

Organic enrichment of sediments from salmon farming in Norway: environmental factors, management practices, and monitoring techniques

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Abstract

Environmental impacts of salmon cage aquaculture resulting from deposition of organic-rich particulate matter to the sea bottom have been thought to be a function of the local environmental conditions and management practices. However, testing of these suppositions have been limited by (1) widely varying monitoring methods employed, and (2) lack of data comparability resulting from the absence of standardized national monitoring schemes.

In order to determine the sensitivity of different monitoring methods in detecting benthic environmental effects, a comparative analysis was undertaken of four methods commonly employed in Norway that vary in cost and expertise required: (1) visual diver surveys, (2) faunal analysis, (3) sediment chemistry, and (4) Sediment Profile Imagery (SPI). Results indicate that all methods agreed in the common “impact zone” under and immediately next to the cages. However, each of the methods differed in their sensitivity in detecting more subtle effects at greater distances from the cages.

Data from 168 environmental survey samples located at various distances from working Norwegian salmon cage farms collected using similar methodology between 1996 and 1998 were analyzed to determine the relationship between environmental variables, management regimes, and levels of environmental impact. Total organic carbon (TOC) levels in sediments were significantly higher immediately adjacent to cages compared to reference sites, and approximately 32% of the samples under the cages showed significant degradation. At intermediate distances (50–100 m), influences from fish farming are not clearly detected by TOC analysis. Further, while neither depth nor current speed alone are good predictors for environmental management, the results suggest

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recovery of sites by periodic abandonment (or fallowing) is one of the best management tools for sustainable salmon farming in cold-water environments.

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1. Introduction

Fish production from marine aquaculture sites generates considerable amounts of effluent including nutrients, waste feed and feces, and by-products such as medications and pesticides. These effluents can have undesirable impacts on the local environment, depending on the amounts released, the time-scale over which the releases take place, and the assimilation capacity and flushing ability of the local recipient water body (Gowen and Bradbury, 1987; Ackefors and Enell, 1994; Wu, 1995; Axler et al., 1996; Kelly et al., 1996).

The environmental impact of dissolved constituents (ammonia, phosphorus, nitrogen, dissolved organic carbon, and lipids released from the diet) depends on the rate at which those products are diluted before being assimilated by the pelagic ecosystem (Black, 2001). In restricted exchange environments, there is a risk of high levels of nutrients accumulating in one area, causing hypereutrophication and potentially creating undesirable effects (Midlen and Redding, 1998; MacGarvin, 2000). However, in the marine environment, the effects of dissolved nutrients from aquaculture waste are considered negligible in relation to other inputs, such as from industry or agriculture (Fernandes et al., 2002), and in Norway, eutrophication to salmon cage farming is not considered a significant environmental impact factor (Skjoldal et al., 1997).

Organic input to the sediment, whether from natural or artificial sources, lead to a series of changes in chemical and physical parameters (Schaanning, 1994), which in turn have both direct and indirect effects on the faunal communities in the area (Pearson and Rosenberg, 1978). The extent of the environmental impact on the sea bottom is a function local assimilative capacity and amount of organic waste generated from aquaculture activities (GESAMP, 1986, 1991, 1996; Black, 2001). The former is largely dependent on local environmental conditions (bottom depth, topography, and current patterns) while the latter is strongly related to management practices (stocking density, feeding rates). The severe effects of salmon farming on the marine environment appear generally to be relatively localized (Brown et al., 1987); however, less severe environmental effects may be spread over a large area. Unfortunately, the combinations of multiple, specific environmental factors and fish farm management practices leading to various levels of severity and extent of environmental impacts have not been widely tested. This deficiency is generally due to a lack of data comparability resulting from the absence of standardized national monitoring schemes, and low statistical power of underlying data resulting from low sample sizes, or not covering a range of environmental conditions and management practices. Furthermore, a variety of field methods have been employed in monitoring surveys to detect the area and scale of environmental impacts. These methods vary widely depending on statutory requirements, size of the fish farm, and the expertise and resources

available to the fish farmer. However, the comparative ability of different field methods in detecting environmental impacts is also not known.

In northern Europe, considerable recent efforts have been made to assess interactions between aquaculture and the environment, the result being a series of models, guidelines, monitoring procedures, and environmental quality standards directed toward salmon farming in cold-water environments (review in [Fernandes et al., 2002](#)). In Norway, environmental quality criteria for fjords and coastal waters were established in 1997 ([Molvær et al., 1997](#); [NSF, 1998](#)). These criteria are presented within a classification system for impacts of nutrients, organic matter, micropollutants, and fecal bacteria, and established water quality standards for various coastal uses ([Maroni, 2000](#)). By 2000, a national standard for monitoring of fish farms was issued ([NSF, 2000](#)), based in large part on the Modelling–Ongrowing fish Farms–Monitoring (MOM) system ([Ervik et al., 1997](#); [Hansen et al., 2001](#)).

The Norwegian R&D Institute Akvaplan-niva annually conducts numerous environmental and technical inspections of sea-cage fish farms in Norway. When monitoring sea farms, the company has followed national survey standards since 1996. Thus, collections of data based on standard methodologies during monitoring surveys are intercomparable from different sites and times. We have collected and analyzed data from baseline and monitoring surveys spanning a range of environmental conditions and management practices in the vicinity of Norwegian salmon cage farms in the period between 1996 and 1998. The aim of the first analysis presented is to elucidate relationships between environmental variables and management regimes. In addition, we also present the results of a comparative field study assessing the comparative ability of four different methods commonly used to carry out monitoring surveys in Norway to detect the severity and extent of environmental impacts around salmon cage farms.

