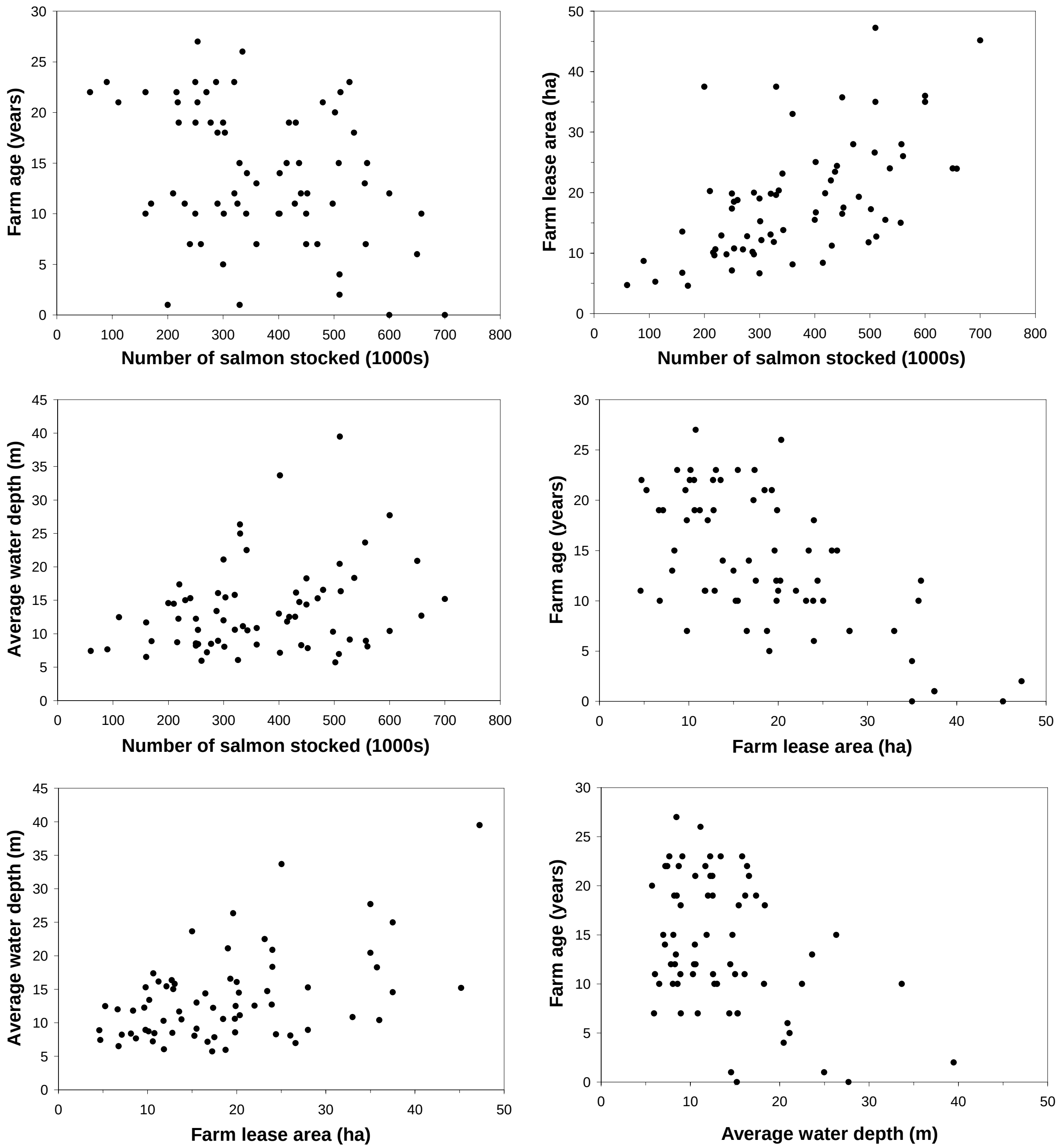


Fig. 6. Relationships among selected farm parameters for the 68 farms in SWNB that stocked salmon during 2005–2008. Top left: number of salmon stocked (most recent stocking during 2005–2008) vs. farm age. Top right: number of salmon stocked vs. farm lease area. Middle left: number of salmon stocked vs. average water depth. Middle right: farm lease area vs. farm age. Bottom left: farm lease area vs. average water depth. Bottom right: average water depth vs. farm age.

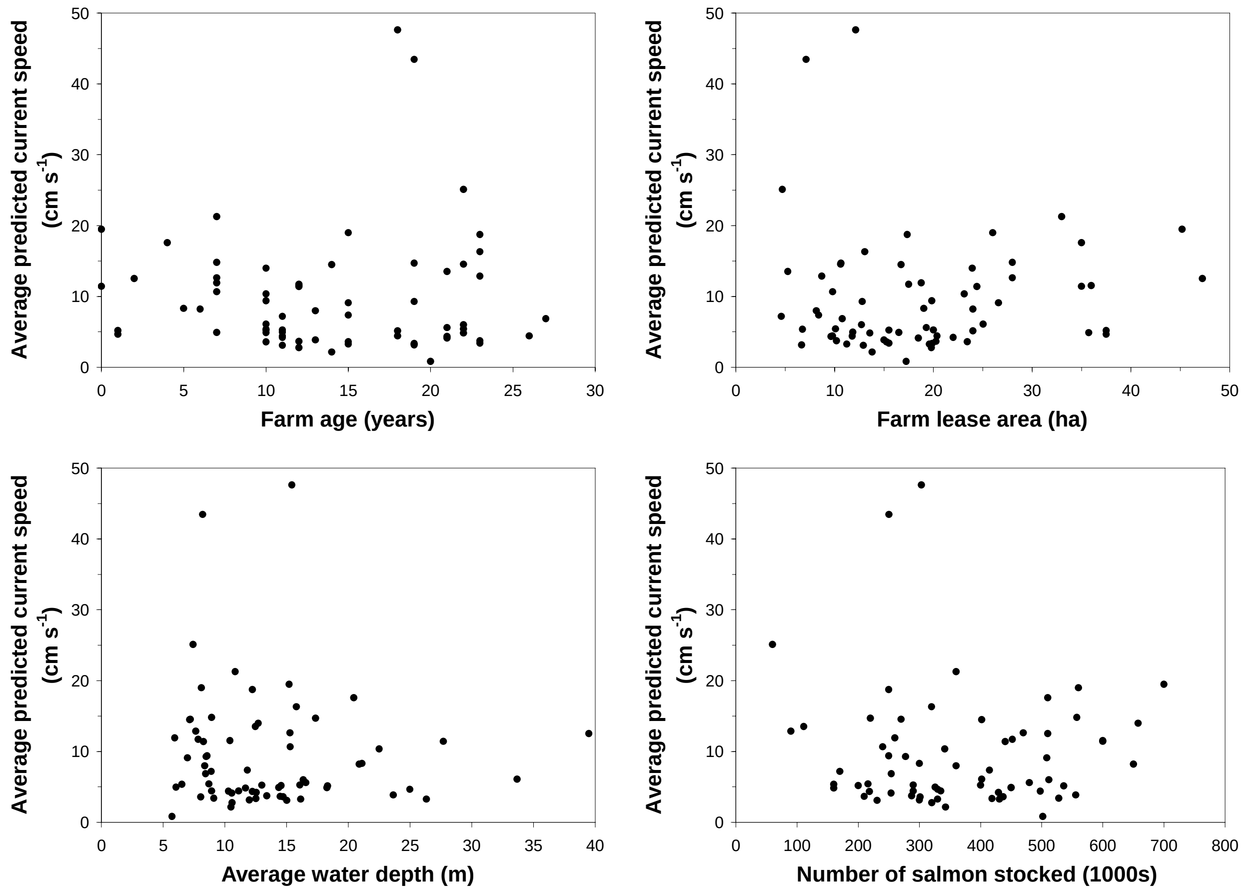


Fig. 6 (concluded). Top left: farm age vs. average predicted current speed. Top right: farm lease area vs. average predicted current speed. Bottom left: average water depth vs. average predicted current speed. Bottom right: number of salmon stocked vs. average predicted current speed.

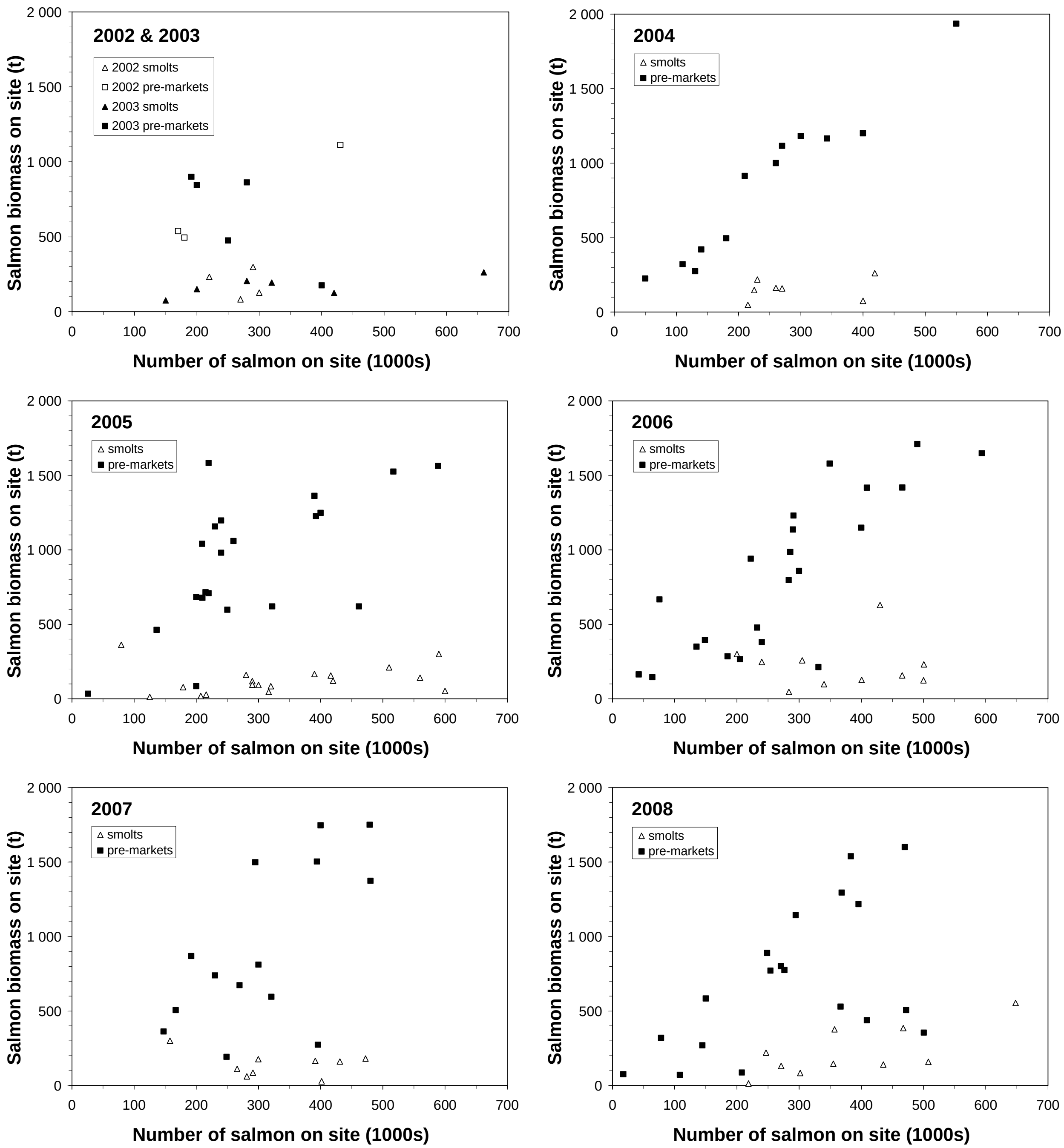


Fig. 7. Relationship between the number of salmon on site and the biomass of salmon on site at the time of Tier 1 monitoring at salmon farms in SWNB, 2002–2008.

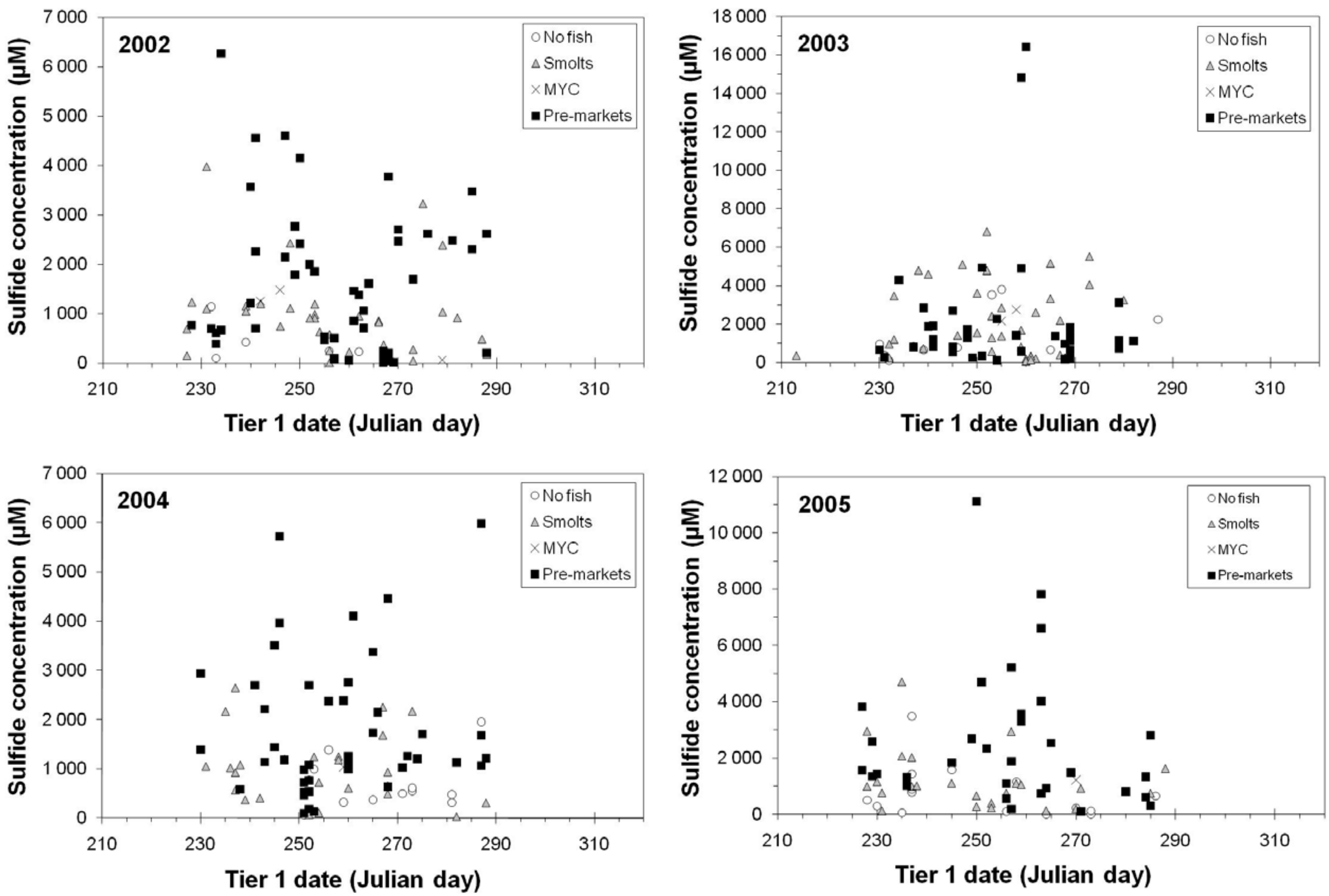


Fig. 8. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the date of monitoring at salmon farms in SWNB, 2002–2008. Tier 1 monitoring should occur between 1 August and 31 October each year (Julian days 213–304, except days 214–305 in leap years 2004 and 2008). MYC = multi-year-class farms (holding smolts and pre-market salmon).

