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Distribution of Sediment Properties in
Coastal Areas Adjacent to Fish Farms
and
Environmental Evaluation of
Five Locations Surveyed in October 1993

Final Report

NIVA - REPORT

Norwegian Institute for Water Research ⬤ NIVA

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Abstract:

Analyses of various chemical properties in sediments collected in various projects during the period 1984-93 was reviewed to establish characteristic environmental gradients at fish farm locations. The multiple property gradient was used to assess the effects of farming activities at five locations along the coast of Norway north of 63 °N. In addition to separate evaluations of each property, integrated pollution indexes derived from electrode measurements of pH, pE and pS were calculated and compared to pollution indexes from the concentrations of N, P, Zn and Cu in the top layer of the sediments.

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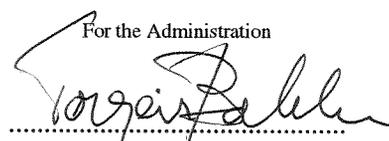
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Distribution of Sediment Properties in Coastal Areas Adjacent to Fish Farms and Environmental Evaluation of Five Locations Surveyed in October 1993

FINAL REPORT

Preface

Contents

Introduction

The first part of this report describes some overall variations and trends in the distribution of chemical properties fit to describe the impacts of fish farming in open net cages in the coastal environment. Each property represent an aspect of a pollution gradient from undisturbed natural sediment to "hot spots" beneath farm cages. The second part of the report gives an example on how the sediment environment at five fish farms surveyed in October 1993 could be ranked in a multiple property pollution gradient.

Objectives

The objectives of the chemical investigation was first to review available data to establish characteristic property gradients at fish farm locations. The second objective was to assess effect levels at five fish farms surveyed in October 1993. Finally, the conclusions of the chemical investigation at the five farms should be compared to the conclusions obtained from simultaneous macrofaunal analyses, SPI image interpretations and diver inspections.

Choice of method

The structure of the benthic macrofauna community is a widely accepted criterion for assessment of the state of the benthic environment. However, the benthic macrofauna interacts with the physical and chemical properties of the sediment and the pore water. Thus one might expect some correlation between community structure and biogeochemical properties. If such correlations were accepted, effects might be more easy to assess by chemical analyses than by analyses of community structure.

Chemical analyses are well suited for pollution monitoring. Accepted chemical analyses are quantitative, numeric, observer-independent and reproducible. With similar resources available, a large number of chemical analyses can be performed for each analyses of community structure. Thus environmental gradients can be precisely determined at a high level of resolution.

Furthermore, in enriched sediments, microbiological processes become increasingly important in controling the pore water environment, and bacterial production of

hydrogen sulphide and methane gas makes the environment intolerable to many benthic species. Anaerobic sediments beneath the farms have been claimed to favour survival of pathogenic bacteria. Rising bubbles, fat droplets or mobile organisms may provide rapid coupling between the anerobe sediment and the fish held in the cages above. Thus, the assessment of the anaerobe processes in the sediment appears to have an immediate relevance to fish health (Refs. 8,9).

In several previous reports, direct potentiometric determination of pH and hydrogen sulphide have been used as a short-cut method to indicate the character and the level of the anaerobic regime in recently loaded sediments.

When substrate limitation occurr to reduce metabolic activities, a number of physical, chemical and microbiological processes will act to reduce high levels of hydrogen sulphide and to restore normal pH values in the sediment. However, solid refractory fractions may be left in the sediment to reveal a previous or remote impact. Furthermore, if fish farm deposits contain anomalous concentrations of certain substances, chemical analyses of the solid fraction of surface sediments might be used to distinguish impacts from fish farms from other potential sources of organic enrichment.

Suitability of electrode parameters

Measurements of pH, pS and pE must be performed on fresh samples as soon as possible after sampling. Samples are not stored for reanalyses. Pitfalls such as worn electrodes, low battery, electric noise, inappropriate conditions in provisionary field laboratory or routines with regard to electrode cleaning, storage, calibration and recalibration, may occassionally cause erroneous measurements. Thus, a successfull performance depend, more than anything else, on the skills, training and vigilance of the field-workers.

On the other hand, the measurements can be rapidly performed with low-cost equipment and independent of laboratory facilities. The results are immediately at hand and relatively high numbers of samples can be analysed. The latter is particularly important at fish farm locations in the Norwegian coastal area, at which natural variations as well as pollution gradients may be very large over small distances along the seabed.

pH

Stoichiometric models (c.f. Ref.7) suggest that in a sediment dominated by bacterial sulphate reduction, the pH may drop to a value close to 7.0 set by the buffering action of HS^- (Ref. 5). Methane production may, however, drive the pH down to 6.1 set by the buffering action of HCO_3^-. Because of the large reservoir of sulphate, methane production is restrained in most marine environments. In fact, even in highly anoxic areas, pH-values below 6,8 have been rarely reported in marine resipients. To our knowledge, one of the few exceptions is the organic deposits below fish farms. Here, pH frequently drops to values in the range 5,5-6,8. Gas vacuoles have been shown to

correlate well with a pH below 7,0. Thus, the pH turn out to be a powerfull indicator on the extent of methane production.

pS

The concentration of hydrogen sulphide can be calculated from the pH and the potential measured on the S^{2-}-ion-selective silver|silversulphide electrode. The results obtained from direct potentiometric determinations are less accurate than conventional spectrofotometric or titrimetric methods and the results are preferably given by the logarithmic expression: $pS = -\log\sum[H_2S]$ (Ref. 10). The electrode is highly sensitive and at the normal pH of marine sediments (7<pH<8), response times have been found to be acceptable down to pS≈9. At higher pS, response is slow and the reading may be biased from preceding samples.

pE

In combination with the direct potentiometric determination of pH and pS, the potential on a platinum electrode (E_h) is easily determined. The theory is that the potential on an inert electrode is proportional to the electron activity $\{e^-\}$ in the sample.[1] The electron activity in sediments increase as the microbial succession shifts from oxygen respiration via quantitatively less important processes such as denitrification, ferric iron and possibly manganese (IV) oxidation, to sulphate reduction and eventually methane production. Unfortunately, because of non-ideal electrode behaviour and variable kinetic properties of the predominant redox-couples, thermodynamic interpretations of Pt-potentials are not recommended. Nevertheless, platinum electrode potentials have been widely implemented as a usefull empirical parameter distinguishing non-polluted, oxygenated environments characterised by positive potentials up to an E_h of about 400 mV (pE ≈ 7), from stagnant, oxygen deficient environments with low and negative potentials down to about -200mV (pE ≈ -3).

Electrode performance

A stable reading of the pH was normally obtained within less than 3 minutes. In samples containing hydrogen sulphide, the potential on the metal electrodes stabilised within the same time interval. At non-detectable levels of hydrogen sulphide, electrodes responded more slowly. Nevertheless, Pt- and Ag|AgS-electrode potentials were always recorded as soon as a stable reading of pH was obtained.

When recording unstable potentials, the pE and pS values obtained will depend on previous samples. Thus, if the electrodes had been recently exposed to hydrogen sulphide, "detection limits" of pS = 9 and pE=4 was obtained allowing a response time of less than 3 minutes. Electrodes which had not been exposed to hydrogen sulphide for

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[1]Formally, $pE = -\log\{e^-\} = E_h/.059$. Strictly, the latter is valid at room temperature only.

a long time (several hours) might yield a pS as high as 20 and pE of 6-7 in the same sample[2].