2. Materials and methods

2.1. Analysis of variables influencing environmental impacts

2.1.1. Samples

A total of 168 samples from 80 sites were collected in surveys conducted from 1996–1998. A sample considered here is a station in the vicinity of a fish farm where data were collected. Stations fall into three categories: (1) located directly under the edge of the cages (“close”), (2) 50–100 m distance (“intermediate”), and (3) a reference sample at a distance of 1000 m. The close and intermediate stations are oriented downstream in the main current direction, while the reference station was upstream. Reference stations were also selected so that depth and bottom type are comparable to the those near the cages. Of the 168 total samples, 41 were close to operating cages, 39 samples were from intermediate distances, 49 were reference stations, and 39 samples came from sites which never have been used for fish farming (baseline surveys).

Sampling was carried out with a 0.1-m² modified van Veen grab. The grab had hinged and lockable inspection flaps constructed of 0.5 mm mesh. The upper side of each flap was covered by additional rubber flap allowing water to pass freely through the grab during

lowering, yet closing the grab to prevent the sediment surface being disturbed by water currents during hauling.

2.1.2. Variables selected

For this review of data, the following subset of variables were chosen because of their assumed importance to fish farm environmental quality and because of the reliability in the data spanning numerous surveys and sites. Environmental variables selected:

1. Total organic carbon (TOC) content of sediment. Wet sediment was weighed into pre-weighed porcelain dishes. The sediment was oven dried at 105 °C to constant weight and thereafter heated to 480 °C for 16 h. The percent weight loss after combustion of oven dried material was then calculated. For classification based on environmental quality criteria, TOC values are normalized following national standards. The normalization is based on the distribution of grain size of the sample and is done in order to correct for artifacts from samples with large average grain sizes (Molvær et al., 1997; see also Table 2).
2. Grain size distribution. Samples were taken from the 0 to 5 cm layer using a PVC corer (5 cm diameter). Surface sediment samples were analyzed following methodology in Buchanan (1984). The samples were split into coarse (>0.063 mm) and fine (<0.063 mm) fractions by means of wet sieving, and dried in a drying chamber at approximately 40 °C. Further analysis was a combination of dry sieving for the fraction above 0.063 mm, and electronic particle counting with a Sedigraph 5100 for the fraction below 0.063 mm. The weights of all fractions were calculated as a proportion (%) of total sediment weight.
3. Depth at cages.
4. Current speed. Measured with electronic current meters (SENSORDATA SD6000) programmed to record temperature, current velocity, and direction every 10 min. Two current meters were placed at the cages, one at cage depth (10 m) and another approximately 2–5 m above the bottom. The normal measurement period was 1 lunar month (approximately 30 days). However, due to logistical constraints, some measurements were of a shorter duration (never less than 14 days).

Management variables selected were as follows:

1. Feed consumption over the last 12 months (metric tons/year);
2. Number of years over which the farms have been operating;
3. A management technique that allows for recovery of sites by abandonment.

2.1.3. Classifying environmental impact at sites

All the sites at which samples were obtained were classified for potential sensitivity to impacts from fish farming based on the average current speed at the site (Table 1), and actual environmental condition based on the normalized total organic content (TOC_N) of the sediment (Table 2). The environmental and management variables selected were then analyzed using univariate statistics, analysis of variance (ANOVA), and correlation tests.

Table 1

Sensitivity classification of average current velocity at a site (cm/s) (from Velvin, 1999)

Current speed	Class	Classification
<3	4	very sensitive
4–6	3	moderately sensitive
7–10	2	slightly sensitive
10–25	1	not sensitive

2.2. Comparative analysis of monitoring methods used to detect impact

2.2.1. Sampling locations

In order to compare the results and practicalities of different survey techniques, in September 1993 a series of surveys were carried out at five fish farm sites along the west coast of Norway: Møre og Romsdal 1 (MR1), Møre og Romsdal 2 (MR2), Nordland (ND), South Troms (ST), and North Troms (NT). Four different sampling methods were assessed in terms of practicality and results obtained. All methods used the same grid of sampling stations for comparative purposes (below the cages, edge of cages, 20 m downstream, and 50 m downstream, and a reference 300–1000 m upstream). All stations were located at depths less than 30 m, with the exception of the reference station at MR2, which was at 35 m depth. The names and exact positions of the farms are withheld to respect confidentiality, but the approximate geographic locations of the sites are shown in Fig. 1.

2.2.2. Description of methods tested

At each site, the same four survey methods currently in use for fish farm monitoring in Norway were carried out covering both visual and quantitative techniques.

2.2.2.1. Full quantitative faunal analysis. Two replicate grab samples for biological analyses and three for chemical analyses were taken at each station. Sample collection was as described in Section 2.1.1. Samples were washed on board through a 1-mm sieve. The residue retained on the sieve after washing was fixed in 4% buffered formaldehyde to which rose bengal stain added. In the laboratory, samples are sorted to remove specimens from remaining sediments, all fauna were identified to lowest possible taxonomic level

Table 2

Classification of sites by normalized TOC (TOC_N^a) values in sediments (Molvaer et al., 1997)

TOC_N (mg/g)	Class	Environmental classification
<20	1	excellent
20–27	2	good
27–34	3	intermediate
34–41	4	poor
>41	5	very poor

Normalization of raw TOC values is conducted in order to adjust for artifacts in samples of differing average grain size.