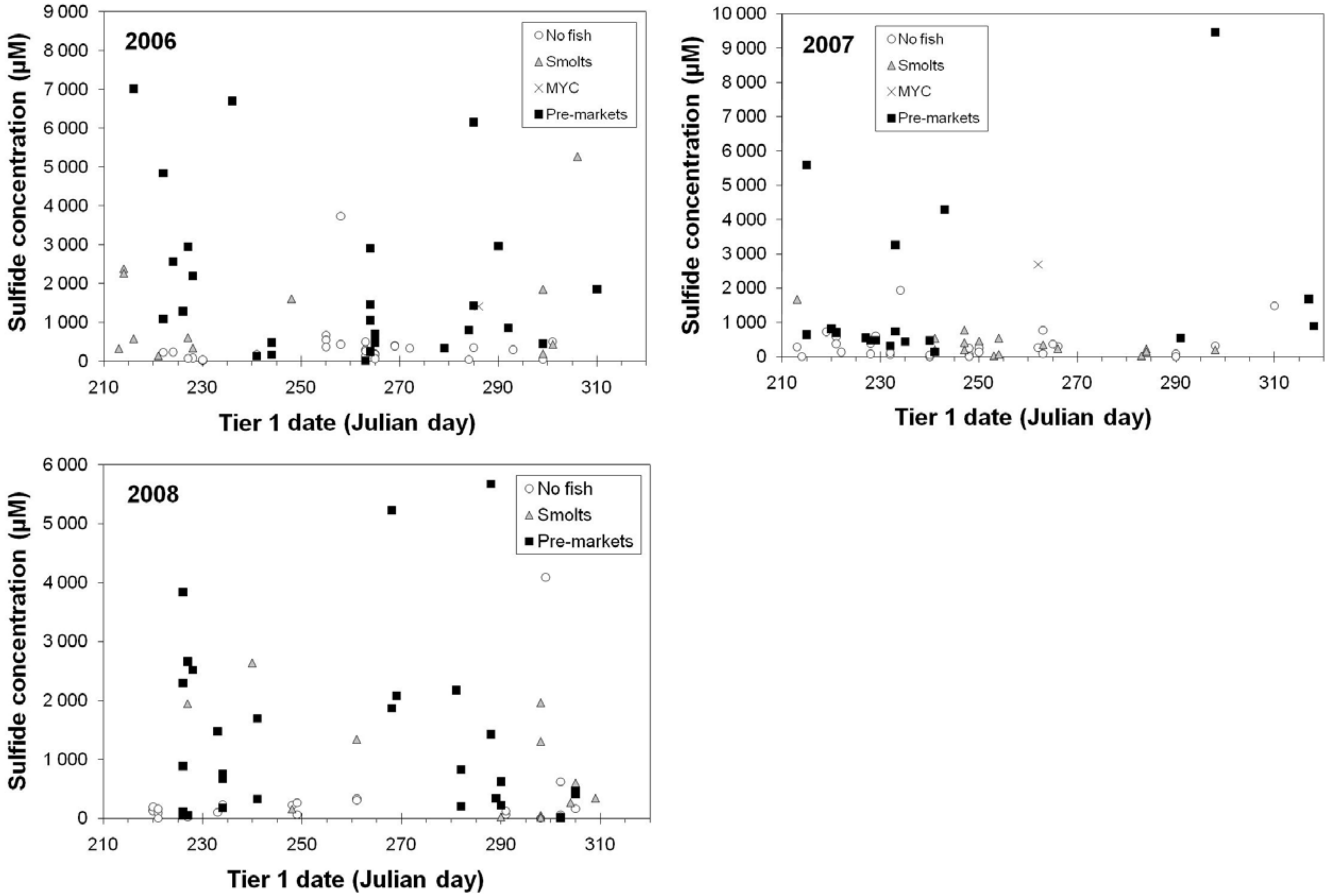


Fig. 8 (concluded).

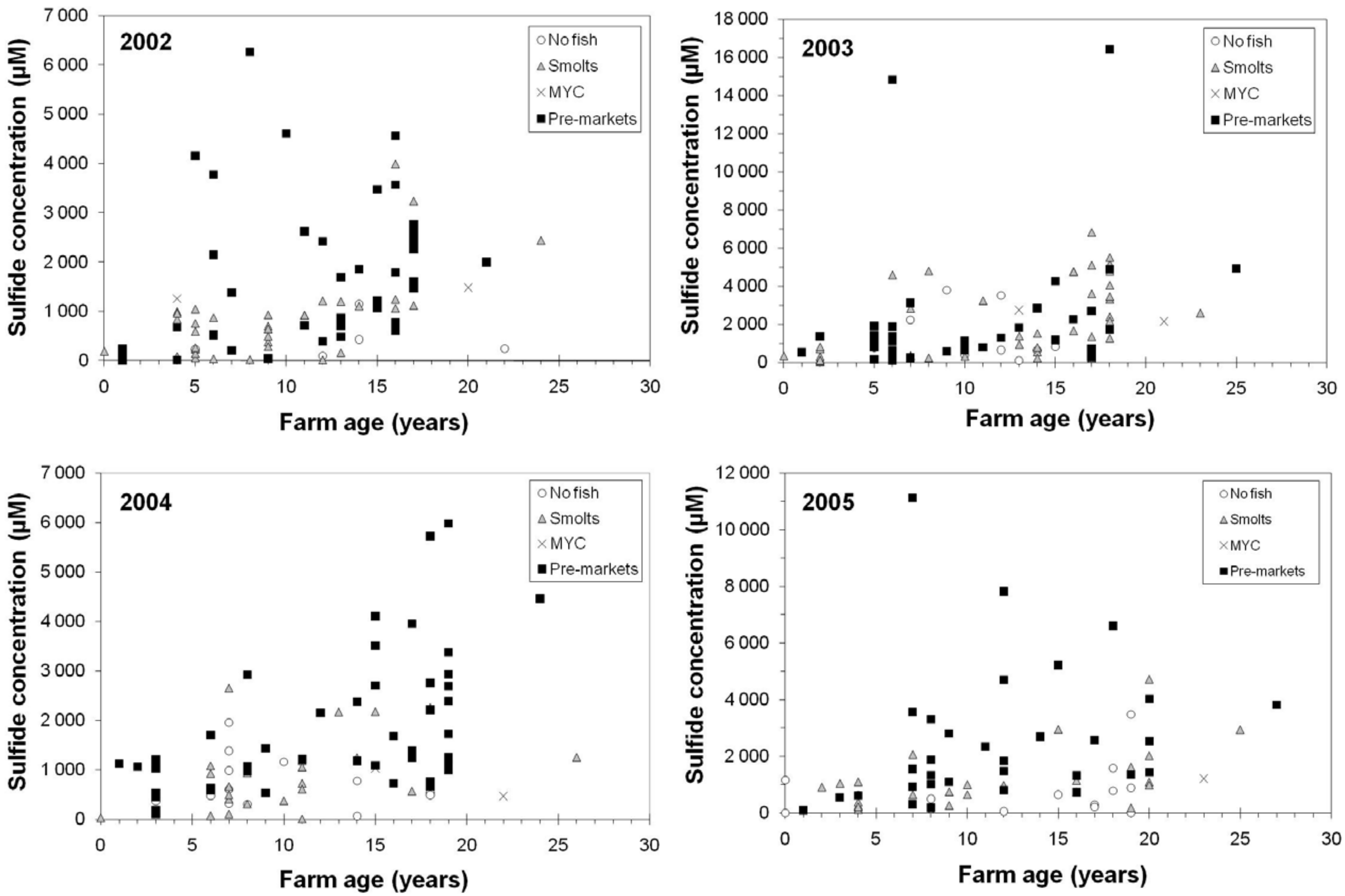


Fig. 9. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the farm age (the number of years since the start of operations) of salmon farms in SWNB, 2002–2008. “0” years indicates the first year of operation; MYC = multi-year-class farms (holding smolts and pre-market salmon).

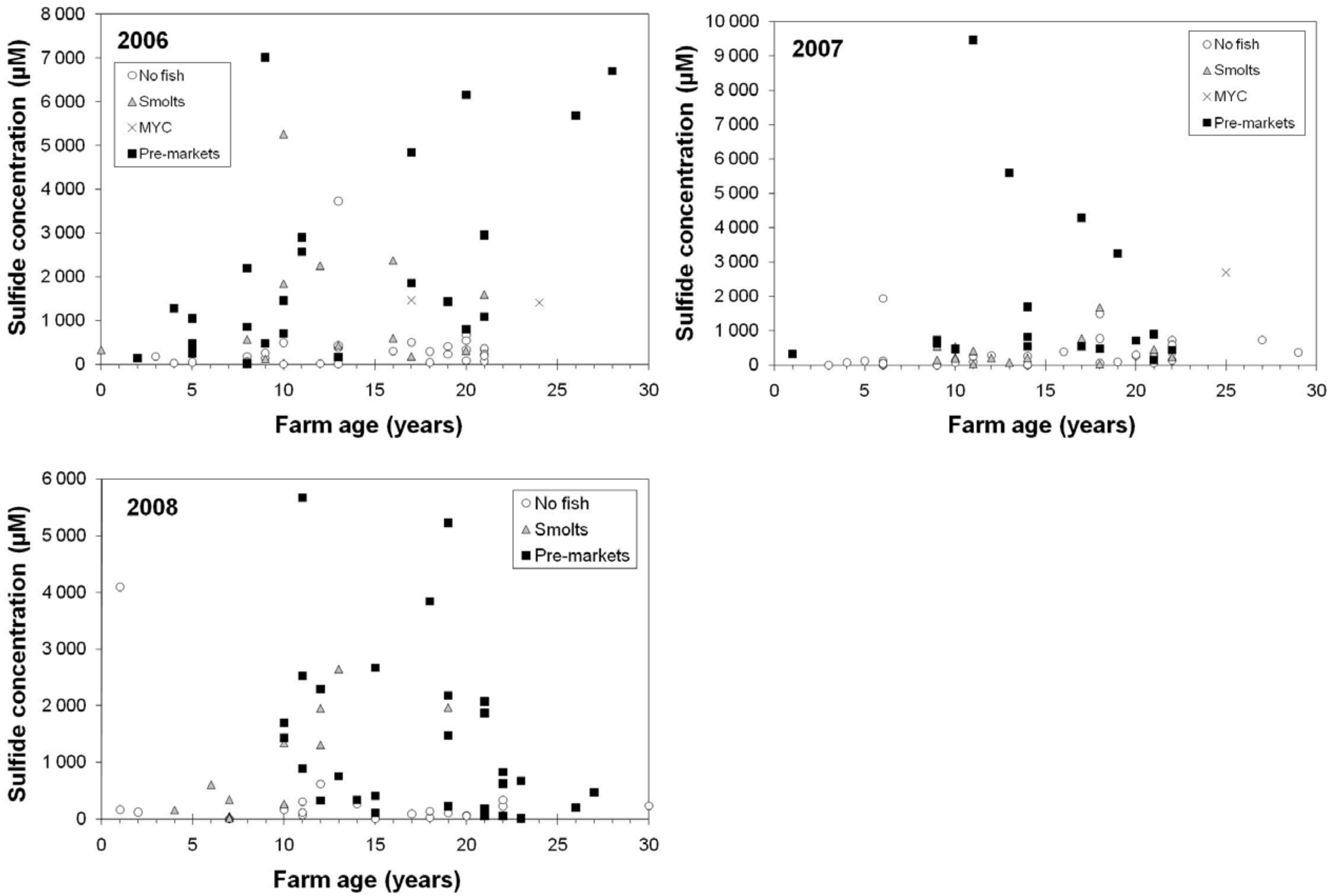


Fig. 9 (concluded).

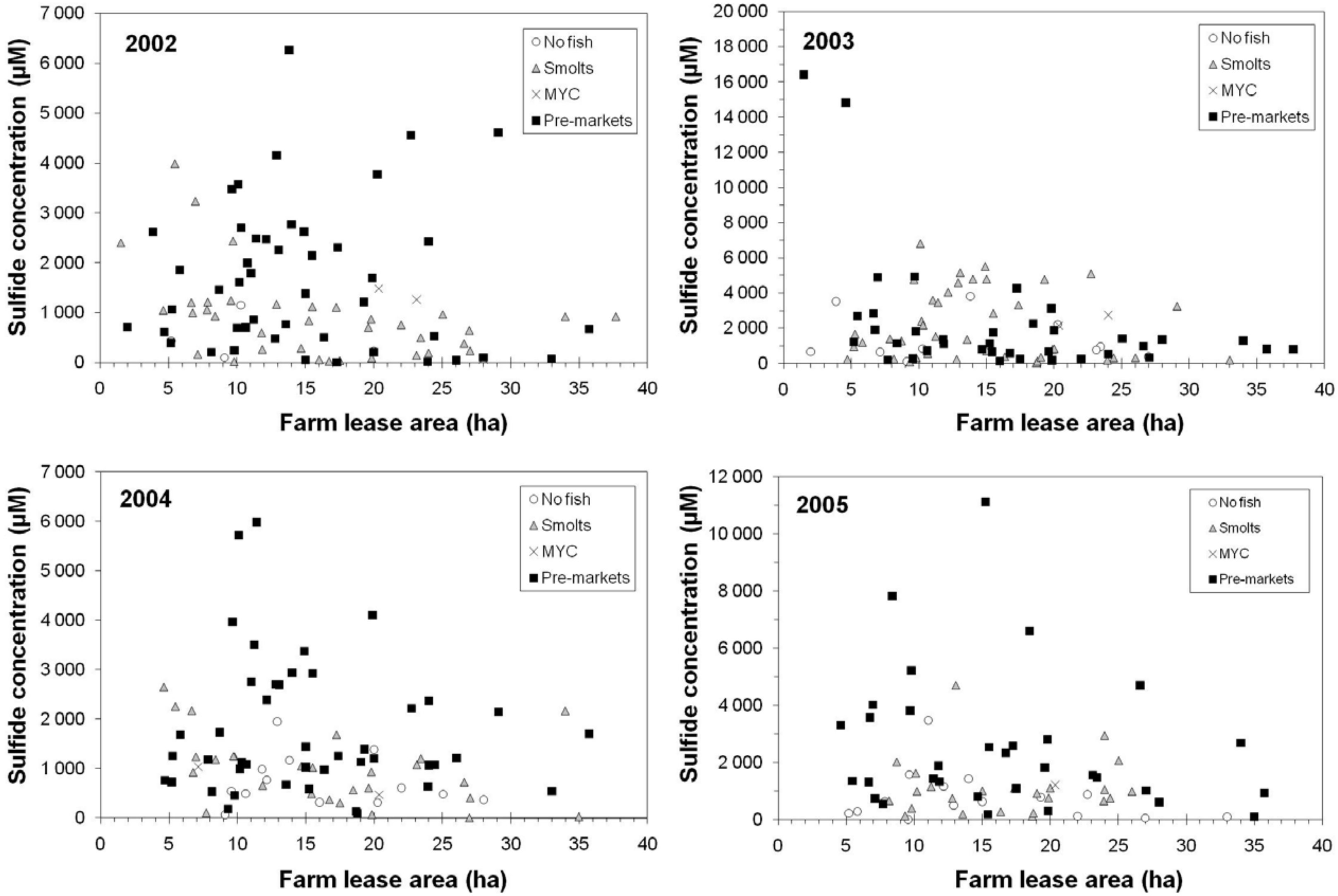


Fig. 10. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the farm lease area of salmon farms in SWNB, 2002–2008. MYC = multi-year-class farms (holding smolts and pre-market salmon).