Most of the results reported below are measured on electrodes pre-exposed to H_2S, and readings taken within three minutes after inserting electrodes. This procedure greatly improved the reproducibility of pE and pS in apparently non-sulphidic samples. During some of the early surveys, high pS-values were transformed using the logical condition:

IF "pS>9.0", REPLACE "pS" WITH "9.0+(pS-9)/5", ELSE "pS"

Characteristic elements in fish feed and farm detritus

The major source of outlet of organic matter from open fish farms is the feed thrown onto the surface of the water inside the net cages. The great majority of the farms surveyed used dry pellets. Before sedimentation, the composition of most of the feed will be transformed by the fish. Some of the feed components are stored in the fish whereas other components are returned to the water as mineralised nutrients (ammonia and urea) and CO_2. The flux to the sediment is primarily composed of fish fecal`s and undigested feed pellets. The total flux may vary according to farm management and health status of the fish. In addition the sediments may receive organic matter from sessile organisms falling off from nets and installations.

Characteristic composition of feed as well as the general direction of the change of the composition which occurrs during digestion and sedimentation, is shown in table 1. The table suggests that enhanced concentrations of cupper, zinc and phosphorous might be expected in sediments affected by outlet from fish farms. The increase of Zn and P in the waste deposits relative to the feed is probably the result of biodegradation in the fish as well as on the seabed, causing a preferential loss of mass, primarily via carbon

Table 1. Characteristic concentration ($\mu g \cdot g$ d.wght.$^{-1}$) of potential tracer elements in fish feed and waste deposits on the seabed below fish farms, compared to sediment background levels.

Element (total)	Feed	Waste	Sediment background
Zink	203[a]	400-1320[b]	<150[d]
Cupper	0.5[a]	77-529[b]	<35[d]
Nitrogen	72 000[c]	35 000[c]	<20 000[e]
Phosphorous	13 000[c]	23 000[c]	<2 000[e]
N:P atom ratio	12.4[c]	3.4[c]	2-26[e]

a) Test diet, Lemm, 1983. b) Range in surface sediments reported by Myhr, 1989, Uotila, 1990, Schaanning, 1991. c) Feeding experiment on ten commercially available feed pellets, Petterson, 1986. d) Fjord sediments, Knutzen og Skei, 1990. e) Presumably non-polluted coastal sediments in Norway north of 63°N, this report.

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[2]A pS of 20 is way beyond linear electrode response and the corresponding electrode potentials are controlled by interfering ions.

mineralisation. The increase of cupper is, however, to large to be completely accounted for by such processes. Cupper is a frequently used antifouling agent on nets and installations. If antifouling agents are the major source of the cupper enrichments, the extent of cupper enrichments should be independent on the enrichment of zinc and phosphorous from the feed material.

Environmental gradients at fish farm locations

In order to show some overall variations and trends in the distribution of certain chemical properties in sediments, data from several surveys (Ref. nos 1-4) in major fish farm districts in Norway north of 63°N, have been analysed. The samples were collected during the period 1984-93 over a depth range of 10-129 m and the physical environment varied from shallow sounds with strong tidal currents to sheltered sill basins with seasonal occurences of anoxic bottom water. Thus, the data will show the variations one may expect to find over a very wide range of benthic environments. Seasonal variations could not be considered since all data were collected during summer and autumn (June-October).

Sediment cores up to 30cm were processed in the field for electrode measurements every 1 to 5 cm, and corresponding core segments were cut off and stored at -20°C until chemical analyses could be performed in the laboratories at the University of Oslo, Jordforsk and NIVA.

Some 350 single point determinations of pH, pE and pS have been taken in 82 sediment cores. Total carbon and nitrogen was determined on the sediment fraction selected samples using Carlo Erba element analyzor after combustion at 800°C. By removal of inorganic carbonate carbon by acid treatment and reanalyses on the Carlo Erba, organic carbon was determined in some of the samples. This method of distinguishing between inorganic and organic carbon has been questioned[3] and total nitrogen was used as a more reliable measure on the organic matter. Total phosphorous, aluminum, cupper and zinc was determined using nitric acid digestion and determination on ICP (Ion Plasma Chromatography). The detection limits of 200 $\mu gP \cdot g^{-1}$, 5 $\mu gZn \cdot g^{-1}$ and 5 $\mu gCu \cdot g^{-1}$ is well below the upper limits of the background levels given in table 1. Many natural sediments, do, however , contain less than 5 $\mu g \cdot g^{-1}$ of zinc and cupper. Therefore, cupper in all samples collected during October-93 survey, was determined on AAS (Atomic Absorption Spectrofotometry) to obtain some data on the low end of the cupper gradient.

Electrode measurements

All measurements have been plotted in the pE-pH diagram in fig. 1. Isolines through positions in the diagram having the same pS were computed from the plotted points using the MacGridzo^{TM} programme for the Macintosh personal computer.

High positive redox potential and a pH of about 8,0 is characteristic for sea water which has been recently equilibrated with the atmosphere. Thus, environments found in the upper right corner are well oxygenated environments with high capacity for biological production.

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[3]Simultaneous loss of nitrogen indicated that some of the organic material may be lost during acid treatment. Since the different laboratories used slightly different procedures, the magnitude of this error may vary from one group of data to another.

1984-93
Tromsø-Kristiansund N.
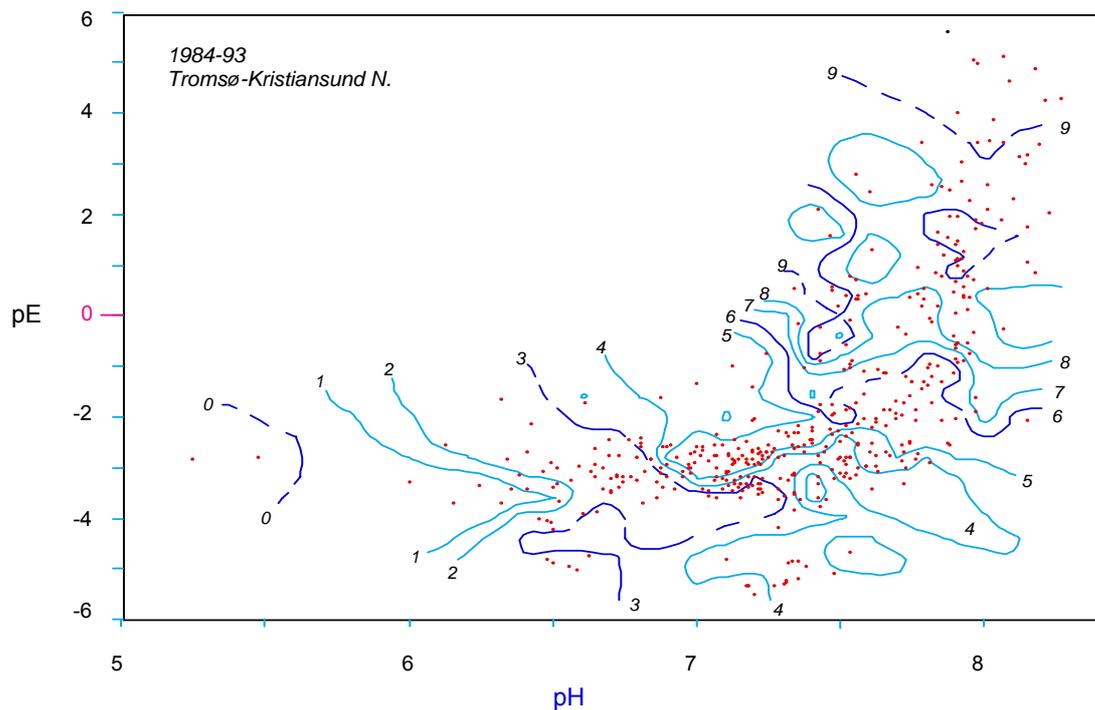
Fig. 1. Isolines of pS superimposed on a pH-pE diagram of observations taken in 83 sediment cores collected during the period 1984-1993 in major fish farm districts in the Norwegian coastal area north of 63°N. The sampled sites ranged from shallow (10 m) sounds with strong tidal currents to sheltered sill basins and fjord bottoms down to 128 m depth. Organic loading varied from natural background levels to extensive sedimentation below farm cages.