^a $\text{TOC}_N = \text{TOC}(\text{mg/g}) + 18(1-F)$, where F is the proportion (%) fine fraction (<63 μm) of the sample.

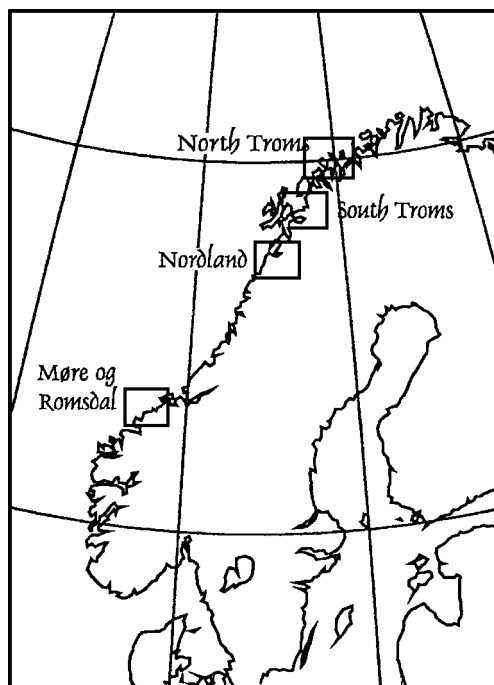


Fig. 1. Regional locations of the fish farms surveyed. Identifications of specific farms are confidential.

(generally to species) and number of individuals per taxon recorded. Station records were summed to give comparable faunal density numbers/0.5 m². Faunal community structure was assessed by means of parameters describing diversity, evenness, and dominance of the fauna (Table 3). While additional univariate and multivariate parameters are obtained from the faunal data, those described are most amenable to the present comparison.

2.2.2.2. Sediment Profile Imagery (SPI). A remotely operated SPI camera was used to obtain images of vertical profiles of sediments on the seabed at stations at the sampling locations. Position fixing was done using GPS. Up to eight replicate SPI images were

Table 3

Description of the parameters from the faunal analyses used to interpret the state of the faunal assemblage

Parameter	Description
A/S	Abundance/species ratio, i.e. number of individuals present, divided by the number of species present in a given sample. High ratios represent affected communities with assemblages dominated by a few numerous species.
Sh–W	Shannon–Wiener (H') diversity index. Gives a measure of faunal diversity. Values >5 indicate a higher degree of diversity within the population, values <5 indicate impacted faunal diversity.
Pielou	Pielou (J) coefficient. Gives an index of the degree of dominance within the faunal community. Values greater than 0.8 indicate a high degree of co-dominance by many species. Values lower than 0.8 indicate a population dominated by few species.

taken at each location using color slide film (50 ASA). The images were analyzed in the laboratory for the following parameters: major grain size mode, prism penetration depth, sediment boundary roughness, apparent redox potential discontinuity mixing depth, infaunal succession status, and additional parameters (presence of a fine flocculent layer, mud clasts, fecal pellets, epifauna, infaunal burrows and tubes, microbial aggregations, outgassing of sediments). A mean Organism–Sediment Index (OSI) was calculated, integrating all of the information gained into a single measure indicative of the environmental status of the location. The parameters used in the comparison are further described in Table 4.

2.2.2.3. Sediment chemistry analysis. Samples were collected by divers using hand corers. Each core was processed immediately after the cores were brought ashore. Electrodes were inserted in the top of the core and pH and electrode potentials on Pt- and Ag|AgS metal electrodes were recorded at 0.5 cm depth. The 0–1 cm section of the core was removed, then electrode potential measurements were taken at 2.0 cm depth, and the 1–3 cm section of the core removed. The same procedure was followed at successive depths down the remaining core. Sectioned cores were immediately frozen at -20°C for transport to the laboratory and subsequent analyses for C, N, Cu, and Zn.

The pH electrodes were calibrated daily using two IUPAC scale pH buffers (pH 4.0 and 7.6 at 10°C). The pH of a substandard was determined. Corrections for electrode drift were made with the substandard before and after processing each core. The Pt-electrode was calibrated against the reference electrode in a Zorbel redox buffer solution.

From 10 years of field data on electrode and elemental analyses of sediments in the vicinity of salmon farms, Schaanning (1994) developed a pollution index describing the environmental situation of the sediment in relation to normal (Table 5).

2.2.2.4. Diving survey. A diver swam a transect under the cages and in the main direction of the current. Photographs were taken at each of the station locations. In

Table 4
Description of variables from Sediment Profile Imagery photographs used in the comparative analysis

Parameter	Description
RPD	Redox potential discontinuity layer. Depth in the sediment profile at which there is a marked decrease in sediment oxygen availability.
Success	Stage of faunal succession, assessed from the faunal features. <i>Stage I</i> : Early succession, characterized by dense populations of small near-surface dwelling organisms which reproduce rapidly, have a fast growth rate and are capable of quickly colonizing recently disturbed or recently vacant niches. <i>Stage II</i> : Intermediate stage, characterized by the absence of recent disturbance. The presence of subsurface deposit feeders is also recognizable. <i>Stage III</i> : Mature, equilibrium faunal assemblages, characterized by large, slow-growing and bioturbating fauna, living at depth within the sediment.
OSI	Organism–Sediment Index: Integrates all the physical, chemical, and biological information obtained from the SPI images into a single measure (range -10 to $+11$) indicative of the status of the location. Values of $+7$ to $+11$ are indicative of undisturbed sediments. Values of $+6$ to $+1$ generally indicated excessive organic input to the system. Values of $+1$ to -10 indicate various degrees of habitat degradation from excessive organic matter, while a value <-6 signals recent disturbance or a site substantially degraded.