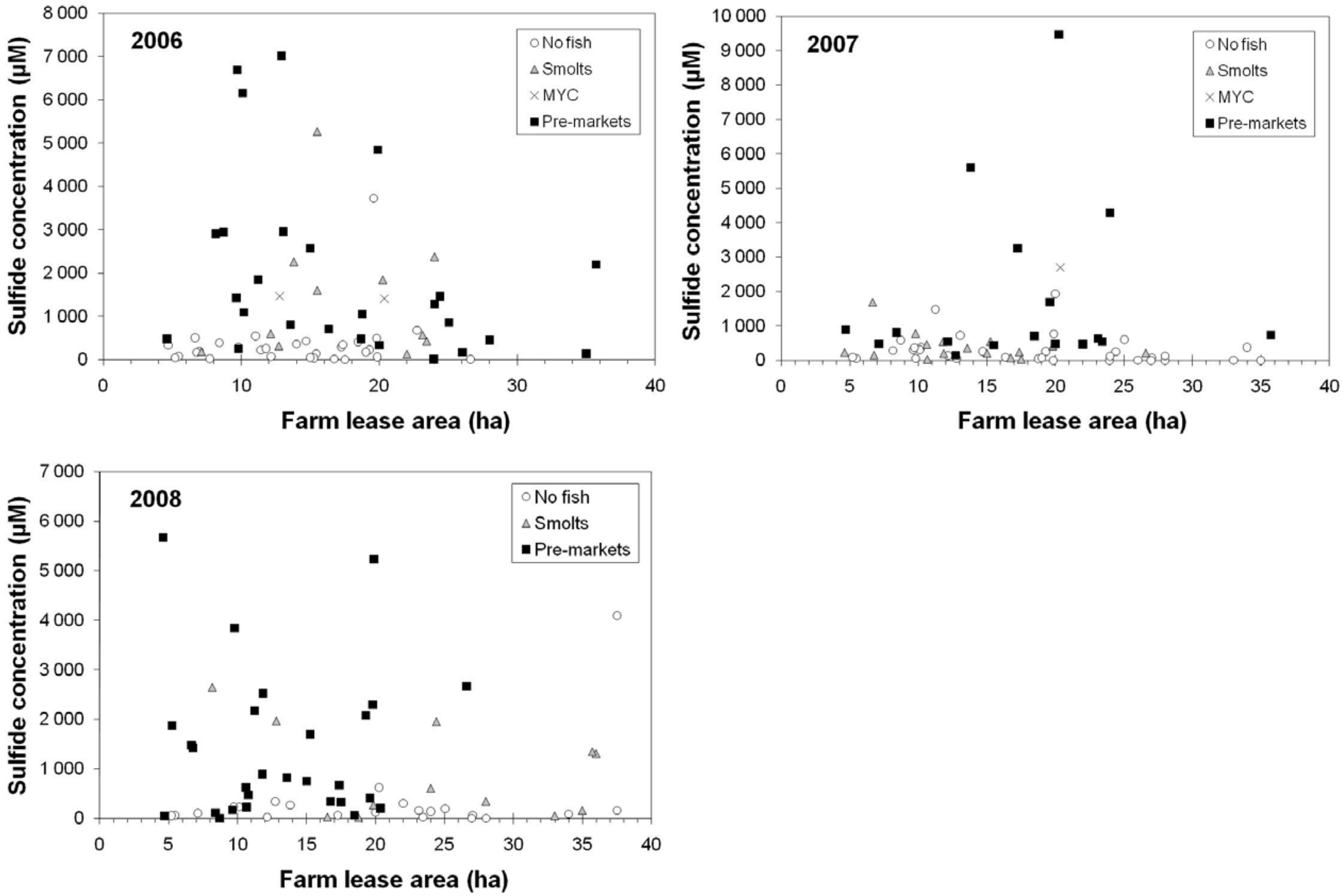


Fig. 10 (concluded).

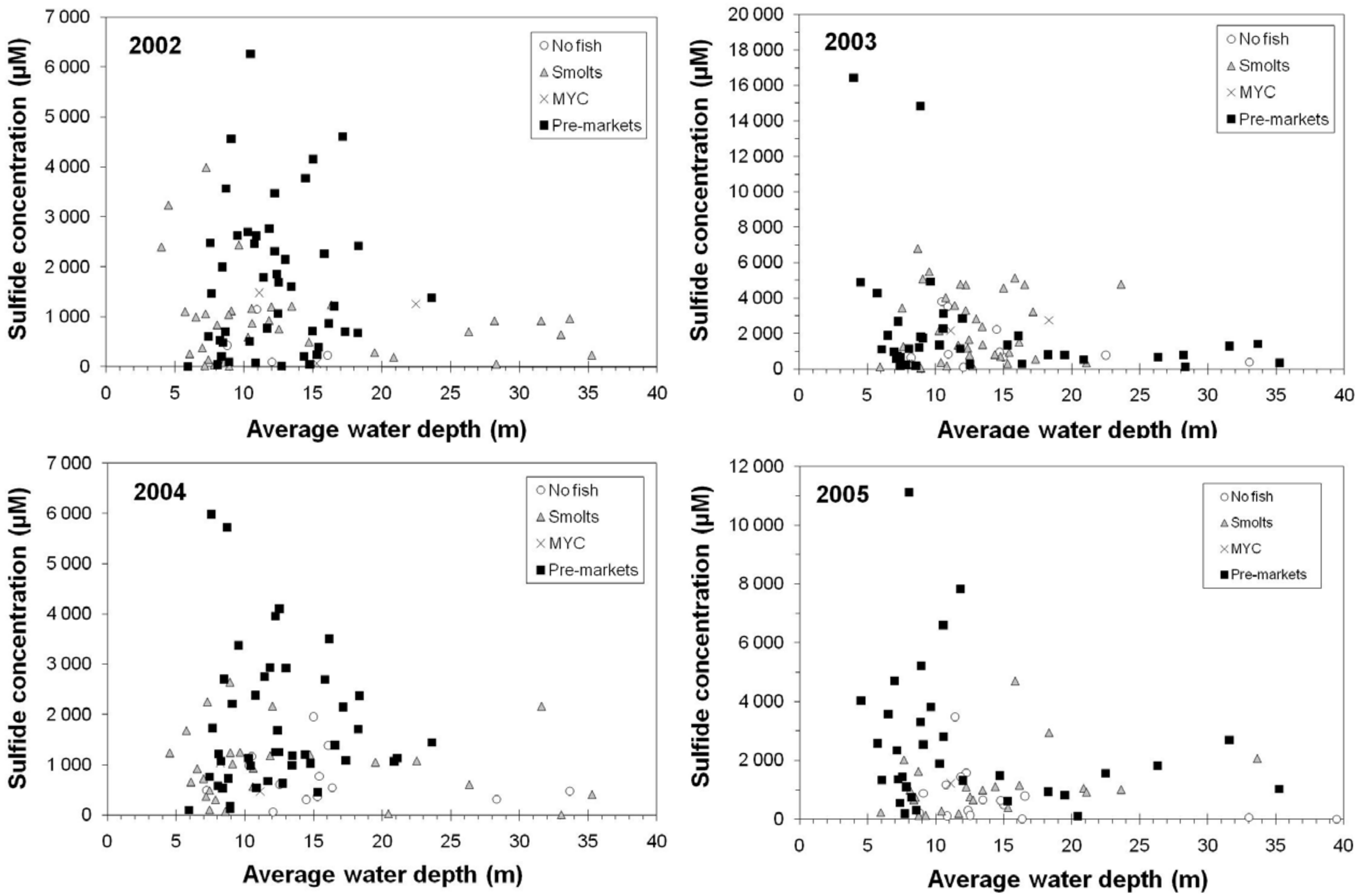


Fig. 11. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the average water depth at salmon farms in SWNB, 2002–2008. Depths are averages of all depth records taken within each farm's lease boundaries; depth records (relative to lowest normal tide) were obtained from Canadian Hydrographic Service field sheets. MYC = multi-year-class farms (holding smolts and pre-market salmon).

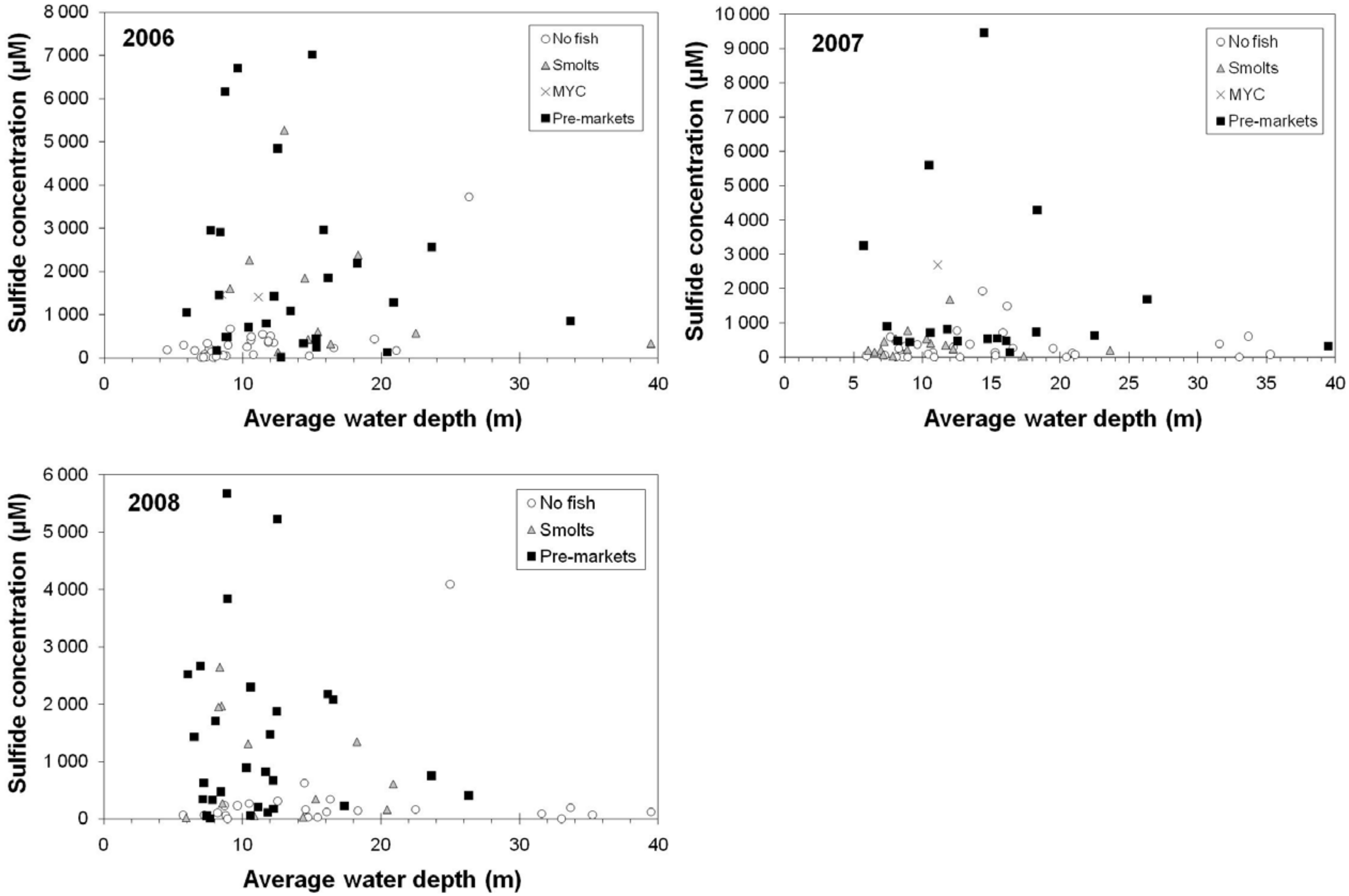


Fig. 11 (concluded).

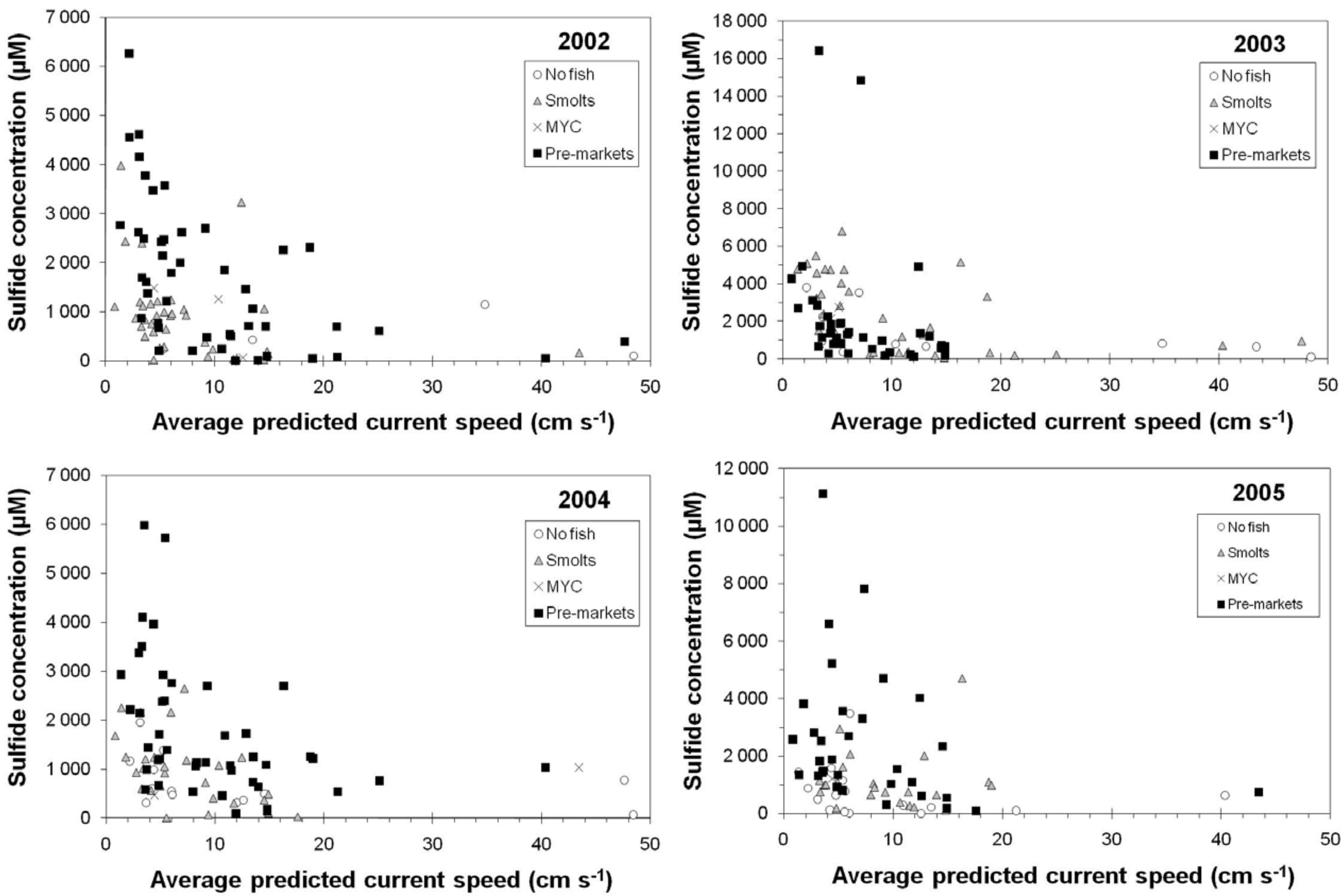


Fig. 12. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the average predicted current speed at salmon farms in SWNB, 2002–2008. Current speeds were predicted using a tidal circulation model (see text). MYC = multi-year-class farms (holding smolts and pre-market salmon).