Within the normal marine range of pH of 6.8-8.2, the pE varied throughout the observed range from +6 to -6 and tended to decrease with decreasing pS. The iso-pS-lines in fig. 1, show a rapid decrease from pS ≥8 to pS≤6 at a pE slightly below zero. A pS of 6 is, approximately, equal to the detection limit of hydrogen sulphide for conventional analytical methods and the human nose. Thus, the pS shift from ≥8 to ≤6 frequently correspond to the familiar transition from a non-smelling, light-coloured sediment, to a darker, sulphide-smelling sediment. Because pS is a better defined parameter than the quasi-sulphide which is measured on a platinum electrode in a sulphidic environment (Ref. 6), the pS-gradient was frequently preferred when assigning a given sample to a pollution gradient.

A sharp decrease of pE with depth is a well known characteristic of many marine sediments and is frequently referred to as the RPD (Redox Potential Discontinuity) layer. A characteristic example on a RPD profile was observed in core 5.6 (fig.2). The depth of the discontinuity has been used as a criterium on the degree of enrichment. However, at many locations with enhanced sedimentation of organic matter, the depth of the RPD-layer as determined on standard size electrodes with a vertical resolution ≥5mm, could not be distinguished from the sediment-water boundary. Furthermore,

from laboratory studies we know that if substrate is added on top of the sediment, the pE may drop near to the sediment surface to produce an inverted RPD profile. In fact
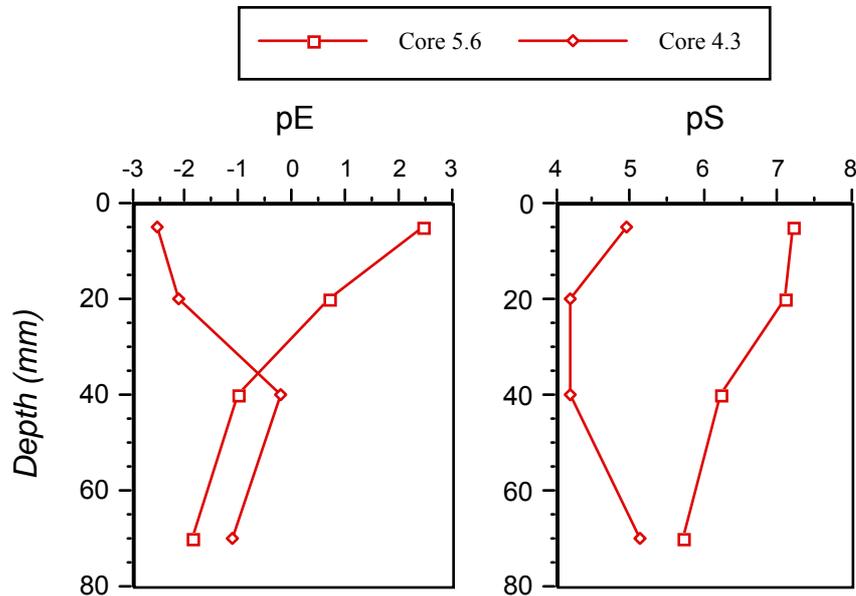
Fig. 2. Vertical profiles of pE and pS measured at fish farm locations in October 1994. The inversion of the natural pE profile and the increased concentration of hydrogen sulphide in core 4.3 was the result of increased sedimentation of organic matter. Thus 5.2 mgN·g^{-1} was observed in the top 0-1 cm layer of core 4.3 as opposed to 2.6 mgN·g^{-1} in core 5.6.

inversed RPD´s were frequently observed in sediments in the vicinity of fish farms (fig. 2, core 4.3). To reduce erroneous interpretations of cores with sharp sulphide gradients, mean values of 2 or 3 recordings at various depths within the top 5 cm of the sediment were always taken to represent a given core sample.

As the pH dropped to values below the lower limit of 6.8 in undisturbed marine sediments, no further decline of pE was observed (fig.1). pS however was found to decrease with decreasing pH and spurious low values were recorded in a few rather extreme samples having pH less than 6.0. As the complete reduction of the seawater reservoir of sulphate would correspond to a pS of 1.5, the lower pS values shown in fig. 1 may result from electrode malfunction or calculation errors occurring at the anomalous low pH. pH<6.8 were exclusively observed underneath fish cages. Such sediments were characterised by harsh odeur, gas pockets and frequent occurrencies of mucous bacterial mats at the sediment surface.

Using the empirical diagram in fig. 1, single point determinations, core average or location mean values can be ranked in a well defined organic enrichment pollution gradient.

In order to assign the range of variations to farm impacts, all stations were grouped according to their position relative to past or present cage position. Thus, the following distinctions were made:

- *abandoned* : cores collected at past cage position (2-40 months),
- *below cages* : underneath cages with fish population (salmon or trout, various size),
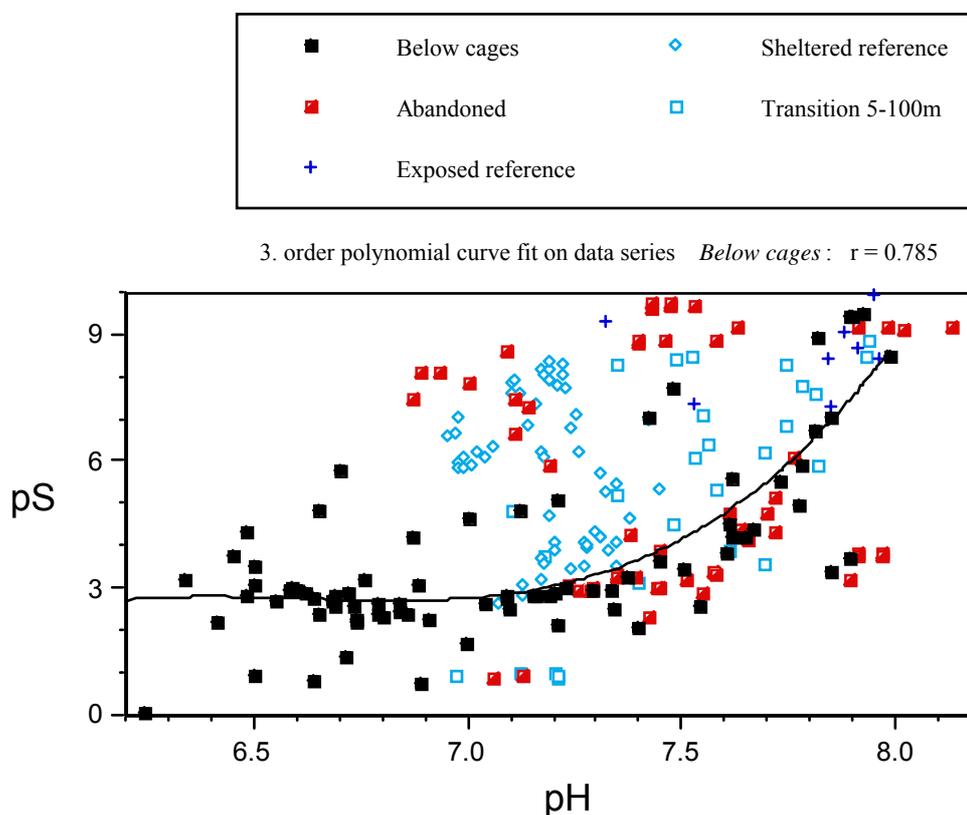
Fig. 3. pH versus pS for grouped samples collected during the period 1984-93 in fish farm districts north of 62°N. Broken line shows the curve fit for the data recorded below cages only.