Table 5

Pollution index criteria used to express deviation from the undisturbed situation based on sediment chemical properties (Schaanning, 1994)

Deviation	Index	pH ^a	pS ^b	pE ^c	N (mg/g)	P (mg/g)	Zn (μg/g)	Cu (μg/g)
Large	3	<6.9	<2	<-2	>16	>10	>650	>150
Moderate	2	6.9–7.2	2–4	-2–0	8–16	2–10	150–650	35–150
Small	1	7.21–7.7	4–7	0–2	2–8	0.5–2	5–150	5–35
No	0	>7.7	>7	>2	<2	<0.5	<5	<5

^a pH: alkalinity.

^b pS = $-\log \Sigma [\text{H}_2\text{S}]$.

^c pE: redox potential = $-\log \{-e\} = E_h \text{ (V)}/0.059$.

addition to photographs, the diver recorded observations on strength of the bottom current, status of the fish in the cages and the natural fish assemblages outside the cages, bottom characteristics and topography, vegetation, observable benthic activity, and uneaten pellet debris, any evidence of organic matter accumulation (outgassing, *Beggiotoa*). The photographs and these ancillary observations were considered together in estimating the level of environmental impact at each station.

3. Results

3.1. Analysis of variables influencing environmental impacts

Summary of the trends in the variables considered to influence environmental impacts are shown in Table 6. In the survey, 27% of the cage farms had a feed consumption over 1000 metric tons/year and 54% less than 500 metric tons/year. Regarding years in operation, 32% of the farms had used the inspected sites for less than 2 years and 24% for more than 6 years. Depth varied from less than 25 m (7% of the farms) to over 75 m (18% of the farms). Only 10% of the farms had average current speeds in the least sensitive class, while 75% had average current speeds in classes 3 and 4 (greatest sensitivity). Fifty-nine percent of the cage farmers employed site recovery by leaving an area to fallow (abandoning) for some time before restocking.

Table 6

Summary statistics of selected different environmental variables

Variable	Classification and frequency			
Fish feed over the past 12 months (metric tons)	0–249	250–499	500–999	>1000
	27%	27%	19%	27%
Number of years in operation	<2	2–4	4–6	>6
	32%	17%	27%	24%
Depth of the site (m)	<25	25–50	50–75	>75
	7%	41%	34%	17%
Average current speed (cm/s)	<3	4–6	7–10	10–25
	24%	51%	15%	10%

Concerning the spatial pattern of TOC_N enrichment of the sediments (Fig. 2), approximately 32% of the farms have environmental classifications poor or very poor immediately adjacent to the cages, while 10% of samples at intermediate distance (50–100 m) and reference sites were similarly characterized. This suggests that, at the sites of this study, approximately 10% of sediments have elevated TOC_N values as a result of natural processes. Classifications of excellent or good were found in 51% of the samples immediately below cages, 76% at intermediate distance, and 84% at reference sites. There are indications that elevated TOC_N levels in sediments are a significant impact of fish farming operations at the sites surveyed. There were significant differences in the normalized TOC_N levels with distance from the farm (ANOVA, $P < 0.01$). Pairwise comparisons reveal that samples from under the cages had significantly higher TOC_N values than the reference sites; however, the stations at intermediate distance (50–100 m) were similar to values at the reference sites (Bonferroni's multiple comparisons test, significance level $P = 0.05$). This result indicates that, with respect to TOC_N in sediments, influences from fish farming have largely disappeared at a distance of 50–100 m, even if there is significant environmental degradation under the cages.

Correlation coefficients (Table 7) revealed a significant relationship between environmental classification and management using recovery ($P < 0.01$) and a basic trend in the relationships between environmental classification and current speeds ($P = 0.08$). The correlation of environmental classification vs. depth, feed consumption and years of operation was not significant.

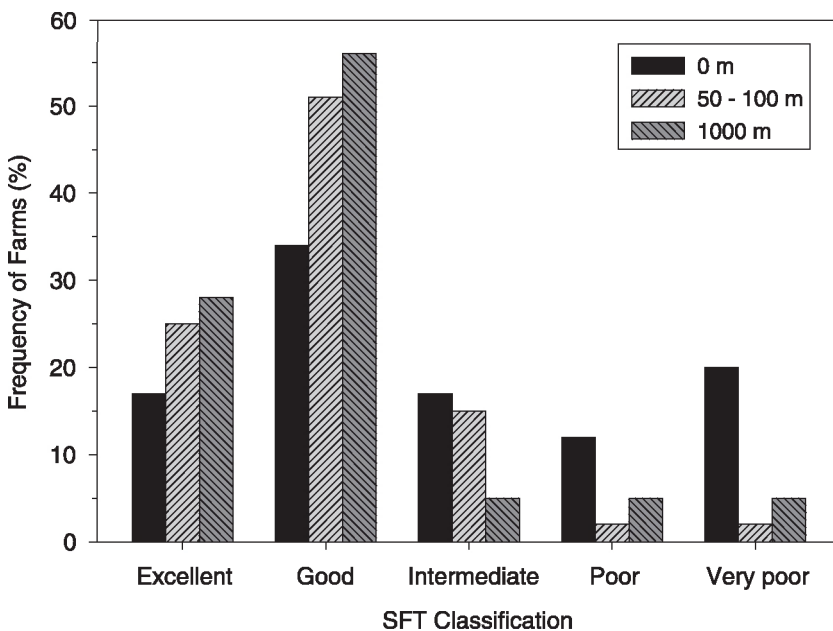


Fig. 2. Comparative frequency of samples in each class (Molvær et al., 1997), by distance from the farm cages.