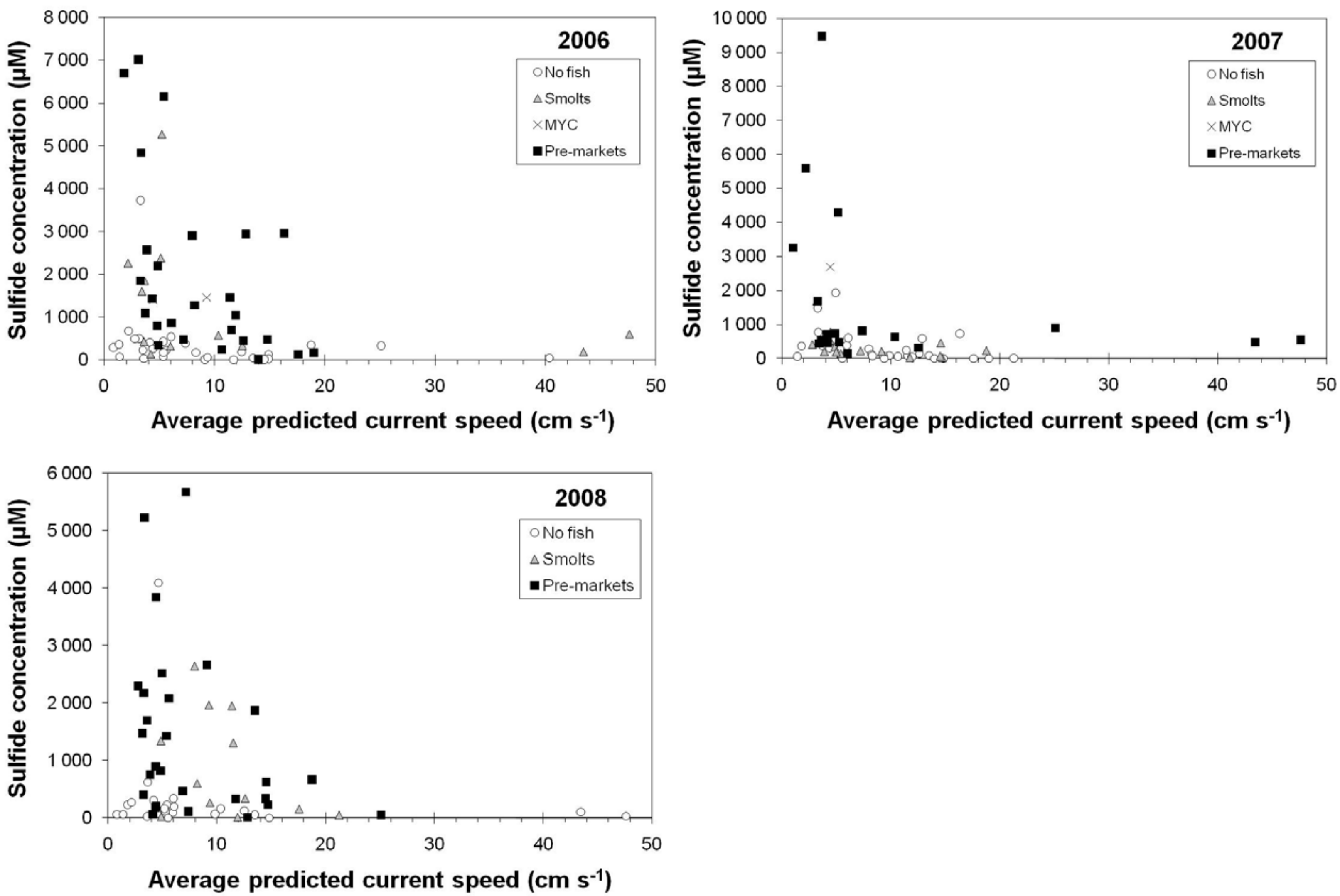


Fig. 12 (concluded).

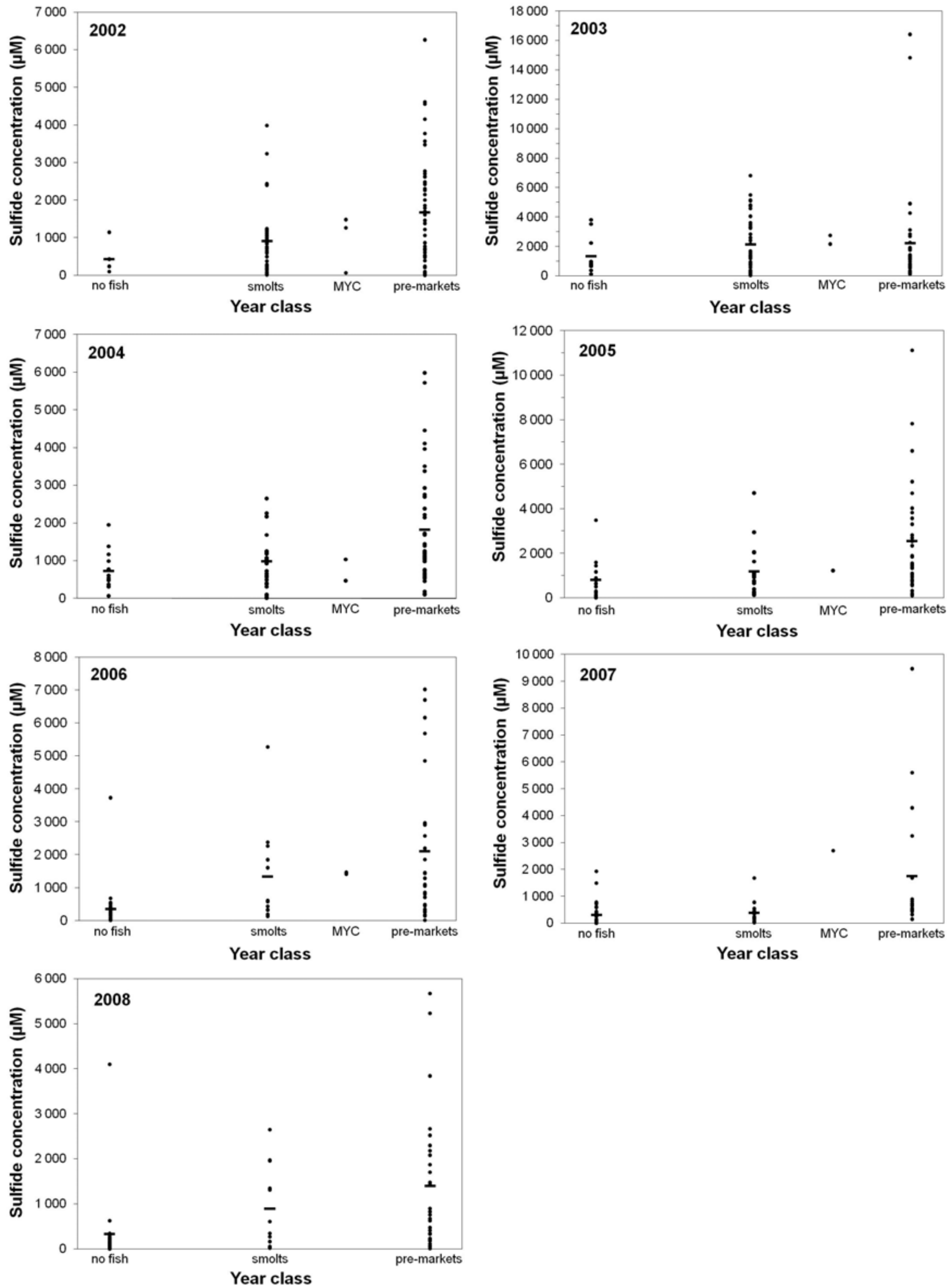


Fig. 13. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the year-class (year of stocking) of salmon on site at the time of monitoring at salmon farms in SWNB, 2002–2008. MYC = multi-year-class farms (holding smolts and pre-market salmon). Short horizontal bars indicate year-class averages.

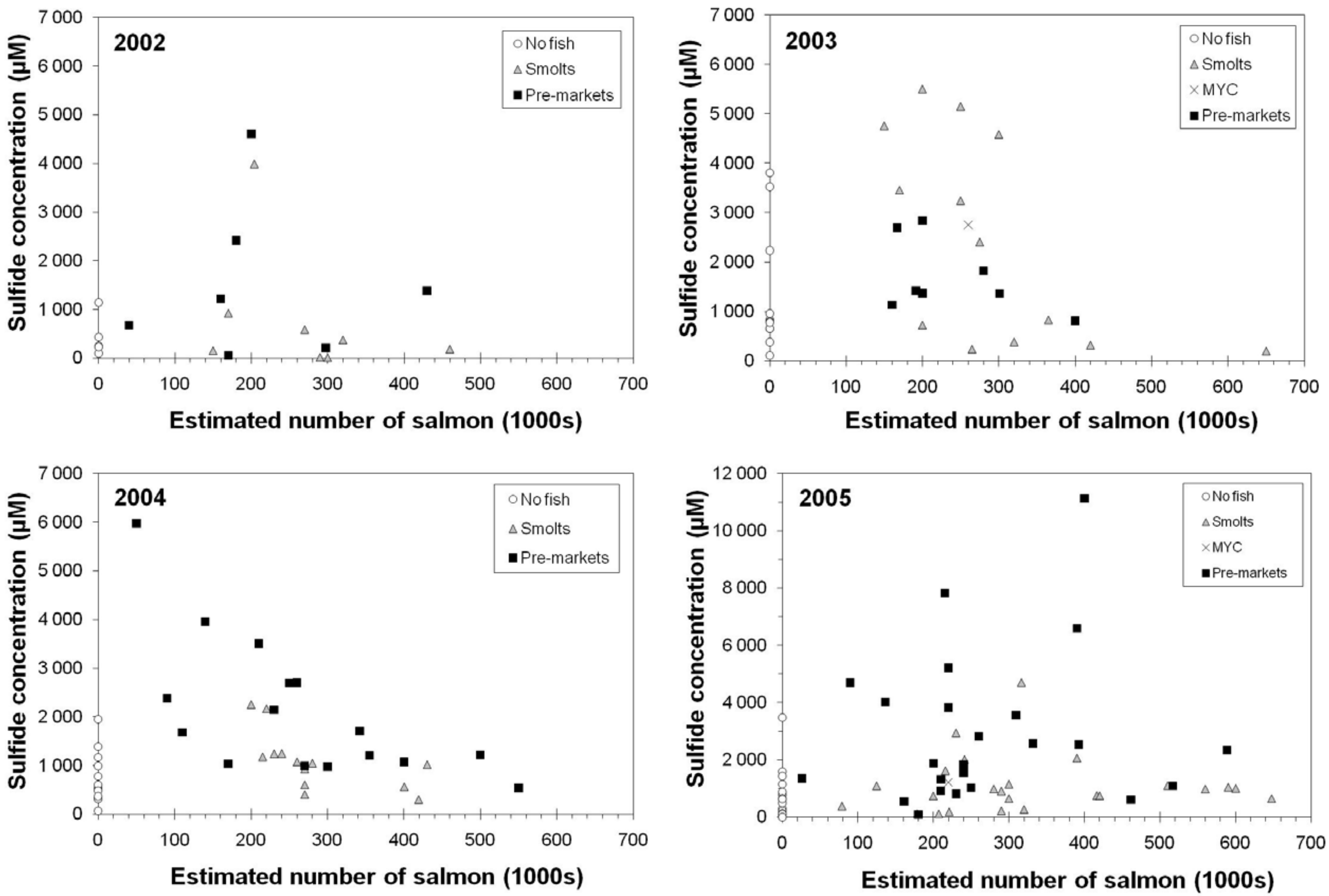
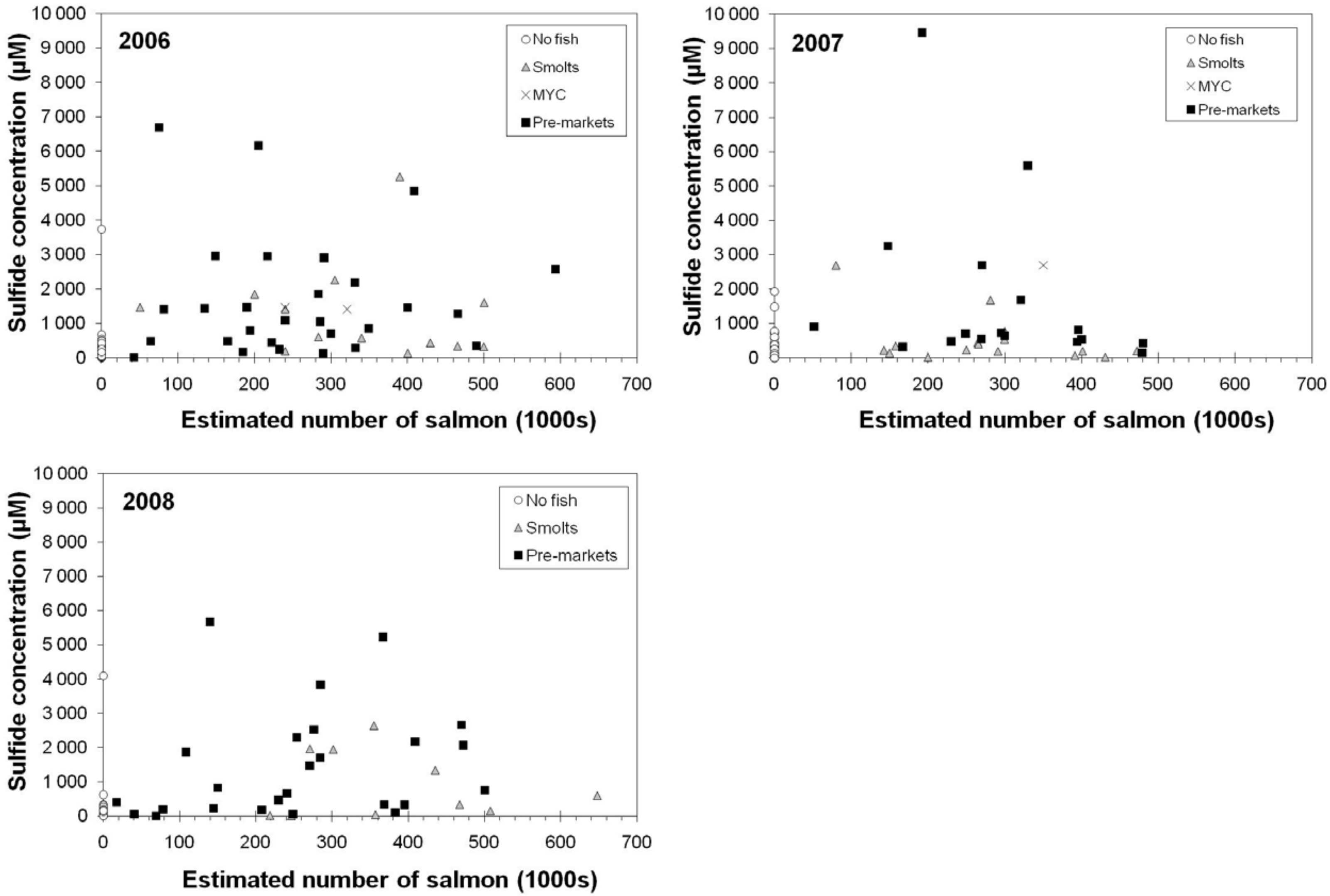


Fig. 14. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the estimated number of salmon on site at the time of monitoring at salmon farms in SWNB, 2002–2008. Numbers of salmon were available for ≤51% of farms monitored in 2002–2004 (see Table 2). MYC = multi-year-class farms (holding smolts and pre-market salmon).