- *transition* : cores sampled between the vertical projection of the edge of cages and a distance at which farm impacts were considered negligible,
- *exposed reference* : sediments unaffected by farming activities and exposed to well oxygenated water and frequently strong tidal or weather generated currents,
- *sheltered reference* : sill basins unaffected by farming activities having more or less stagnant bottom water and seasonal oxygen deficiencies may occurr.

Fig. 3 showed that exposed reference locations were characterised by high pH (range = 7,24-8.03, median = 7.61) and pS (range = 7,27-9.92, median = 8.57), whereas the sheltered reference locations had lower pH (range = 6.95-7.57, median = 7.22) and pS (range= 2.61-8.35, median =5.99). Below cages, minimum recorded values of pH and pS was 5.47 and -.19, respectively. The exceptional low values of pH and pS have been

omitted in fig. 3. Variations within transition zone sediments and abandoned cage sites ranged throughout most of the total range of the data at pH≥6.87.

Thus, because pH less than 6.87 was only observed in sediment cores sampled from below farm cages, the lower limit of pH set by hydrogen sulphide buffering:

$$pH_{lim} \approx pK_{HS/H2S} = 6.8 \text{ at } S‰=35, t=10°C \text{ (pK in Ref.11)}$$

was only perturbated in sediments sampled below fish farm cages. Also, gas vacuoles were only found in sediment cores sampled beneath cages having the characteristic low pH-values. Thus, the data supported the hypothesis put forward in previous reports (Refs. 2 and 4) that significant production of methane may lower the pH to values corresponding to the first dissociation constant of carbonic acid:

$$pH_{lim} \approx pK_{HCO3/H2CO3} = 6.1 \text{ at } S‰=35, t=10°C \text{ (pK in ref 12)}.$$

Another interesting trend of the data at 6.87≤pH≥7.7, is the frequent combination of high pS at moderate low pH (6.87-7.7) in abandoned sediments and sheltered reference locations, but never below cages. This suggests that the successive changes from an undisturbed, well ventilated sediment to an overloaded methane producing sediment follows a more narrow and predictable pathway, as indicated by the high correlation coefficient of the curve fit shown in fig. 3 on the "below cage" data, whereas the less predictable reverse pathway produce a larger scatter of the pH-pS data.

Element analyses

C, N and P

As shown in table 1, fish feed and in particular fish fecals, are phosphorous enriched relative to average marine organic matter (Redfield composition, C:N:P = 106:16:1) and sediments. The data presented in fig. 4, showed that below cages the total concentration of phosphorous ranged from 1.32% to 6.34% (median =4.80%). At the reference locations, maximum concentrations of .200% and .095% were found at sheltered and exposed sites, respectively. Thus, high concentration of P appears to be an unequivocal indicator on the presence of detritus from aquacultural activity. A low ratio between organic matter (org. C, tot. N) and phosphorous should be a sensitive indicator on farm impacts in recipients with multiple sources of organic pollution.

Ref. 13 found that 1/4-1/3 of the total phosphorous in fish fecals and bottom deposits was present in the least soluble, inorganic, Ca-bound phosphorous fraction. If this fraction was less biodegradable than the bulk of the farm waste, some phosphorous would remain present in the sediment after removal of the organic nitrogen. Thus, the discontinuity of the plot of N versus P in fig.4 probably result from the presence of Ca-bound phosphorous, having different remobilisation rates than the bulk organic matter.

Data to the left of the line of the Redfield ratio in fig. 4, shows C or N enrichment relative to P, whereas data to the right of the line indicate P enrichment. Whereas inorganic nitrogen is not known to be present in sediments, inorganic carbon from carbonate structures in plankton skeletons and shell fragments may displace data to the left of the Redfield line. The fact that nitrogen data from most of the abandoned farm sites and sheltered reference locations plotted close to the Redfield ratio, showed that inorganic fractions did not constitute any major fraction of neither one of the N- and P-pools at these locations. The presence of conciderable amounts of inorganic carbon did however, displace the majority of these samples to the left of the Redfield C:P line.