Table 7

Results of Spearman rank order correlation between environmental classification and environmental variables and management practices

Variable	Depth	Years of operation	Feed level	Fallowing	Currents
Correlation	0.0244	0.0648	0.1580	−0.4652	0.2715
P value	0.8787	0.6855	0.3220	0.0023	0.0857

3.2. Comparative analysis of monitoring methods used to detect impact

3.2.1. Reliability of the different methods in conditions encountered

The diving survey was fully completed at all sites, with no particular problems encountered. The faunal analysis was successful at all sites where the bottom was composed mainly of sand or a combination of sand and gravel. However, the bottom was very rocky and steeply sloping at ST, and it was not possible to obtain a full set of quantitative samples for faunal analysis due to inadequate penetration of the sampling device into the sediment. Full sediment chemistry analyses were carried out at all of the farms with sediment cores brought to the surface by divers. The diver was able to search for suitable positions to obtain cores in cases where there was much rock in the area. In this way, cores were successfully obtained via a diver where a remote device perhaps would have failed. The Sediment Profile Imagery (SPI) survey was carried out successfully at NT and ST sites, although in the latter case, the camera was unable to penetrate the sediment at all of the stations, taking surface photographs instead. At ND, the camera malfunctioned at the reference station.

It appears therefore that survey methods involving a diver are relatively independent of the bottom type under and around a site, while remote sampling is hindered by stony, rocky, or steeply sloping bottom conditions. Where penetration of the sediment is not possible using the diver operated SPI, surface photographs can still be obtained.

3.2.2. Comparison of results from different monitoring methods

Table 8 shows a summary of results from each of the four survey methods. Close to the cage group, all survey methods revealed severe disturbance to the sea floor. There was however considerable variation in conclusions at a distance of 50 m from the fish farm. At NT, analysis of sediment chemical parameters such as pH, Eh, and pS, as well as Sediment Profile Imagery (SPI) showed the conditions to be within normal limits, with succession stage III and a high Organism–Sediment Index. The diver survey also concluded conditions to be normal, while analysis of faunal characteristics showed the area to be moderately disturbed. Although the diversity statistics are not unusually low, the species composition shows disturbance. Again, at the reference station at this site, all methods except the faunal analysis pronounced the conditions to be normal, while the faunal community structure still indicated some influence of organic enrichment.

At ST, the results of each survey method showed the conditions in the immediate vicinity of the cages at each site to be severely disturbed. At the 50-m station, the SPI and diver surveys showed conditions to be normal or nearly normal, whereas the results of the chemical analyses indicated moderate disturbance. Although quantitative faunal analysis

Table 8

Intercomparison of results between the four survey methods tested at different sites

Category	Biological			Sediment chemistry				SPI		Diver	
Parameter	A/S ^a	Sh–W ^b	Pielou ^c	pH	Eh	pS	Poll. Index ^d	RPD ^e	Success ^f	OSI ^g	Observation
<i>NT</i>											
Below	–	–	–	6.57	–125	1.94	2.43	<0.5	I	0	severe
0 m	16	4.09	0.65	7.56	23	8.21	0.71	3.8	I	7.5	moderate–severe
20 m	–	–	–	7.59	26	8.68	0.71	5.2	III	11	normal
50 m	16	5.50	0.79	7.83	50	8.91	0.57	5.7	III	11	normal
Reference	11	4.93	0.78	7.98	201	9.45	0.00	5.7	III	11	normal
<i>ST</i>											
Below	–	–	–	6.13	–170	0.99	2.71	<0.5	I	–5	severe
0 m	*	*	*	7.07	–177	2.10	1.57	<0.5	I	2	moderate–severe
20 m	–	–	–	7.81	–172	3.40	0.86	1.8	I	4	slight
50 m	*	*	*	7.73	–71	6.12	0.71	2.1	III	8	slight–normal
Reference	*	*	*	7.92	156	7.21	0.00	5.0	III	11	normal
<i>ND</i>											
Below	–	–	–	6.95	–184	2.45	2.43	<0.5	I	1	severe
0 m	241	0.09	0.03	7.55	20	5.28	0.86	<0.5	I	2	moderate–severe
20 m	–	–	–	7.93	22	7.69	0.29	1.2	II	6	moderate
50 m	32	1.51	0.34	8.14	177	8.79	0.29	*	*	*	normal
Reference	10	3.38	0.64	7.91	67	8.59	0.43	*	*	*	normal
<i>MR1</i>											
Below	–	–	–	7.16	–171	3.36	2.14				severe
0 m	5	1.91	0.55	7.91	–54	7.50	1.43	*	*	*	moderate–severe
20 m	–	–	–	7.78	202	7.94	0.71	*	*	*	–
50 m	25	4.17	0.65	7.82	152	7.75	0.43	*	*	*	normal
Reference	10	5.52	0.79	7.92	178	8.94	0.00	*	*	*	normal
<i>MR2</i>											
Below	–	–	–	7.04	180	2.82	2.14				severe
0 m	71	0.90	0.18	7.66	–128	4.66	1.57	*	*	*	moderate–severe
20 m	–	–	–	7.61	76	6.54	1.14	*	*	*	–
50 m	537	0.30	0.05	7.60	145	7.20	0.71	*	*	*	normal
Reference	13	4.56	0.69	7.55	164	7.52	0.71	*	*	*	normal

A full interpretation of the results is given in a separate report (Cochrane, 1994). See Tables 3–5 for explanation of the parameters. – indicates sampling not attempted, * indicates incomplete analysis due to bottom conditions or equipment malfunction.