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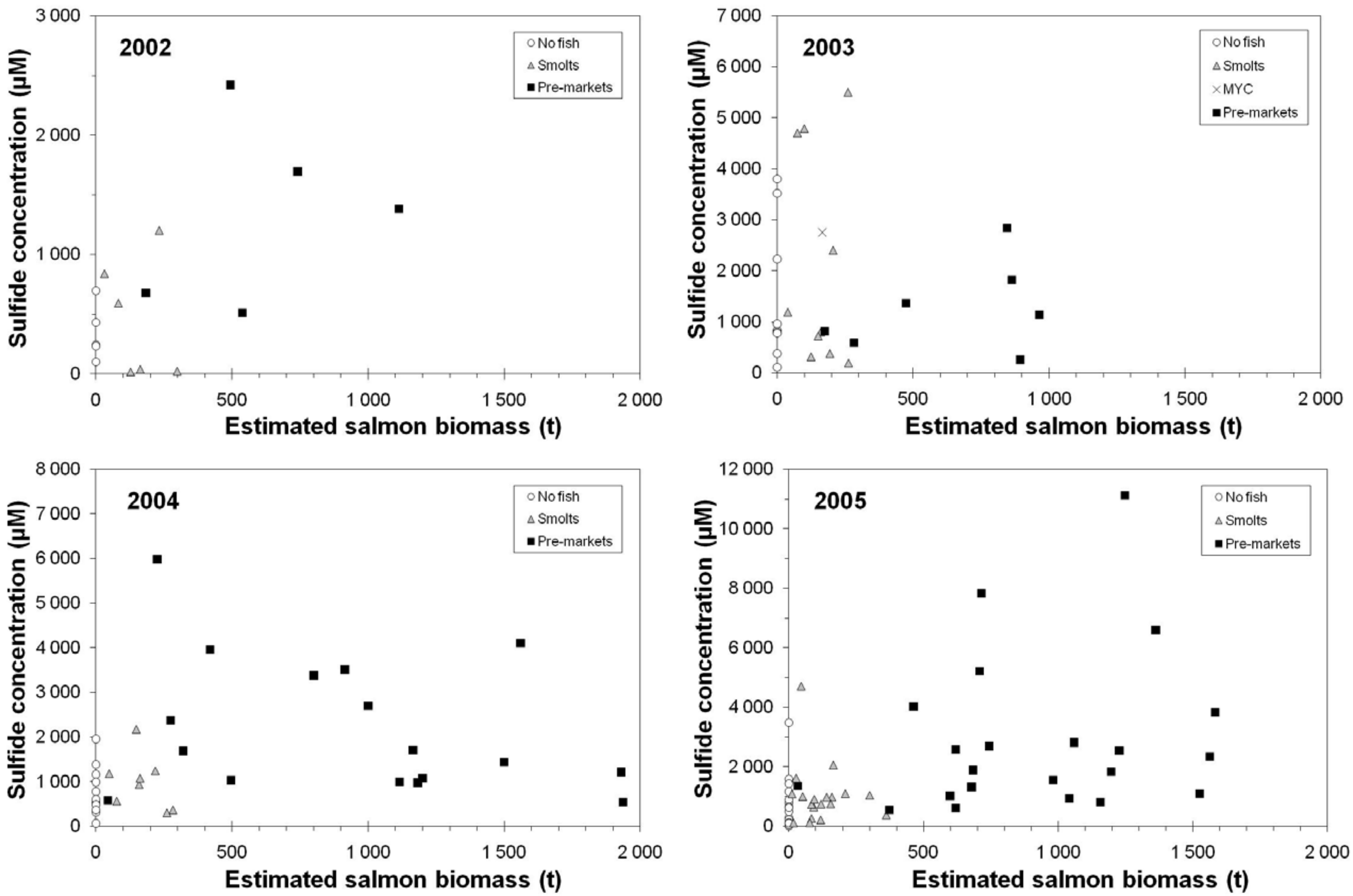

Fig. 15. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) and the estimated biomass of salmon on site at the time of monitoring at salmon farms in SWNB, 2002–2008. Biomass data were available for ≤43% of farms monitored in 2002–2004 (see Table 2). MYC = multi-year-class farms (holding smolts and pre-market salmon).

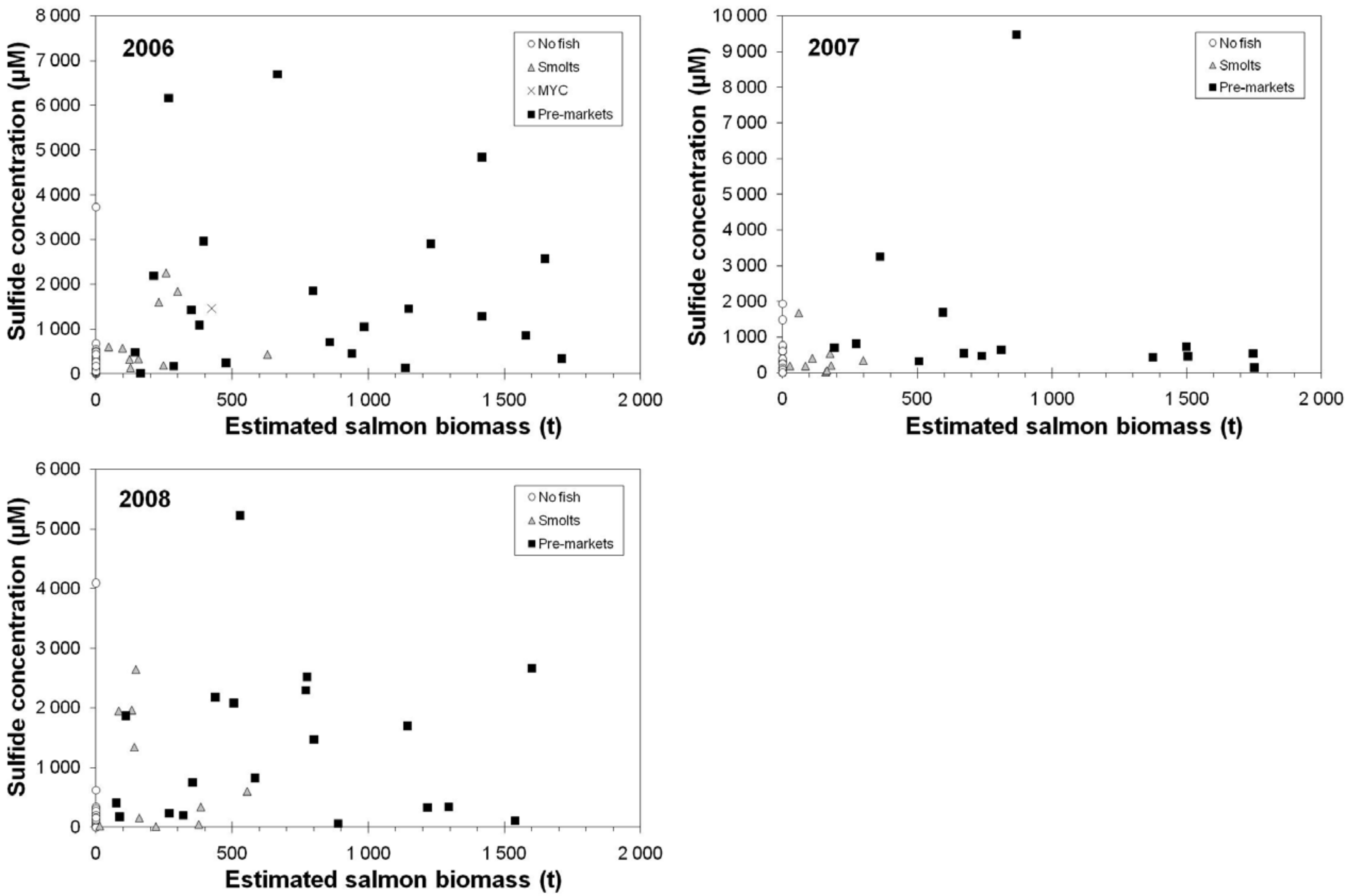

Fig. 15 (concluded).

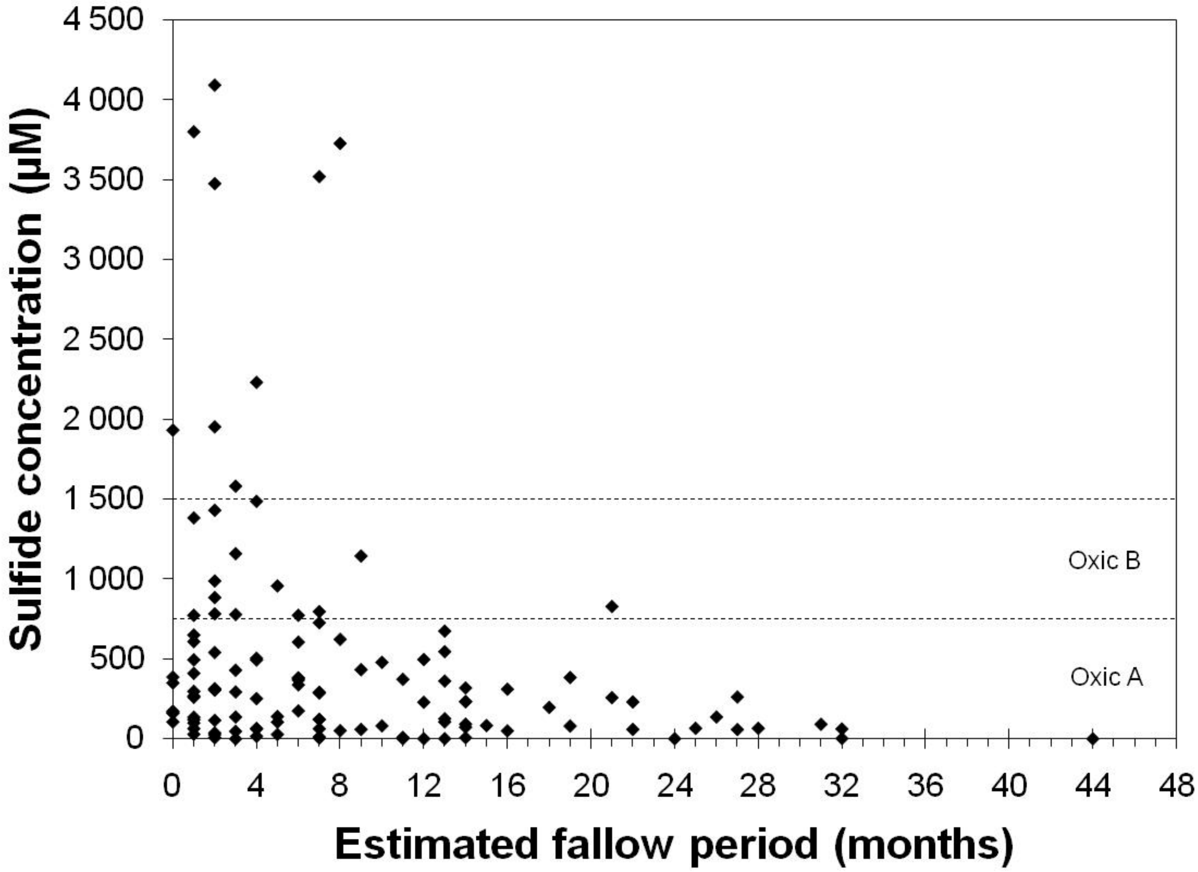

Fig. 16. Relationship between the Tier 1 monitoring sediment sulfide concentration (total S^{2-}) at fallowed farms (holding no salmon at the time of monitoring) and the estimated fallow period (months between harvesting and monitoring), at salmon farms in SWNB, 2002–2008. The dashed lines represents the upper limits of the Oxic A (750 µM S^{2-}) and Oxic B (1 500 µM S^{2-}) environmental ratings. The 120 data points represent 79 farms; 36 farms were monitored more than once while fallowed during the years 2002–2008.

A HISTORY OF THE ANNUAL BENTHIC MONITORING PROGRAM FOR MARINE FINFISH FARMS IN THE SOUTHWESTERN NEW BRUNSWICK AREA OF THE BAY OF FUNDY, 1991–2010

INTRODUCTION

The Environmental Management Program (EMP) for marine finfish farms in southwestern New Brunswick (SWNB) is administered by the New Brunswick Department of Environment (NBDENV). The overall goal of the program is "to guide the long-term environmental sustainability of the marine finfish cage aquaculture industry in New Brunswick" and the primary purpose is "to accurately evaluate the condition of the marine sediments under the marine finfish cage aquaculture sites and provide a reliable indicator of compliance with the MEQO [Marine Environmental Quality Objective]" (NBDENV 2006a). The MEQO with regard to organic enrichment of sediments under marine finfish aquaculture sites is oxic conditions. The environmental indicators for achieving the MEQO have also been defined, and are described below. The program requires that each farm be monitored annually in the late summer or fall, during the peak of growth and feeding.

Marine cage culture of finfish in SWNB started in 1978. There are now more than 90 licensed finfish farms in this area, of which approximately 60% are currently active, mostly growing Atlantic salmon (*Salmo salar*). Finfish farms in SWNB are located in relatively shallow, nearshore waters, where depths are <40 m below normal lowest tide. Most farms in SWNB are located over soft substrate, where sediment samples can usually be collected fairly easily; however, some farms are located over rocky/cobble substrates where the collection of sediment samples can sometimes be difficult.

The EMP has developed from research that has been conducted on the benthic impacts of salmon aquaculture in SWNB. In a 1985 study in the Letang area, anoxic conditions (negative redox potential in sediments under the farm) were found in one of ten operating farms that were sampled (Wildish et al. 1986). In a follow-up study in 1986–87, anoxic conditions were found in some samples at three of nine sites sampled (Wildish et al. 1988). The results of these studies led to the development of a proposal for environmental monitoring of the industry, noting the need for annual monitoring of all fish farms in SWNB (Wildish et al. 1990a). Additional research found anoxic sediments (based on redox potential) at some salmon farms in SWNB in 1988–1990 (Wildish et al. 1990b, 1990c).