At exposed reference locations, concentrations of nitrogen were low. The median concentration of 0.2% was close to the detection limit of 0.1%. The concentration of phosphorous was not correspondingly low, indicating the presence of an inorganic fraction of about .02-.06% P. The fraction is probably primarily constituted by ortho-phosphate adsorbed onto clay minerals. This natural P-enrichment relative to nitrogen at low P-levels was clearly separated from the much larger P-enrichment (at concentrations of P > 0.2%) observed in the vicinity of cage sites.
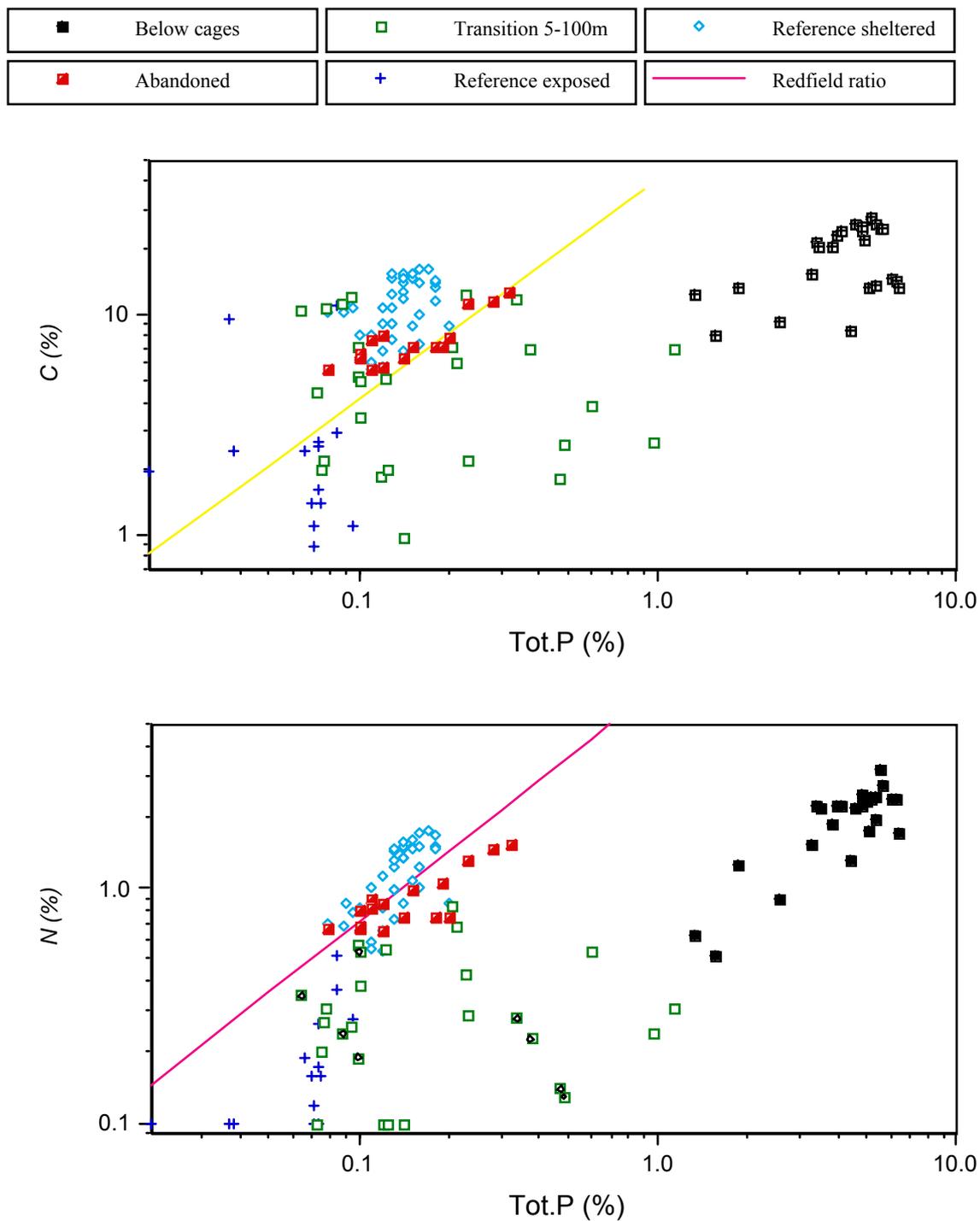
Fig. 4. Total carbon and nitrogen plotted versus total phosphorous for grouped samples collected during the period 1984-93 in fish farm districts north of 62°N. Note logarithmic scale of both axes. In the lower diagram, filled squares highlight the eight transition zone samples used for statistical comparison in table 2.
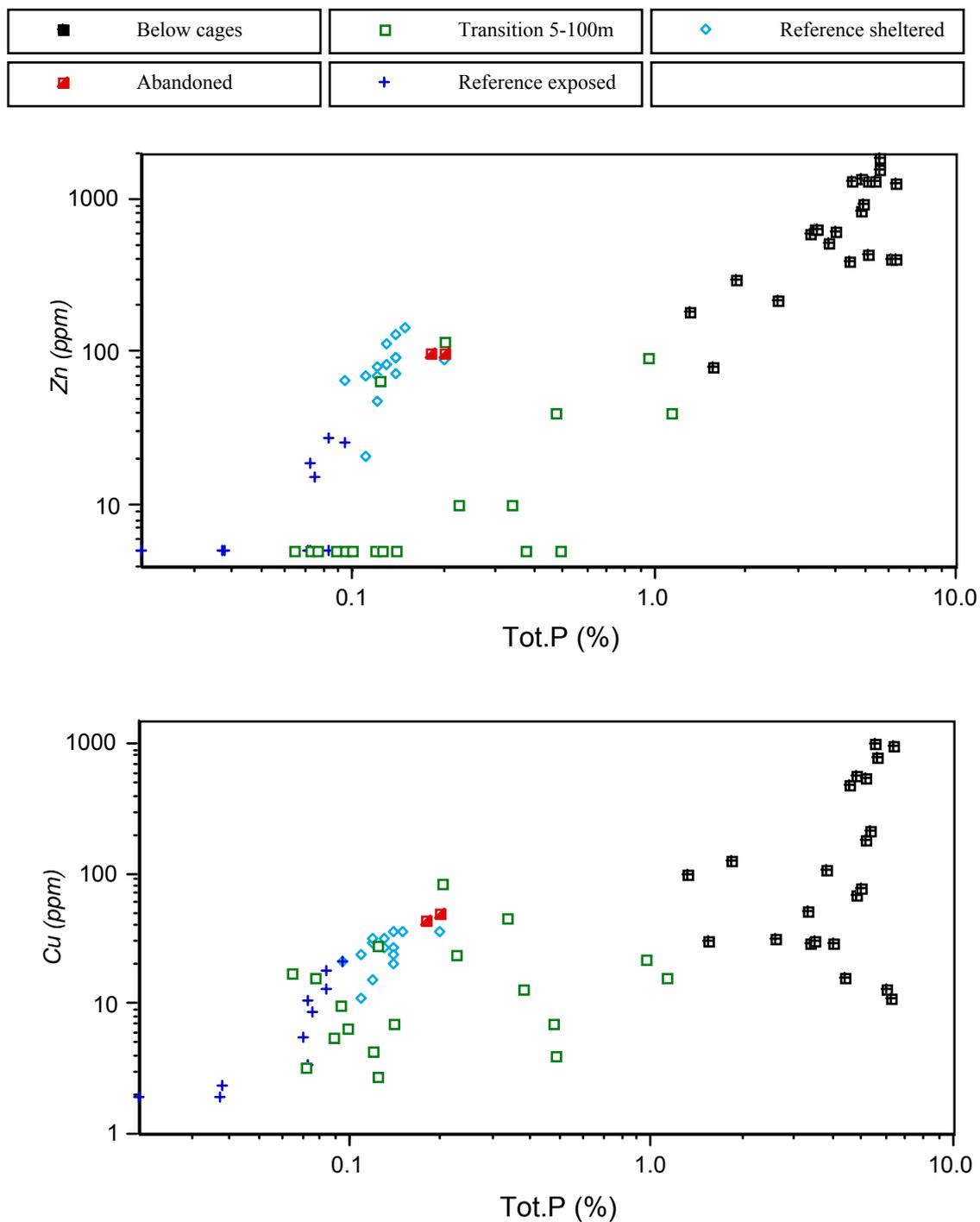
Fig. 5. Total zinc and cupper plotted versus total phosphorous for grouped samples collected during the period 1984-93 in fish farm districts north of 62°N. Note logarithmic scale on both axes.
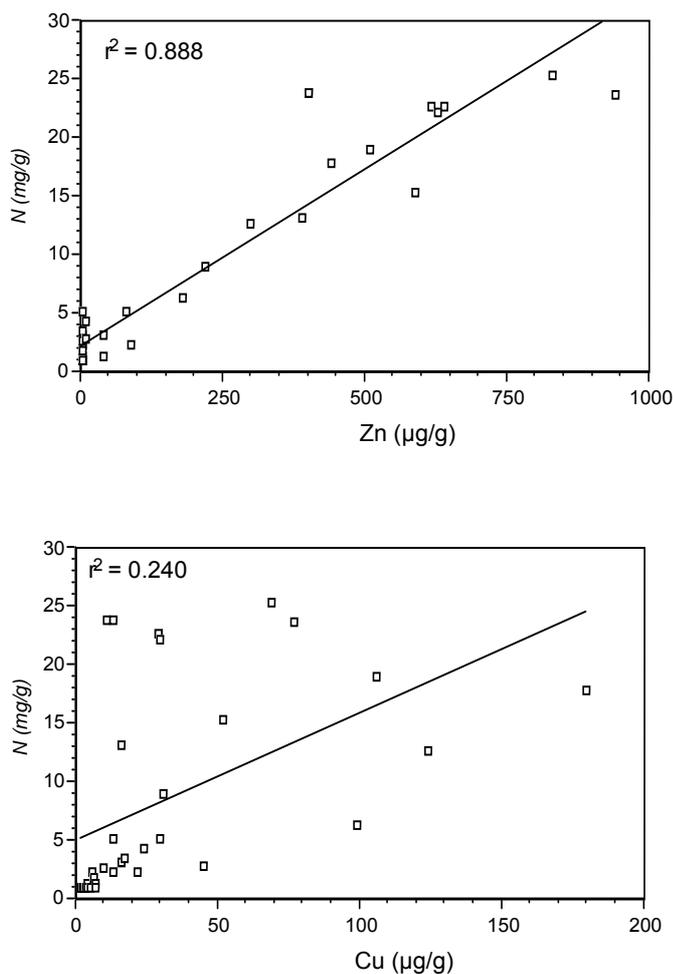
Fig. 6. Total zinc and cupper plotted versus total nitrogen for samples collected at five fish farms surveyed in October -93.