^a A/S: abundance/species ratio.

^b Sh–W: Shannon–Wiener (*H'*) diversity index.

^c Pielou: Pielou (*J*) coefficient.

^d Poll. Index: pollution index.

^e RPD: redox potential discontinuity layer.

^f Success: stage of faunal succession.

^g OSI: Organism–Sediment Index.

was not possible at this site, visual assessment of the grab samples also indicated moderate environmental disturbance. The chemistry, SPI, and diver surveys all showed conditions to be normal at the reference station, while the faunal results were inconclusive, due to the lack of quantitative samples.

The results of all four surveys at the cage group at ND indicated severe environmental disturbance. Only the faunal analysis indicated severe disturbance at the 50-m station, while the SPI and diver surveys estimated a moderate level of disturbance at this distance from the cages. However, the sediment chemistry indicated conditions to be normal at the same station. No further SPI images were obtained beyond this point in the survey, but the reference station was classed as normal by both the diver and the chemistry surveys, while faunal analysis still revealed a moderate level of environmental disturbance.

The faunal and chemical analyses and the diver survey concluded severe disturbance at the station closest to the cages at the MR2. At both the 50 m and the reference stations, the diver and chemistry surveys indicated normal conditions, while faunal analysis showed moderate disturbance at both these stations.

At MR2, the results of the diver survey show only slight environmental effects close to the cage group, while both chemical and faunal analysis indicated severe disturbance. The faunal results showed moderate disturbance at both the 50 m and the reference station, while the chemistry survey indicated only slight disturbance. The diver survey concluded conditions to be normal at the same stations.

4. Discussion

Because of the intensive nature of fish farming techniques and high concentrations of biomass and wastes, fish farming will unavoidably have some impact on the environment. It is therefore important to establish levels of acceptability, below which the environmental changes are not considered hazardous (Molvær et al., 1997; SEPA, 1998; Fernandes et al., 2002). In eutrophic, cold-water northern environments such as Norway and Scotland where salmon are farmed, the most apparent environmental impact of cage-based aquaculture is the organic loading resulting from the deposition of organic-rich particulate matter (from feces or uneaten food pellets) to the sea bottom. Establishing acceptability criteria depends upon understanding the assimilation capacity and local characteristics of the recipient water body, and understanding the interaction between the multitude of environmental variables and management factors that lead to severe environmental impacts.

Of the environmental variables of a fish farm site, the depth and current strength are often implicated as prime considerations governing the potential for degradation of the sea bottom (Gowen and Bradbury, 1987; Gowen, 1991; Iwama, 1991; Wu, 1995; Black, 2001). In shallow waters, with weak currents, solid waste products from aquaculture installations will settle to the bottom close to the discharge point. In this case, continued production can give rise to a rapid local accumulation of waste material on the sea floor. Effluent released into deeper waters or where the bottom is well swept by strong currents will be dispersed over a larger area minimizing local impact. This supposition is supported by modeling studies showing the deposition of particulate matter from a fish farm given

specific bottom topography and currents (Panchang et al., 1997; Cromey et al., 1998, 2000, 2002; Silvert and Cromey, 2000). Management variables, such as feeding rates and the length of time a fish farm has been operating, also are considered important variables. However, the present analysis of data from more than 80 active sites in Norway shows that neither depth nor current speed alone are good predictors for environmental quality of the sedimentary environment. Instead, the study gives strong indications that the management practice of periodic abandonment of sites to allow recovery (fallowing) is one of the best management tools for sustainable fish farming. As abandonment for recovery is not an environmental variable, but a management practice, it would be difficult to incorporate such a factor into estimating the carrying capacity of a new site.

Defining the scale and area of impact demands that monitoring surveys are carried out consistently, and that the limitations and sensitivities of various methods used to detect environmental impacts are known and understood. Otherwise, the results from different surveys, even at the same site, are impossible to compare.

Each of the four monitoring methods examined in this study differed in a number of respects, and had advantages and disadvantages in comparison to the other methods employed (Table 9). Quantitative faunal analysis proved to be a very sensitive method in the detection of environmental effects from the cage groups. Environmental effects were detected up to several hundred meters from the fish farm, although the most severe effects were generally within 50 m of the cage group. Faunal communities appear to undergo noticeable changes in response to organic enrichment, even while chemical parameters in the sediment represent background levels. However, the laboratory costs involved in this method are extremely high (Kingston and Riddle, 1989), essentially limiting this method from being employed as a widespread standard monitoring technique, especially at small

Table 9
Summary of the comparative advantages and disadvantages of each of the four methods compared in the survey