Another early study, conducted in 1986–87 in Dark Harbour, a semi-enclosed bay on Grand Manan Island, found substantial benthic impacts (based on the abundance of two macrobenthic indicator species) under salmon cages (Rosenthal and Rangeley 1989). The Huntsman Marine Science Centre (HMSC) conducted benthic biodiversity monitoring at some newly-established farms in SWNB during 1989–1991; changes in species richness and abundance were detected under cages, but did not extend beyond about 50 m from cages (Lim 1991; Pohle et al. 1994). Further HMSC research in 1994–1995 found detectable impacts up to 150 m away from a farm that had been operating for 12 years in the Letang area, as well as indications of some bay-wide organic enrichment in two bays in this area which contained several salmon farms (Pohle and Frost 1997; Pohle et al. 2001).

The first industry-wide monitoring of SWNB aquaculture farms was conducted in 1991 and 1992. This monitoring program was largely based on the Wildish et al. (1990b) proposal. The monitoring program has evolved since then, in response to suggestions emanating from research and monitoring results, as well as to changes in farm size, cage type and farm layout. In the early years of the industry, farms were mostly 1 ha in area or less, holding just a few thousand fish. The earliest cages used in SWNB had wooden octagonal collars, 10–12 m in diameter, with nets 4–6 m deep, holding 1 200 – 3 000 fish per cage. Square steel collars were used starting around 1986; these collars were usually 12–15 m wide, with nets 5–6 m deep, holding 3 000 – 6 000 fish per cage. Both the wooden and steel cages were arranged in rafts of connected cages. Larger circular plastic collars were first used in the late 1980s, and now dominate the industry. These cages are arranged in arrays of 1–3 rows, usually with about 10–20 m of water separating adjacent cages. Currently, the most common cage sizes are 70–100 m in circumference (22–32 m diameter) with nets 8–12 m deep, holding 15 000 – 30 000 fish per cage. Most farms initially were allowed to have more than one year-class of fish on site, but since 2000, farms have been required to become single-year-class operations. The average farm size in 2009 was 19 ha, and salmon farms operating in that year held an average of about 330 000 fish.

THE BAY OF FUNDY SALMON AQUACULTURE MONITORING PROGRAM, 1991 AND 1992

The first industry-wide monitoring of SWNB aquaculture farms was the Bay of Fundy Salmon Aquaculture Monitoring Program conducted in 1991–1992 (Thonney and Garnier 1992, 1993). The purpose of the program was to assess the impacts of salmon farming operations on the marine environment in SWNB, with an overall objective "to collect the type of information which could provide a site specific assessment of the industry's impact on the natural environment" (Thonney and Garnier 1992). Specific goals of this initial monitoring program were (Thonney and Garnier 1992):

- to qualitatively determine the area of seabed impacted by the cage operations;
- to document the physical oceanographic characteristics at each cage site;
- to document the operational characteristics of each site through contact with workers, including production information supplied by each operator;
- to characterize the benthic community structure in the vicinity of the cage site for comparison with a distant control site.

The data from this survey were used to measure the extent of environmental degradation at each farm and to identify those in need of remedial action.

Each farm was monitored in late summer or fall of 1991 and 1992. At each farm, one 100-m transect was laid on the seafloor (Fig. A1), extending in the downstream direction of prevailing currents from the edge of the oldest market fish cage (most farms at this time were multi-year-class sites). Sediment samples were collected by divers using 50 cm long × 5 cm diameter cores;

the top 5 cm was kept for sediment analyses. Sediment samples were collected under the cage at the farm end of the transect, as well as at a control location 100 m away at the other end of the transect (in 1991, sediment samples were also collected along the transect at 10 m and 25 m from the farm). Benthic samples were also collected at the same locations for analysis of macrobenthos. Video recordings were made along the transects, and diver descriptions of the seafloor were also recorded. In addition, current meters were deployed at each farm.

The parameters measured included: water depth; mean bottom current speed and direction; sediment conditions (% silt/clay, redox potential, abundance of Capetellid worms); bacterial coverage (*Beggiatoa* sp.) on the seafloor; presence of gas bubbles released from sediments; and observations on the abundance and diversity of benthic macrofauna. The environmental conditions directly under the cage area were given qualitative ratings of low, moderate, or high environmental impact, based on the criteria shown in Table A1.

In 1991 and 1992, most farms showed only minor to moderate signs of seafloor degradation. The few farms which showed high levels of degradation were expected to recover quickly if fallowed (Thonney and Garnier (1993). The most important variables affecting seafloor conditions were: water depth, current speed, cage configuration (cages clustered vs. spread out), and husbandry practices (feeding techniques, net cleaning methods, fallowing). A conclusion of the program was that “With proper site selection and prudent husbandry practices, this industry has the potential to grow without jeopardizing the integrity of the marine environment” (Thonney and Garnier 1993).

THE ENVIRONMENTAL MANAGEMENT PLAN FOR THE MARINE FINFISH AQUACULTURE INDUSTRY IN THE BAY OF FUNDY, NEW BRUNSWICK, 1995–2001

The results from the initial monitoring program in 1991 and 1992 were used to develop the Environmental Management Plan for the Marine Finfish Aquaculture Industry in the Bay of Fundy, New Brunswick, which was implemented for all farms starting in 1995 (there was no industry-wide monitoring conducted in 1993 and 1994). The program used in 1995–2001 (Washburn & Gillis 1995; Janowicz and Ross 2001) was similar to the earlier program, with a few modifications. The time frame for monitoring was more precisely specified: monitoring was to be conducted between 1 September and 15 November of each year. One video transect was required for every raft of cages holding a maximum of 75,000 fish; in 1998 this was changed to one transect for each group of cages holding a maximum of 100,000 fish. For each transect, sediment samples were taken by divers, using 5-cm diameter core tubes (the top 5 cm was used for sediment analyses): directly under the cages, at the edge of the cage raft, at the downstream end of the 50 m transect (Fig. A2), and at a control site (except farms receiving a “low impact” rating in the previous year were only required to collect sediment samples under the cages and at a control site). Farms were given qualitative ratings, according to Table A2. Farms receiving a “high impact” rating were required to repeat the monitoring in the following spring. Since the qualitative ratings meant that they were somewhat dependent on the judgment of the consultant conducting the monitoring, it was recommended that one consultant be used for all farms, in order to reduce the potential for inconsistency among ratings (Washburn & Gillis 1995; Janowicz and Ross 2001).

THE ENVIRONMENTAL MONITORING PROGRAM OF THE ENVIRONMENTAL MANAGEMENT GUIDELINES FOR THE MARINE FINFISH CAGE AQUACULTURE INDUSTRY IN NEW BRUNSWICK, 2002–2005

The major shortcoming of the early monitoring programs was the subjective nature of the ratings. Furthermore, as the industry grew, it became less feasible to have one consultant conduct monitoring at all farms. Additional research resulted in a recommendation to replace the qualitative monitoring program with a cost-effective, quantitative method based on sediment geochemistry (Hargrave et al. 1995, 1997, 1998; Wildish et al. 1999, 2001a, 2001b). The suggested sediment geochemistry parameters were the redox potential (Eh, in mV_{NHE}) and sulfide concentration (total S^{2-}, in µM), measured in surface sediments under farms. To test the usefulness of redox potential and sulfides, these parameters were measured starting in 1998, for comparison with the qualitative rating system. Redox potential was measured using platinum electrodes and sulfide concentration was measured using silver/sulfide electrodes. The electrodes were inserted into sediment samples collected in the annual monitoring program. Analyses of these data showed that the sediment geochemistry parameters produced similar ratings to the previous qualitative ratings, while being more objective (Wildish et al. 2001b).

Consequently, a new Environmental Monitoring Program (EMP), based on sediment redox potential and sulfide concentration, was developed in 2001 as part of the Environmental Management Guidelines for the Marine Finfish Cage Aquaculture Industry in New Brunswick. The new monitoring program was implemented starting in 2002 (NBDELG 2001). In the new EMP, a minimum of two video transects was required per farm, or one for every 100,000 fish or part thereof. Each transect began 50 m from the cage and proceeded against the direction of the prevailing current to the centre of the cage with the highest biomass. For each transect, three sediment samples (using 5 cm diameter cores; the top 5 cm was used for sediment analyses) were taken by divers under the cage at the end of the transect: at the cage centre, 10 m toward the cage edge (in the direction of the prevailing current), and mid-way between the first two samples (Fig. A3). The dates for monitoring were also modified, to between mid-August and mid-October.

Separate protocols were provided for farms where the water depth at the lease centre was >30.5 m at mean low tide, where divers could not be used due to safety concerns. At these farms, sediment samples were to be collected using surface-deployed grabs or gravity corers. Four replicate sediment samples were to be taken at the centre of the farm and at each corner of the cage array, regardless of the number of fish on site. During 2002–2005, there were 4 farm leases where the average depth was >30.5 m.

Ratings were given according to Table A3. Site ratings were based on the average redox potential and sulfide concentration of all sediment samples taken at a farm; in the event that the redox potential and sulfide concentrations would result in different ratings, the site was given the "better" rating. For the purposes of fish habitat protection, anoxic conditions were considered to be unacceptable, while hypoxic conditions were of concern, and would require remediation measures to prevent progression to anoxia (Janowicz and Ross 2001). Anoxic sites were required to conduct additional monitoring within the same fall period, collecting samples from under 50% of the cages on the site.

The 2004 Standard Operating Practices (SOPs) for the EMP provided more precise descriptions of transect locations (Fig. A4; NBDELG 2004): transects were to be located at cages along the perimeter of the site (for ease of access); cages with the highest biomass were to be selected for transects; and the transect locations were dependant on the water current patterns. There was also a slight change in the locations of the three sediment samples for each transect at farms with water depth <30.5 m. The three samples were now taken along a line extending from the transect end to the cage centre: at the cage edge, 5 m toward the cage centre, and 10 m toward the cage centre (Fig. A4). Also, the minimum core length was set at 30 cm, and only the top 2 cm were used for sediment analyses. Protocols for sediment samples at farms where the water depth at the lease centre was >30.5 m were not changed.

THE ENVIRONMENTAL MONITORING PROGRAM OF THE ENVIRONMENTAL MANAGEMENT PROGRAM FOR THE MARINE FINFISH CAGE AQUACULTURE INDUSTRY IN NEW BRUNSWICK, VERSION 2.0 (2006–PRESENT)

Further research by Wildish et al. (2004, 2005) indicated that redox potential monitoring results were highly variable and therefore were not a reliable indicator of sediment condition. It was suggested that sediment sulfide concentration alone should be used for rating sites, although it was noted that another independent approach should be included to confirm the sulfide results; however, such an independent approach has not yet been developed. In the Environmental Monitoring Program Version 2.0 (EMP 2.0), implemented in 2006, site ratings are based on the sediment sulfide concentration alone (Table A4; NBDENV 2006a). Redox potential is still measured for all sediment samples, and videos and diver observations are still made, as part of the overall site assessment, and to aid in developing management responses.

The EMP 2.0 uses a Performance Based Standards (PBS) approach to the regulation of marine environmental quality. Under the PBS approach, farms with Hypoxic B or worse ratings are required to provide strong justification to maintain or increase the numbers of fish stocked. Any further increase in the intensity of impact requires progressively more rigorous mitigation and remediation measures.

Monitoring is also 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 (NBDENV 2006a). Fisheries and Oceans Canada established a sediment sulfide concentration of 3000 µM as the level at which a farm is likely causing adverse benthic conditions, and a FAA may be required. When the sulfide concentration reaches 4500 µM, the farm is considered to be causing adverse benthic conditions, and a FAA will likely be required.

A FAA grants the authority to cause a HADD, but requires the proponent to provide compensation for the lost fish habitat. The amount of compensation is based on the area of lost habitat. Therefore, there is the need to estimate the area of degraded impact when a FAA is required. The annual summer-fall monitoring program in place prior to 2006 was intended to provide an indication of the general magnitude of organic enrichment; it was recognized that it would not describe the temporal or spatial variability of organic enrichment of the seafloor under fish farms.

The EMP 2.0 uses a multi-tiered approach (Table A4). Every site is required to conduct annual Tier 1 monitoring between 1 August and 31 October. The site's rating is based on the average sulfide concentration of all samples taken in the Tier 1 monitoring. If the average Tier 1 sulfide concentration is >3000 µM, then Tier 2 monitoring must be conducted within 20 d. The Tier 2 monitoring has two purposes: to confirm the Tier 1 results and to provide an estimate of the spatial variability of the impact. Tier 3 monitoring must be conducted in the following spring if the average Tier 1 sulfide concentration is >4500 µM, and an additional Tier 2 monitoring is required within 20 d if the average Tier 3 sulfide concentration is >3000 µM.

In the Tier 1 monitoring protocols used starting in 2006 (NBDENV 2006b), the number and locations of transects were the same as those used since 2004, but there was a change in the sediment sample locations: at each transect, three sediment samples were to be taken at the cage edge, in close proximity, in similar substrate types (Fig. A5); in practice, the three samples were usually taken within a 1 m^2 area. At farms where the water depth at the site centre was <30.5 m (at mean low tide), core samples were to be taken by divers. At farms where the water depth at the lease centre was >30.5 m (5 farm leases during 2006–2010), the locations and numbers of samples were the same as for shallower sites, but the samples were to be collected using surface-deployed grabs or gravity corers. The change in the exact sample locations was implemented due to safety concerns related to divers operating directly under cages at shallow sites, and the inability to obtain samples under cages when using surface-deployed grabs or corers at deeper sites. If no fish are present at the site, no transects are required, but sediment samples are to be taken at two locations (total of 6 samples), at locations used in the most recent Tier 1 or Tier 3 monitoring at the site.

Tier 2 monitoring in 2006 (NBDENV 2006b) consisted of five transects per site: one at each corner of the cage array, and one at the site centre, with three sediment samples taken at the cage edge for each transect (Fig. A6). It was subsequently determined that this would not provide adequate spatial information, and a revised Tier 2 was put in place in 2007 (NBDENV 2007), based on advice produced by Fisheries and Oceans Canada (DFO), Science Branch (DFO 2006). This monitoring requires considerably more sample locations: at 4 locations around each corner cage, one location at the outside edge of all cages situated along the perimeter of the cage array, and mid-way between each pair of cages, with triplicate samples at each location (Fig. A7). The intent of this monitoring design is to provide an estimate of the area of any degraded habitat below the cage array, at a spatial scale of about 100 m. Tier 3 monitoring follows the same protocols as Tier 1 (Fig. A5).

There were minor changes to the standard operating practices for monitoring implemented in 2010. The precise locations for the three sediment samples at each transect are now more clearly defined: they must be taken within a 1 m^2 area, in similar substrate types (previously, the three samples were to be taken "in close proximity", in similar substrate types). Diver-deployed cores are now to be used only if all monitoring locations at a farm are <30 m depth at mean low tide; if one or more monitoring locations are >30 m depth, surface-deployed grabs will be used for all locations (previously, surface-deployed grabs or corers were to be used only where the depth at the centre of the farm was >30.5 m).

HISTORICAL TRENDS IN ENVIRONMENTAL RATINGS

Because the monitoring protocols and ratings categories have changed over the years, exact comparisons between years cannot be made. Nevertheless, if we consider the qualitative ratings of Low, Moderate, and High impacts from the qualitative ratings during 1995–2001 to be roughly equivalent to Oxic, Hypoxic, and Anoxic ratings, respectively, based on geochemical measurements since 2002, we can compare the frequencies of ratings over the years (Fig. A8). The data suggest that there have been fewer farms causing Hypoxic or Anoxic conditions (Moderate to High impacts) in recent years.