Because some of the transition zone samples had a very unique combination of high P (>0.3%) at low concentration of organic matter (N< 0.3%), P appears to be a very sensitive indicator on the presence of farm detritus at low levels of organic enrichment. In table 2, below, a statistical analyses on significant deviations of all the chemical parameters in the four samples having high P and low N (highlighted in fig. 4) from a control group of four samples having similar N but low concentrations of P.

The table shows that the mean water content and the concentrations of C and N, were slightly higher in the low P control group. This was the opposite of the general direction of the pollution gradient.

Aluminium was higher in the low P-control group. As evident from the data given in Appendix 1, table A2, the Al-gradient was directed from low below fish farms to high at reference locations. Thus, the distribution of Al tended to confirm a slight farm impact at the high-P locations. The difference was, however, not significant at the 95% level.

As for aluminum, slight enrichments of Cu and Zn and a lowering of the pH were consistent with a slight farm impact. However, the pE and the pS were the only parameters beside P to show statistically significant deviations from the control group.

The conflicting direction of the deviations of P and N in table 2, was an intended result of the grouping of the data. The fact however, that water, C and N consistently showed a slightly more eutrophic character of the low-P group, made the pE and pS come out of this test as very sensitive indicators on effects from the adjacent fish farms.

Table 2. Evaluation of the sensitivity of various chemical parameters at low-level effects of fish farm detritus. Two groups of selected samples were compared using one factor ANOVA (StatViewII™) statistical analyses. All samples were chosen to have similar low background levels of nitrogen. High P showed the presence of farm detritus in one group. Yes/no means significant or no significant difference at the 95% level. pH, pE and pS were measured at 5mm and 20mm depth. The other components were analysed on the top 0-1cm core segment. All samples were taken during the 1993-survey.

PARAMETER		HIGH P-LOW N			LOW P-LOW N			DIFFERENCE	
		MEAN	Std.Dev.	n	MEAN	Std.Dev.	n	P value	Sign.
Tot. P	(%)	.417	.073	4	.084	.015	4	0.99	yes
Tot. N	"	.20	0.07	4	.33	.15	4	0.40	no
Tot. C	"	5.8	4.7	4	9.9	1.8	4	0.65	no
H2O	(% wet)	37.6	12.1	4	53.8	5.5	4	0.68	no
Al	(μg/g)	2520	983	4	3700	817	4	0.56	no
Zn*	"	≤15	-	4	≤5	-	4	-	no
Cu	"	17.2	18.9	4	6.7	4.6	4	0.25	no
pH		7.55	0.23	8	7.67	0.20	8	0.17	no
pE		-1.12	2.08	8	0.95	1.15	8	0.44	yes
pS		4.89	1.91	8	8.09	0.58	8	0.95	yes

*Detection limit = 5.0

Cu and Zn

In fig. 5 the somewhat more scarce data on cupper and zinc showed that zinc was clearly enriched in all sediments sampled below cages. Thus, a range of concentrations from 80 to 1846 μg·g^{-1} (median = 618 μg·g^{-1}) was observed below cages. A low range from less than the detection limit of 5 μg·g^{-1} to 28 μg·g^{-1} was observed at exposed reference locations whereas concentrations up to 115 μg·g^{-1} was found at sheltered reference stations. This difference between the exposed and sheltered reference locations may result from differences in particle size distribution. Trace metals are frequently associated with the smaller size fractions sedimenting at sheltered locations. In addition, some of the latter locations received run-off from agricultural activities and a scattered population. Thus, the higher metal concentrations in the sheltered locations may have received contributions from anthropogenic sources other than aquaculture.

As should be expected from the fact that both zinc and phosphorous is introduced from feed materials whereas cupper is primarily introduced with antifouling agents, enrichment of cupper below cages was more variable than the enrichment of Zn. Thus, a range of 11-1016 $\mu g Cu \cdot g^{-1}$ (median = 99 $\mu g \cdot g^{-1}$), was found below cages whereas a range of 2.8-85 and a median of 11 $\mu g Cu \cdot g^{-1}$, was found at sheltered reference locations. At exposed reference locations concentrations were down to a range of 1.9-21 and a median of 7.1 $\mu g Cu \cdot g^{-1}$.

An important question with regard to eutrophication and bioacumulation is wether the N, P, Cu and Zn sedimented below the farms are recycled to the coastal water or biota, or wether they are permanently removed from the biogeochemical cycle by burial in the sediment. If the discontinuity of the N versus P plot in fig. 4 resulted from the presence of a Ca-bound phosphorous phase which was less mobile than nitrogen, a similar discontinuity might be expected in the plot of N versus Zn if Zn was less mobile than N. As evident from fig. 6, no such discontinuity was observed. On the contrary, the high correlation coefficient r^2 of .888 indicated that zinc is introduced to and remobilised from the sediments at the same rate as nitrogen. If, for example, the low concentration of nitrogen in the group of samples characterised with high P and low N (fig.4 and table 2) was the result of remineralisation or assimilation of organic nitrogen from aged farm detritus, whereas the Ca-bound phosphorous had remained in the sediment, fractions of zinc with mobilisation rates faster or similar to nitrogen should have been lost from the sediments whereas fractions with mobilisation rates similar to P should have remained in the sediment. Thus, the low concentrations of zinc in these samples appears to result from the coupled cycling of zinc and organic nitrogen in fish farm detritus.

The correlation between cupper and nitrogen (fig. 6) was not significant. This may result from independent sources of input (antifouling agents versus feed materials) as well as from different rates of remobilisation.

Evaluation of five fish farm locations surveyed in October 1993

<u>Sampling and core processing</u>

The method is only briefly described in this report. Details on sample collection, field measurements, core processing and calculations, can be found in Ref. 2.

The survey encountered five fish farm locations situated in various coastal environments. The five locations shall be referred to by numbers 1-5 reflecting the chronological and geographical order of the survey. On each location, 7-9 cores were sampled by divers. Each core is identified by notations such as 4.6 which denotes farm no 4, core no 6. Cores no 1, 2 and 3 were sampled directly beneath the cages. The transect stations 4-7 were taken at depths corresponding to those below the cages (i.e. 15-40m). Core no 4 was taken less than 5 m outside the vertical projection of the outer edge of the cages. Cores no 5, 6 and 7 were taken at respective distances of 20 m, 50 m and at a reference location up to 300 m away from the cages. The cores taken at the reference stations and at the 50 m stations were taken adjacent to the fauna and SPI samples.