Method	Advantages	Disadvantages
Faunal	<ul style="list-style-type: none"> • Highly sensitive to biological indicators, both gross and subtle • Some detection of variation from 'normal' several hundred meters from the farms • Most severe effects limited to 50 m 	<ul style="list-style-type: none"> • Extremely expensive to conduct: necessary to have specialized equipment in the field and specialized laboratory and taxonomic expertise • Semiquantitative a possible alternative
Sediment chemistry	<ul style="list-style-type: none"> • Detected severe effects within 10 m radius of farms • Work is based in field only: limited laboratory followup 	<ul style="list-style-type: none"> • Categorized stations as normal even while biological parameters indicated some effects • Specialized equipment
SPI	<ul style="list-style-type: none"> • Clear visual images and impressions, interpretable by laymen • Information on sediment profile • Digital image analysis of photos provides quantifiable parameters that can be standardized 	<ul style="list-style-type: none"> • Underestimate of spatial extent of affected area • Specialized and expensive equipment necessary to conduct analysis • Equipment not always reliable under field conditions (improving)
Diving survey	<ul style="list-style-type: none"> • No specialized equipment necessary (other than a diver, whom most farms already employ) • Immediate feedback on overall condition 	<ul style="list-style-type: none"> • Insensitive to subtle environmental changes • Results subjective and mostly qualitative • Working depth limited to 30–40 m

farms. Sediment chemistry parameters (pH, sulphide, and redox potential) revealed marked deviations from the ‘normal’ situation within a relatively localized area around the farm sites. In most cases, severe effects were restricted to an area within a 10-m radius of the cage group. Analysis of the sediment profiles shows the most adverse conditions to be in the upper layers of the sediment. The measurements were carried out in the field, with a minimum of laboratory work. Sediment Profile Imagery gave clear and visual images of the conditions under and around the cage groups. This method also offers information on the sediment profile and is simple to interpret, even by nonspecialists. In addition, digital image analysis gives quantifiable parameters that can be used in a standard manner (see also [Karakassis et al., 2002](#)). Processing and analysis time for the images is short, and the photographs can be developed at any photographic laboratory. Diving surveys offered much visual information, in addition to an overall assessment of the spread of effects. However, the results of such a survey will always be somewhat subjective, therefore can vary depending on extrinsic conditions (i.e. individual carrying out the survey). The other main limitation in the use of a diver is the depth restrictions due to decompression requirement.

The results of all four surveys are generally in agreement when assessing severe effects close to the cage group. There is some discrepancy however at more peripheral sampling stations. The methods based on visual assessment of the conditions have a consistently lower threshold in the detection of environmental changes than methods that rely on direct measurement of quantifiable parameters. Thus, although the diver survey offers a good overview of the conditions under the fish farm, the method has a limited use in determining the spatial extent of effects. Analysis of the SPI images also showed a trend for conditions to be pronounced as normal, while quantitative measurements still indicate an environmental impact. Although assessing more stations would be required before drawing conclusions, it appears that this method may also have a relatively low threshold for detection of the spread of environmental impact at lower intensities of enrichment.

Because of the differences in both the sensitivity of these methods as well as their costs and the equipment and expertise needed to carry them out, none is perfect for all situations. The main methods for environmental monitoring discussed above may also be combined in such a way as to use the most relevant aspects of each, according to the questions being addressed and the resources available. For example, photographic techniques may be combined with core samples, which can be used for visual as well as chemical or biological analysis. In order to design an optimal program of combined sampling, it is necessary to assess the applicability and value of the results obtained from each as well as the costs involved.

References

- Ackefors, H., Enell, M., 1994. The release of nutrients and organic matter from aquaculture systems in Nordic countries. *J. Appl. Ichthyol.* 10 (4), 225–241.
- Axler, R., Larsen, C., Tikkanen, C., McDonald, M., Yokom, S., Aas, P., 1996. Water quality issues associated with aquaculture: a case study in mine pit lakes. *Water Environ. Res.* 68, 995–1011.
- Black, K.D. (Ed.), 2001. *Environmental Impacts of Aquaculture*. Sheffield Academic Press, Sheffield, UK. 214 pp.