DISCUSSION

The ultimate goal of most environmental monitoring programs is to prevent unacceptable changes to habitat. The SWNB EMP focuses on sediment conditions under fish farms, specifically the impacts of organic enrichment on benthic biodiversity. The program has changed over the years, reflecting the results of research on environmental impacts of salmon farms in SWNB, as well as changes in cage types and farm layouts, and increases in farm sizes. The original monitoring programs used in SWNB used qualitative ratings, based on a number of criteria. These were later replaced with quantitative ratings, based on sediment geochemical variables.

A traditional approach to measuring the impacts of organic enrichment in the benthos has been to study changes in the diversity of the benthic invertebrate community in and on the sediments. However, such an approach is difficult to apply in an annual industry-wide monitoring program, due to the high costs and the delay in getting results due to the time required to process samples. As a result, various geochemical variables have been examined for use as proxies for measuring changes in benthic biodiversity (Wildish et al. 2001a; Hargrave et al. 2008; Hargrave 2010). In SWNB, redox potential and sulfide concentration were initially chosen, but the current SWNB EMP ratings are based on sediment sulfide concentration alone, although the redox potential is still measured to assist in the site assessments.

In the current EMP, a farm's environmental rating is based on the average sulfide concentration of all samples collected in the Tier 1 monitoring (triplicate samples from 2–8 locations, at cage edges). The cages selected for monitoring are the highest biomass cages located on the perimeter of the cage array. This means the ratings are based entirely on samples taken at cages holding higher biomasses of fish, and therefore are intended to represent the higher impacted areas at farms, rather than the average conditions; however, because only perimeter cages are sampled, the highest biomass cages at a farm will not always be monitored. The monitoring design also means that the EMP is designed to examine only localized (near-field) effects.

In 2005–2007 spatially intensive sediment sampling was conducted at some SWNB salmon farms to examine small-scale variability in the sulfide concentration (Chang et al. 2011). The results showed that the distribution of the sediment sulfide concentration under salmon farms was very patchy: elevated sulfide concentrations were only found in a small portion of the total area under the cage array, but in some cases were found outside the cage array. In some cases, there was considerable variability in sulfide concentration among subsamples taken from the same grab sample. Previous studies by Wildish et al. (2001a, 2001c) also found considerable small-scale patchiness under salmon farms in SWNB. These data suggest that the limited number of sample locations in the EMP Tier 1 monitoring (2–8 locations per farm) would not adequately describe this spatial heterogeneity, and therefore may not provide accurate environmental ratings for farms. Even though the intent of the Tier 1 monitoring is to sample the higher impacted areas, if the small-scale heterogeneity is as great as these studies suggest, there is the possibility that the high sulfide patches could be missed.

Tier 2 monitoring is intended to provide an estimate of the spatial extent of the impacted area of the seafloor (as well as to confirm the Tier 1 results). However, the Tier 2 monitoring protocols used in 2006, with only five sample locations per site (NBDENV 2006b), would not provide a precise or accurate estimation of the spatial extent of any benthic impacts. The Tier 2 monitoring locations used since 2007 (NBDENV 2007), with considerably more sample locations, should be adequate to describe the sulfide distribution under the cage array area at a resolution of about 100 m, but would miss any high sulfide areas that extended beyond the cage array, since sampling was only within the perimeter of the cage array. Therefore if one of the goals of the Tier 2 monitoring is to estimate the total area of impact, then sampling must be expanded to include locations outside the cage array. Recent research (Chang et al. 2011) suggests that sampling at distances of about 150–200 m from the cage array should be sufficient to determine the extent of near-field benthic impacts at most farms. Much less is known about the extent and magnitude of far-field effects of fish farms (Hargrave 2003).

The results from the Chang et al. (2011) study suggest that further improvements in the EMP may be required. That study indicated that the existing sediment sulfide monitoring program includes considerable imprecision due to temporal and spatial variability which may not be detectable in a cost-effective monitoring program. This underlines the need to monitor additional parameters, to avoid dependence on this one variable.

The current EMP is only applicable at sites with soft bottom types. As such, it is feasible at all currently active farms in SWNB, although some farms are located over rocky/cobble substrate where sediment sample collection can be difficult. Regulators and researchers are in the process of developing methodologies for monitoring hard bottom sites, such as may be found further offshore in SWNB, in southern Newfoundland, and in British Columbia.

Comparison of ratings between years suggests that there has been a trend toward improved environmental ratings in recent years in SWNB. While part of this trend may be an artifact of the changes in the monitoring protocols and ratings categories over the years, there have been changes in the management and regulation of the industry which should have facilitated improved environmental conditions at salmon farms in SWNB. These changes include the implementation of the PBS approach to regulation, mandatory fallowing of farms between successive year-classes, cleaning of nets on shore (rather than on site), and improvements to feeds and feeding practices.

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Table A1. Qualitative ratings of benthic impacts used in the Bay of Fundy Salmon Aquaculture Monitoring Program in 1991 and 1992 (based on Thonney and Garnier 1993).

Degree of impact	*Silt/clay*	*Bacterial coverage*	*Gas bubbles*	*Benthic macrofauna*	*Water depth*	*Mean bottom current speed*
Low	<33%	<25%	No	Wide diversity of epibenthic macrofauna; hard bottom/strong current species	>10 m	>5 cm/s
Moderate	25-90%	25-100%	No	Less diversity, but higher biomass than control sites; low oxygen tolerant species; absence of hard bottom/ strong current species	>10 m	>5 cm/s
High	>90%	Grey or absent	Yes	No epibenthic macrofauna or benthic infauna	<10 m	<5 cm/s

Table A2. Qualitative ratings of benthic impacts used in the Environmental Management Plan for the Marine Finfish Aquaculture Industry in the Bay of Fundy, New Brunswick, 1995-2001 (based on Washburn & Gillis Associates Ltd. 1995 and Janowicz and Ross 2001).

Impact Rating	*Sea floor*	*Silt/clay*	*Bacterial Coverage*	*Gas bubbles*	*Benthic macrofauna*
Low (A)	Erosional	<30%	<25%	No	Wide diversity of epibenthic macrofauna; hard bottom/ strong current species
Moderate (B)	Moderately depositional	25-90%	25-100%	No	Less diversity, but higher biomass than control sites; low oxygen-tolerant species; absence of hard bottom/ strong current species
High (C)	Depositional	>90%	Grey or absent	Yes	No epibenthic macrofauna or benthic infauna

Table A3. Quantitative ratings of benthic impacts, based on sediment geochemistry, used in the Environmental Management Guidelines for the Marine Finfish Cage Aquaculture Industry in New Brunswick, 2002-05 (based on NBDELG 2001).

Site Classification	*Measured sediment conditions*		*Actions required*
	Redox potential (Eh) (mV_{NHE})	*Sulfide concentration (µM)*	
Oxic 1	>100	<300	None
Oxic 2	0 to 100	300 to 1 300	None
Hypoxic	-100 to 0	1 300 to 6 000	Develop measures to prevent progression to anoxia
Anoxic	<-100	>6 000	Conduct confirmation monitoring in fall & spring; develop Remediation Management Plan

Table A4. Quantitative ratings of benthic impacts, based on sediment sulfide concentration, used in the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick (Version 2.0), since 2006 (based on NBDENV 2006a).

Site classification	*Sediment sulfide concentration (µM)*	*Actions required*
Oxic A	<750	Tier 1 monitoring; follow OBMP[1]
Oxic B	750 to 1 500	Tier 1 monitoring; follow OBMP[1]
Hypoxic A	1 500 to 3 000	Tier 1 monitoring; adjustments to OBMP[1]
Hypoxic B	3 000 to 4 500	Tiers 1 & 2 monitoring; additional OBMP[1]; FAA[2] may be required
Hypoxic C	4 500 to 6 000	Tiers 1, 2 & 3 monitoring; enhanced OBMP[1]; FAA[2] likely required
Anoxic	>6 000	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

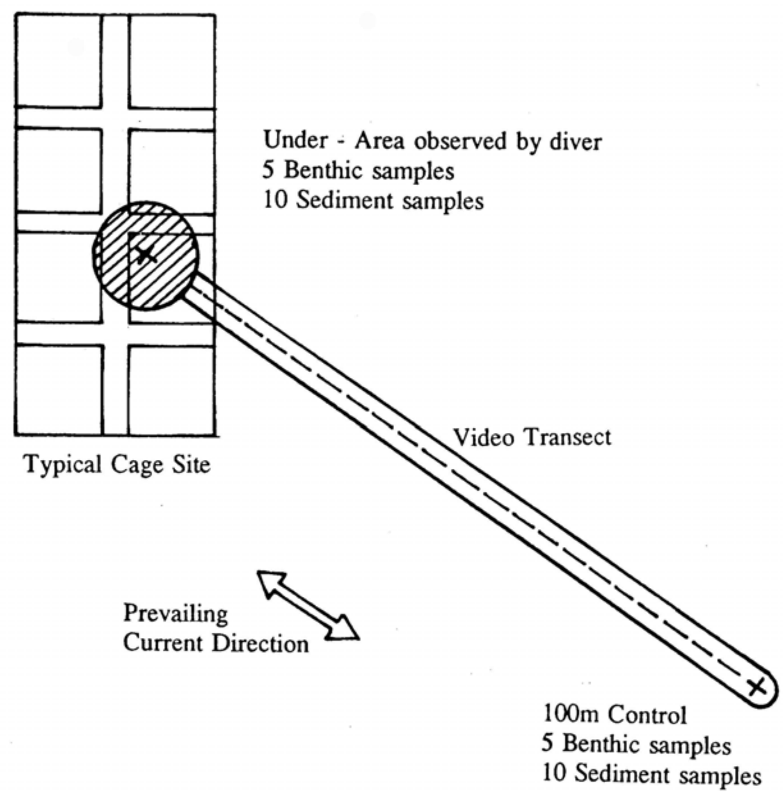

Fig. A1. Locations of transects and samples used for benthic monitoring in the Bay of Fundy Salmon Aquaculture Monitoring Program, in 1991 and 1992 (from Thonney and Garnier 1993).

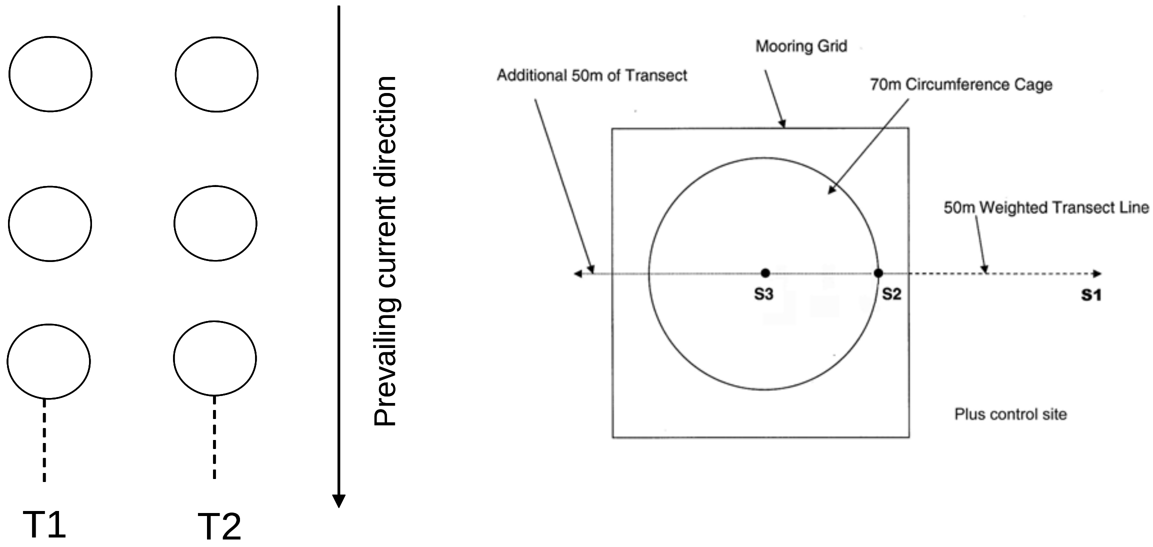

Fig. A2. Locations of transects and samples used for annual benthic monitoring in the Environmental Management Plan for the Marine Finfish Aquaculture Industry in the Bay of Fundy, New Brunswick, 1995-2001 (based on Washburn & Gillis 1995). Left: farm layout, showing locations of transects (T1 and T2) and current direction. Right: close-up of a cage showing locations of 3 sediment samples for each transect (S1 at downstream end of transect; S2 at cage edge; S3 at cage centre).

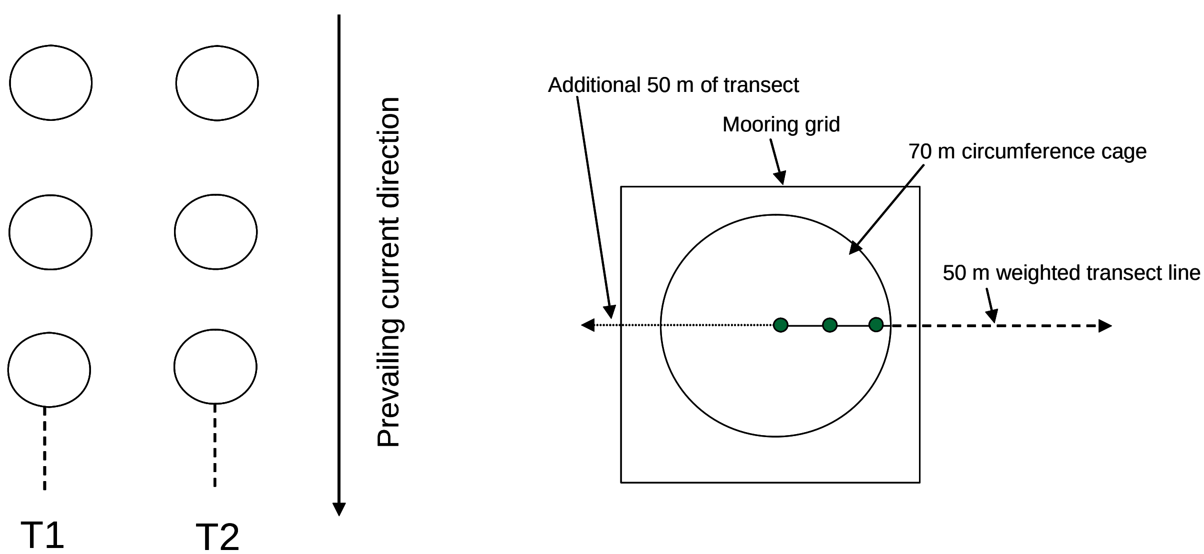

Fig. A3. Locations of transects and samples used in the Environmental Monitoring Program of the Environmental Management Guidelines for the Marine Finfish Cage Aquaculture Industry in New Brunswick, in 2002 and 2003 (based on NBDELG 2001). Left: farm layout, showing locations of transects (T1 and T2) and current direction. Right: close-up of a cage showing locations of 3 sediment samples for each transect (at cage centre, 10 m toward cage edge, and mid-way between the first two).