Table 2B. Location terms used in this report and main report.

This report	Main report
Farm 1	North Troms
Farm 2	South Troms
Farm 3	Nordland
Farm 4	Møre og Romsdal 1
Farm 5	Møre og Romsdal 2

At location no 3, the cages were tied to a floating pier extending northward from a fixed land base. Two years before our sampling, the direction of the pier had been shifted to the west by an angle of approximately 30°. The team agreed to consider the abandoned area beneath the old position of the pier. Thus, cores 3.8 and 3.9 were collected at the abandoned position, some 20-50m to the east of the present position. The gradient cores 3.4, 3.5 and 3.6 were taken 0m, 20m and 50m to the west of the pier, but the reference station was taken 300 m to the east of the pier towards the head of an open bight.

Each core was processed immediately after the cores had been brought ashore by the diver. Electrodes were inserted on top of the core and the pH and electrode potentials on Pt- and Ag|AgS metal electrodes were recorded at .5 cm depth before the top 0-1cm layer were pushed into a sectioning chamber, cut off and transferred to a tightly sealed sample container. The electrodes were again inserted and potentials recorded at 2 cm depth. The 1-3 cm section were also transferred to sample containers, before recording the potentials at successive depths down the remaining core. The samples were immediately put to storage at -20°C untill analyses for C, N, P, Cu and Zn could be performed at the NIVA laboratory in Oslo.

The pH-electrodes were calibrated daily, at sample temperature using two IUPAC scale pH buffers having pH of 4.00 and 7.06 at 10°C. The pH of a seawater substandard was determined, allowing at least 10 minutes to obtain a stable reading. Corrections for

electrode drift was done by recalibration in the substandard before and after the processing of each core.

The Pt-electrode was checked against the reference electrode in a Zobell redox buffer solution. The standard potential against the hydrogen electrode (E^0) of the reference electrode was added to the recorded cell potentials on the Pt and Ag|AgS electrodes. This gives the redox potential E_h and sulphide-ion half-cell potential E_s. The latter is linearly related to the activity of S^{2-}-ions. Thus the concentration of hydrogen sulphide ($=[H_2S]+[HS^-]+[S^{2-}]$) can be calculated from E_s and pH as shown in Ref. 2. The standard potential (E_s^0) of the Ag|AgS electrode must be determined in samples with known sulphide ion activities. An E_s^0 of .6689V was used throughout this survey.

Result of electrode measurements

All single point determinations of pH, pS and pE are given in Appendix 1, table A1. In fig. 7 the pH within the top 3 cm of each core was plotted versus the corresponding pS. These plots yield an internal rank of the sediment environment beneath the cages and at each distance away from the cage site.

Beneath cages

The three upper diagrams in fig. 7 show low pH and high concentrations of hydrogen sulphide below cages at all farms surveyed. Farm 2 showed quite low pH (5,36 and 6,30) in two of the cores. Also farm 1 and 3 showed pH well below 7,0 in two cores.

The mean pH, pS and pE in the top 0-3cm layer of all cores collected beneath cages are given in table 1. The pE ranged from -2.51 to -3.08. The higher value of -2.51 at farm 2 is probably a result of the low pH affecting the non-ideal electrode behaviour. At the remaining four farms, the variation was larger than the range of the mean values. Thus, pE gave no evidence for ranking the five farms in a pollution gradient.

Table 3. pH, pS and pE in the top 0-3cm layer beneath cages at farms 1-5. The table shows mean values and standard deviations of recordings at 0,5 cm and 2,0 cm in each of the three cores sampled (n=6). The table is sorted by ascending pH.

Farm	pH		pS		pE	
no	mean	st.dev.	mean	st.dev	mean	st.dev
2	6.15	0.66	0.85	1.54	-2.51	0.53
1	6.75	0.40	2.33	0.32	-2.90	0.43
3	6.89	0.37	1.94	1.53	-3.18	0.53
5	7.06	0.26	2.78	0.50	-2.88	0.46
4	7.12	0.38	3.15	1.14	-3.08	0.34

pH and pS did, however, show a consistent trend. At farm 2, both pH and pS was lower than at farm 4 and 5. At farm 1 and 3 pH and pS was intermittent between farm 2 and the higher values at farm 4 and 5. Considering the larger variation of the pS at farm 3 as well as the relative importance of the two parameters with regard to the farming activity the rank given by the mean pH in table 3, appears to be the best available rational for ranking the environment beneath the cages. It should, however, be pointed out that this rank is a rank between sediments severely loaded with organic detritus from the farming activity.
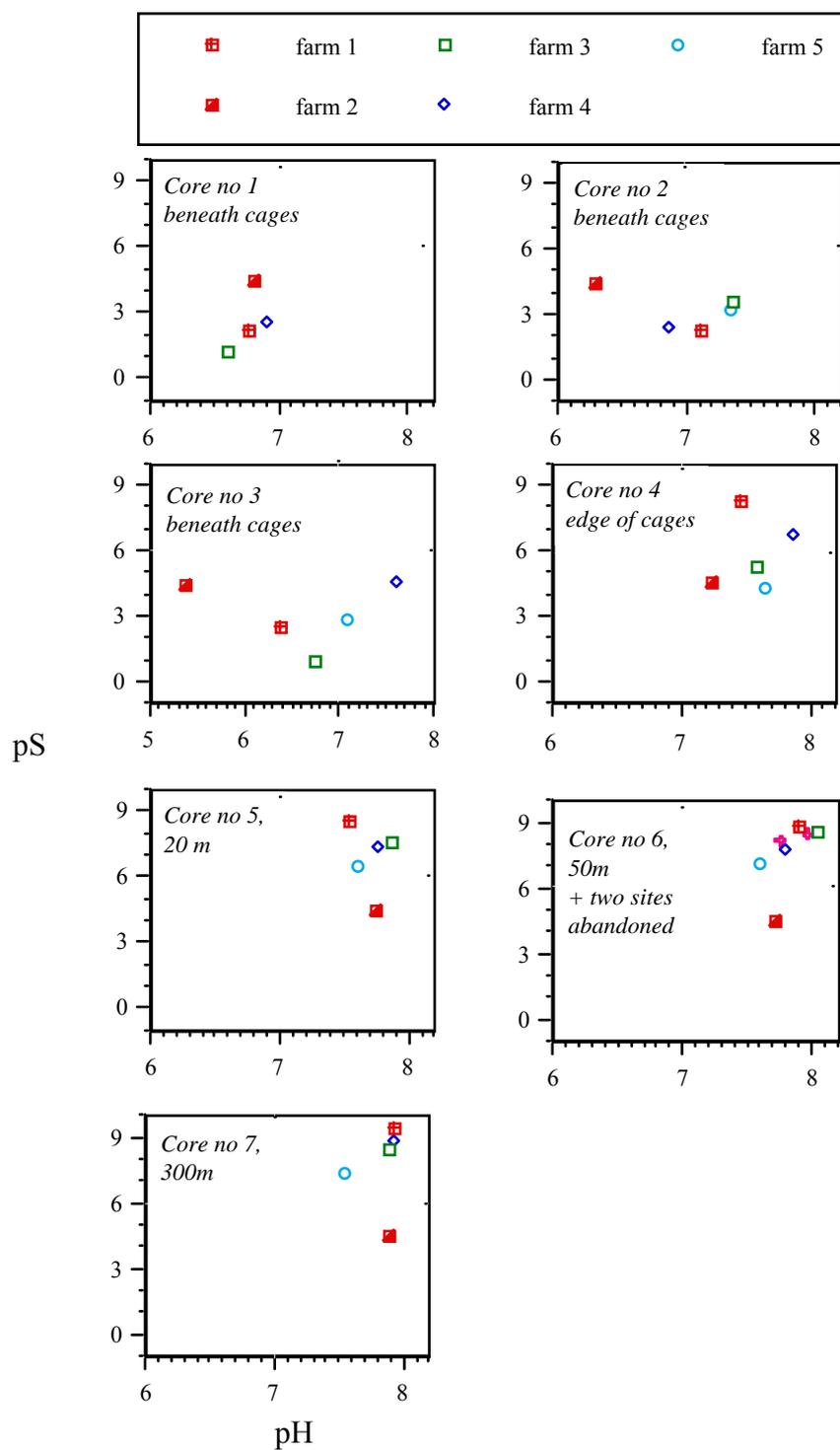
Fig. 7. pH and pS in top 3 cm of sediments at five fish farms surveyed in October 1993. In core no 1, the plot representing farm no 5 is hidden by the plot representing farm no 1. Dotted lines at pH=7,0 and pS=6 are drawn as guides to the assignment of core data to either one of three groups of environmental conditions (see text).