- Brown, J.R., Gowen, R.J., McLusky, D.S., 1987. The effect of salmon farming on the benthos of a Scottish sea loch. *J. Exp. Mar. Biol. Ecol.* 109, 39–51.
- Buchanan, J.B., 1984. Sediment analysis. In: Holme, N.S., McIntyre, A.D. (Eds.), *Methods for the Study of Marine Benthos*, 2nd ed. BP Handbook, vol. 16. Blackwell, Oxford, UK, pp. 41–65.
- Cochrane, S.C., 1994. Assessment and development of methods for monitoring of sediment under fish farms. Akvaplan-niva Report No. 631.93.320. Tromsø, Norway. 49 pp.+appendices.
- Cromey, C.J., Black, K.D., Edwards, A., Jack, I.A., 1998. Modelling the deposition and biological effects of organic carbon from marine sewage discharges. *Estuar. Coast. Shelf Sci.* 47, 295–308.
- Cromey, C.J., Nickell, T.D., Black, K.D., 2000. DEPOMOD (version 2.3). A Model for Predicting the Effects of Solids Deposition From Mariculture to the Benthos. Dunstaffnage Marine Laboratory, Oban, Argyll, UK. 120 pp.
- Cromey, C.J., Nickell, T.D., Black, K.D., Provost, P.G., Griffiths, C.R., 2002. Validation of a fish farm waste resuspension model by use of a particulate tracer discharged from a point source in a coastal environment. *Estuaries* 25, 916–929.
- Ervik, A., Hansen, P.K., Aure, J., Stigebrandt, A., Johannessen, P., Jahnsen, T., 1997. Regulating the local environmental impact of intensive marine fish farming: I. The concept of the MOM system (Modelling–Ongrowing Fish Farms–Monitoring). *Aquaculture* 158, 85–94.
- Fernandes, T.F., Eleftheriou, A., Ackefors, H., Eleftheriou, M., Ervik, A., Sanchez-Mata, A., Scanlon, T., White, P., Cochrane, S., Pearson, T.H., Read, P.A., 2002. MARAQUA: The Management of the Environmental Impacts of Marine Aquaculture. Final Report: European Union FAIR Programme, PL98–4300. Fisheries Research Services, Aberdeen, Scotland. 70 pp.+appendices.
- GESAMP, 1986. Environmental capacity: an approach to marine pollution prevention. GESAMP Reports and Studies No. 30. United Nations Food and Agriculture Organization, Rome, Italy. 49 pp.
- GESAMP, 1991. Reducing Environmental Impacts of Coastal Aquaculture. GESAMP Reports and Studies No. 47. United Nations Food and Agriculture Organization, Rome, Italy. 35 pp.
- GESAMP, 1996. Monitoring the ecological effects of coastal aquaculture wastes. GESAMP Reports and Studies No. 57. United Nations Food and Agriculture Organization, Rome, Italy. 38 pp.
- Gowen, R.J., 1991. Aquaculture and the environment. In: De Pauw, N., Joyce, J. (Eds.), *Aquaculture and the Environment*. Spec. Publ. Eur. Aquacult. Soc., vol. 16, pp. 23–48.
- Gowen, R.J., Bradbury, N.B., 1987. The ecological impact of salmonid farming in coastal waters: a review. *Oceanogr. Mar. Biol. Annu. Rev.* 25, 563–575.
- Hansen, P.K., Ervik, A., Schaanning, M., Johannessen, P., Aure, J., Jahnsen, T., Stigebrandt, A., 2001. Regulating the local environmental impact of intensive, marine fish farming: II. The monitoring programme of the MOM system (Modelling–Ongrowing fish farms–Monitoring). *Aquaculture* 194, 75–92.
- Iwama, G.I., 1991. Interactions between aquaculture and the environment. *Crit. Rev. Environ. Control* 21, 177–216.
- Karakassis, I., Tsapakis, M., Smith, C.J., Rumohr, H., 2002. Fish farming impacts in the Mediterranean Sea studied through sediment profile imagery. *Mar. Ecol., Prog. Ser.* 227, 125–133.
- Kelly, L.A., Stellwagen, J., Bergheim, A., 1996. Waste loadings from a fresh-water Atlantic Salmon farm in Scotland. *Water Res. Bull.* 32 (N5), 1017–1025.
- Kingston, P.F., Riddle, M.J., 1989. Cost effectiveness of benthic faunal monitoring. *Mar. Pollut. Bull.* 20, 490–496.
- MacGarvin, M., 2000. Scotland's Secret? Aquaculture, Nutrient Pollution, Eutrophication and Toxic Blooms. World Wildlife Fund, Perth, Scotland. 21 pp.
- Maroni, K., 2000. Monitoring and regulation of marine aquaculture in Norway. *J. Appl. Ichthyol.* 16, 192–195.
- Midlen, A., Redding, T., 1998. *Environmental Management for Aquaculture*. Chapman & Hall, London, UK. 223 pp.
- Molvaer, J., Knutzen, J., Magnusson, J., Rygg, B., Skei, J., Sørensen, J., 1997. Classification of environmental quality in fjords and coastal waters: a guide. Norwegian State Pollution Control Authority (SFT) publication 97:03. Oslo, Norway. 36 pp. in Norwegian.
- Norges Standardiseringsforbund (NSF=Norwegian Board of Standards), 1998. NS 9423: Water quality Guidelines for quantitative investigations of sublittoral soft-bottom benthic fauna in the marine environment. NSF, Oslo, Norway. 16 pp. in Norwegian.

- Norges Standardiseringsforbund (NSF=Norwegian Board of Standards), 2000. NS 9410: Environmental monitoring of marine fish farms. NSF, Oslo, Norway. 22 pp. in Norwegian.
- Panchang, V., Cheng, G., Newell, C., 1997. Modelling hydrodynamics and aquaculture waste transport in coastal Maine. *Estuaries* 20, 14–41.
- Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Annu. Rev.* 16, 229–311.
- Schaanning, M.T., 1994. Distribution of sediment properties in coastal areas adjacent to fish farms and environmental evaluation of five locations surveyed in October 1993. Norwegian Institute for Water Research (NIVA), Report No. O-93205, O-93062. Oslo, Norway. 29 pp. + appendices.
- Scottish Environmental Protection Agency (SEPA), 1998. Regulation and Monitoring of Marine Cage Farming in Scotland—A Manual of Procedures. Scottish Environmental Protection Agency, Stirling, Scotland.
- Silvert, W., Cromey, C.J., 2000. Modelling impacts. In: Black, K.D. (Ed.), *Environmental Impacts of Aquaculture*. Sheffield Academic Press, Sheffield, UK, pp. 154–181.
- Skjoldal, H.R., Aure, T., Dahl, F.E., Fredriksen, S., Gray, J.S., Heldal, M., Røed, L.P., Olsen, Y., Tangen, K., Molvær, J., 1997. The Norwegian North Sea Coastal Water—Eutrophication: Status and Trends. Expert Group Report. Norwegian Pollution Control Authority, Oslo, Norway. 76 pp.
- Velvin, R., 1999. Environmental effects from Fish farming. In: Poppe, T. (Ed.), *Textbook of Fish Health and Fish Diseases*. Universitetsforlaget, Oslo, Norway, pp. 340–347. In Norwegian.
- Wu, R.S.S., 1995. The environmental impact of marine fish culture: towards a sustainable future. *Mar. Pollut. Bull.* 31, 159–166.