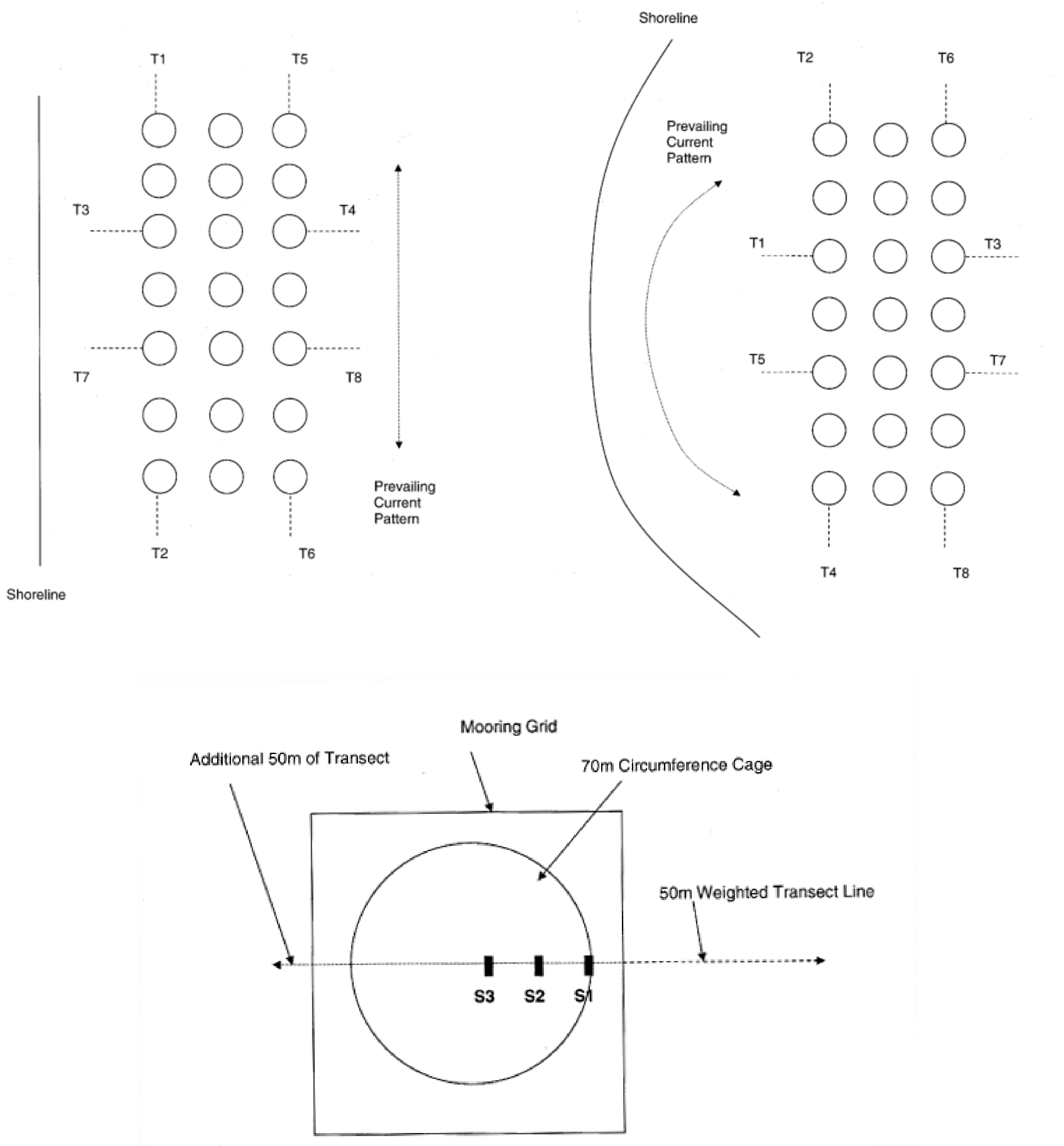

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Fig. A4. Locations of transects and samples used in Tier 1 and Tier 3 monitoring in the Environmental Monitoring Program of the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick, Version 2.0, in 2004 and 2005 (from NBDENV 2004). Top left: transect locations for sites with generally linear and/or moderate to strong currents. Top right: transect locations for sites with generally curved and/or weak currents. Bottom: close-up of a cage showing locations of 3 sediment samples for each transect (at cage edge, 10 m toward cage centre, and mid-way between the first two).

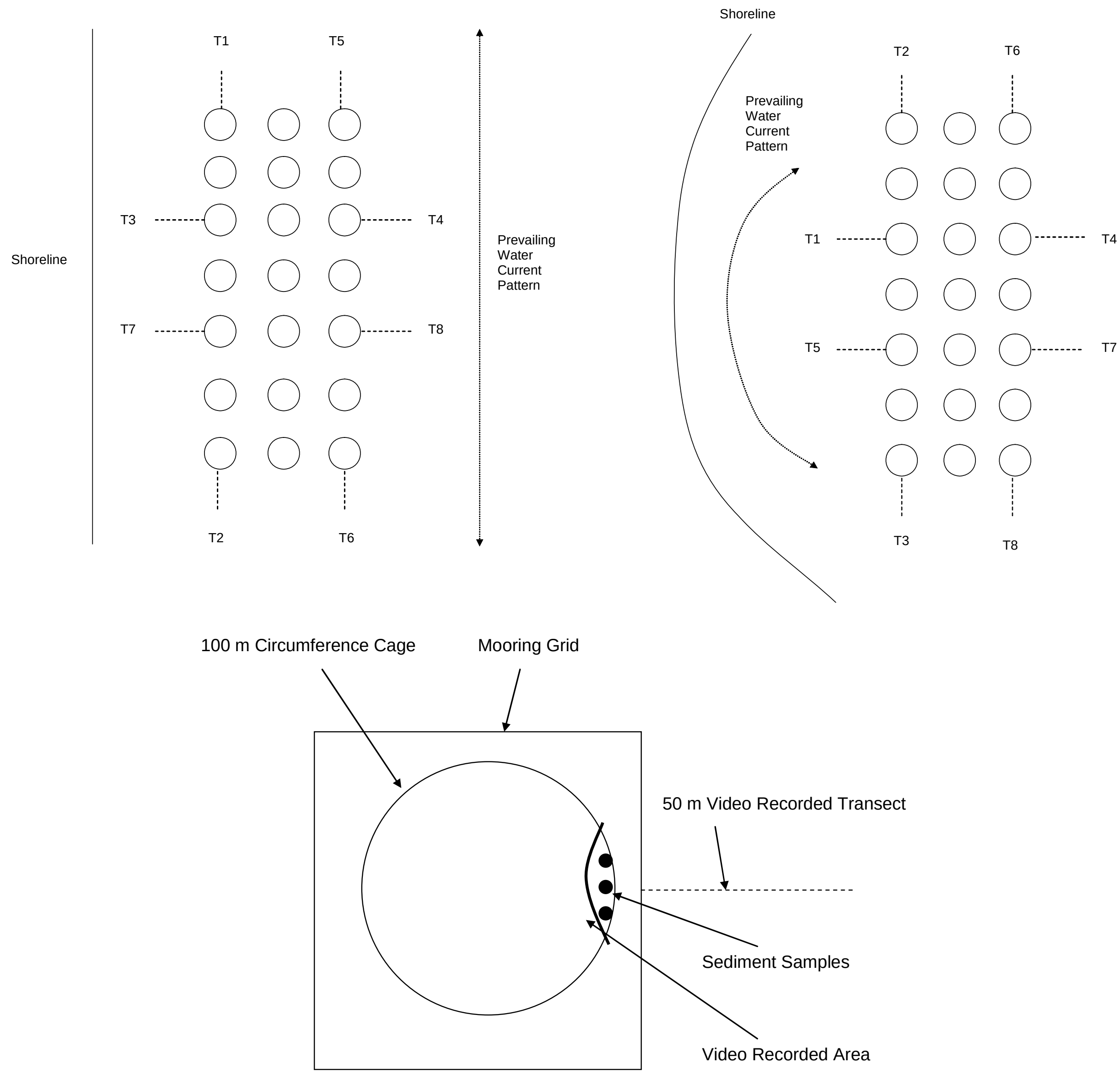

Fig. A5. Locations of transects and samples used in Tier 1 and Tier 3 monitoring in the Environmental Monitoring Program of the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick, Version 2.0, since 2006 (from NBDENV 2006b, 2007). Top left: transect locations 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 locations of 3 sediment samples taken at the cage edge (in close proximity to each other, in similar substrate types) for each transect.

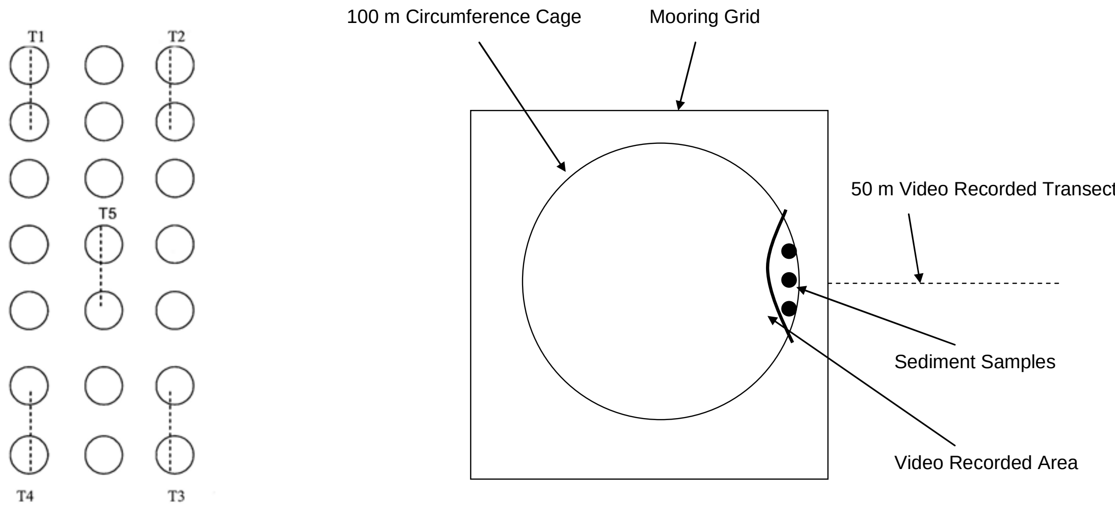

Fig. A6. Locations of transects and samples used in Tier 2 monitoring in the Environmental Monitoring Program of the Environmental Management Program for the Marine Finfish Cage Aquaculture Industry in New Brunswick, Version 2.0, in 2006 (from NBDENV 2006b). Left: transect locations (dotted lines). Right: close-up of a cage showing locations of sediment samples for each transect (same locations as for Tiers 1 and 2 in 2006).

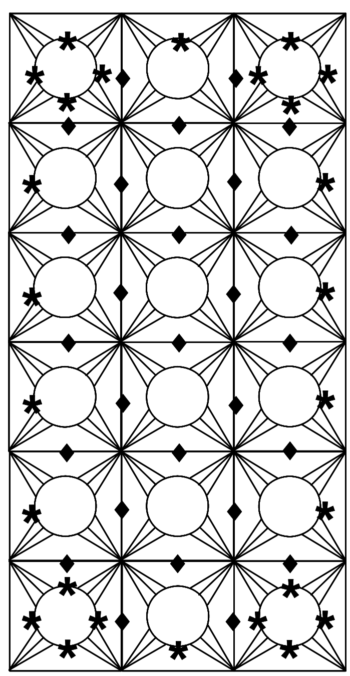

Fig. A7. Locations of samples used in Tier 2 monitoring in the Environmental Monitoring Program of the Environmental Management Program for the Marine Finfish Aquaculture Industry in New Brunswick, Version 2.0, since 2007 (from NBDENV 2007). Triplicate samples taken at each location marked by ∗ and ♦ (large circles represent cages).

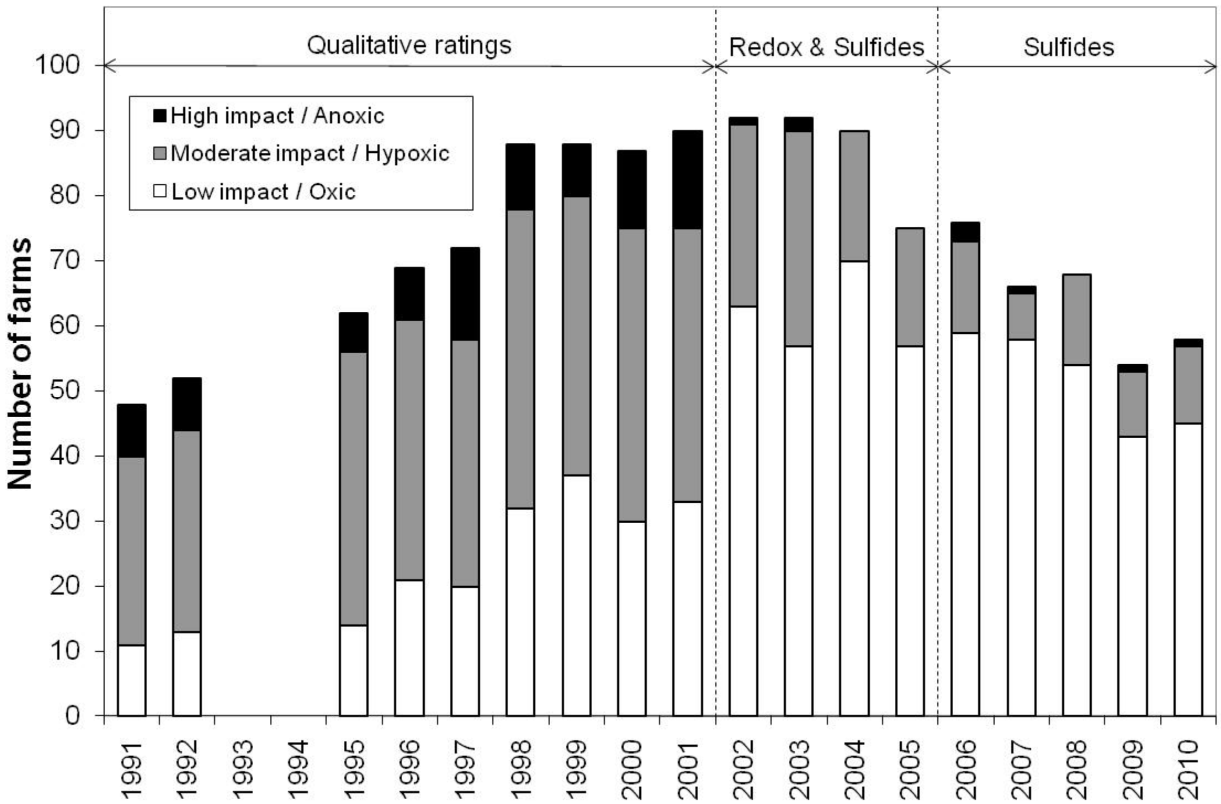

Fig. A8. Summary of environmental monitoring results for the southwestern New Brunswick marine finfish aquaculture industry, 1991-2009. There was no monitoring in 1993 and 1994. Because monitoring protocols and rating criteria have changed over the years, exact comparisons among years cannot be made. Qualitative ratings of high, moderate, and low impact were used in 1991–1992 and 1995–2001; geochemical ratings of anoxic, hypoxic, and oxic have been used since 2002. Data sources: E. Garnier (Dominator Marine Services Inc.); New Brunswick Department of Environment.