The transect

Both pH and pS increased rapidly when crossing the vertical projection of the edge of the cages. Thus, as shown in fig.7, none of the cores collected adjacent to the cages gave pH<7.0. However, the concentration of hydrogen sulphide was high at the edge of farm 2 (pS=2.61). Significant sulphide activities were observed also at the edge of farm 3 (pS=5.31) and farm 5 (pS=4.26).

The trend of increasing pH and pS continued with increasing distance from the farms. The diagrams (fig. 7) show that the normalization of pH and pS at farms 2 and 5 tended to occurr at a greater distance from the cages. At the reference stations, weak sulphide activities were recorded at farms 2 and 5 only. In additon, the pH at the reference location at farm no 5 were significantly lower than the pH at the other reference locations.

Abandoned site at farm 3

The result of the pH and pS analyses in the two cores taken at farm 3 at the position of the cages before shifting the angle of the pier (cores 3.8 and 3.9), are shown with reduced symbol size in the 50m diagram in fig. 7. It appears that with regard to pH and pS those sediments did not differ much from the bulk of sediments sampled 50 m away from the cages. A minor pH deviation was observed in one of the cores. A preliminary evaluation of the chemical analyses of the sediment tend to confirm this deviation by showing a slight phosphorous enrichment in the same core. Because, however, of the short distance to the present cage position, it cannot be assessed wether these effects resulted from a present or previous farm impact.

Evaluation of farms based on pH, pS and pE

The state of the sediment environment with regard to organic pollution was evaluated by considering the pH and pS at 0,5 cm and 2,0 cm depth in three cores collected beneath the cages and 4 cores collected in a transect from 0 to 300m away from the cages. In a report on fish farm locations in Frøya and Hitra (Ref. 4), advice to the farmers were based on the assignment of the locations to either one of three groups:

- Group I: undisturbed, no actions required.
- Group II: moderately disturbed, sediment monitoring was recommended and steps to reduce input should be taken if conditions become adverse.
- Group III: severely disturbed, input reduction or site abandonment was recommended.

In fig. 7, boundary pH of 7,0 and pS of 6,0 was adopted to assign each core to either one of these groups. The rationale for these boundaries were that a pS of less than 6.0

show that hydrogen sulphide is accumulating in the sediment and that a pH of less than 7.0 show an immediate risk of methane accumulation and outgassing.

From the mean values of the three cores sampled below the cages (table 1), farms 1, 2 and 3 should be clearly assigned to group III, whereas farm 4 and 5 may be considered group II close to group III. However, all farms had pH less than 7.0 in at least one core. Thus, applying a "worst case principle", all farms should be assigned to group III.

The most strongly affected sediments were found beneath the cages at farm no 2 and the transect was clearly affected to a distance of more than 50 m off the cages. At farms 3 and 5, the sediment environment normalized to group I conditions less than 20 m off the cages. Farm 1 and 4 had the least dispersal of effects, showing group I conditions less than 5 m beyond the vertical projection of the edge of the cages.

At farm no 5, the electrode measurements showed an increase of sulphide activities at 4 and 7 cm depth in all cores sampled outside the cage area (see Appendix table A1). Wether this was a result of aquacultural activities, or other factors such as a general eutrophication of the area or restricted water exchange, shall be further discussed below.

Results of the element analyses

Total concentrations of C, N, P, Zn and Cu as well as the N:P atom ratio within the top 0-1 cm of the sediments in each of the cores sampled at all farm locations are given in fig. 8.

Total carbon (left hand diagrams, left hand ordinate, square symbols) ranged 84-252 mg/g beneath the cages declining to minimum values ranging 9-109 mg/g at the reference stations. Total nitrogen (left hand diagrams, right hand ordinate, diamond symbols) ranged 5.2-25.3 mg/g beneath the cages. At four of the five reference stations, nitrogen was below the detection limit of 1.0 mg/g.

At farms 1, 2 and 3 the drop of C and N at the edge of the cages was much more pronounced than at farms 4 and 5. In fact, only nitrogen showed significant enrichments below farms 4 and 5. At all farms, the total C:N atomic ratio were about 10 below the cages increasing to high values of 20-50 at the surrounding stations (Appendix 1, table A2). Whereas a ratio of about 10 is a normal organic C:N ratio in marine sediments, total C:N higher ratios may result from an additional phase of terrestrial organic matter or, more often, inorganic carbon from planktonic skeletons and shell fragments. Thus, the absence of total carbon enrichment below cages at locations 4 and 5 was primarily a result of a higher contribution of inorganic carbon at the surrounding stations.

Total phosphorous (fig. 8, middle diagrams, left hand ordinate, square symbols) ranged 13-63 mg/g beneath the cages declining to <.8 mg/g at the reference stations. As shown above, high P and low N:P ratios are very characterisic indicators on the presence of fish farm detritus. Thus, whereas the major drop of nitrogen and phosphorous occurred at the edge of the cages between core 3 and 4, the N:P ratio remained low also in core no 4 at four of the five locations. This showed that, though present in less

concentrations, the nitrogen and phosphorous in these cores were dominated by farm outlets. Furthermore the gradual increase of the N:P ratio with increasing distance from the farms revealed the presence of farm detritus at greater distances than revealed by any other chemical parameter. Thus, the N:P ratios shown in fig. 8 (middle diagrams, right hand ordinate, diamonds) show the presence of some farm detritus in most of the sampled locations. In fact the only cores appearing to be completely beyond any impact from farm detritus were those taken at stations 1.6, 1.7 and 5.7.

Zinc and cupper is shown in the right-hand diagrams in fig. 8. The concentration of Zn was less than the detection limit of 5 μg/g at all reference locations. Therefore, the lower range of the Zn enrichment gradient from the farms may be hidden below the
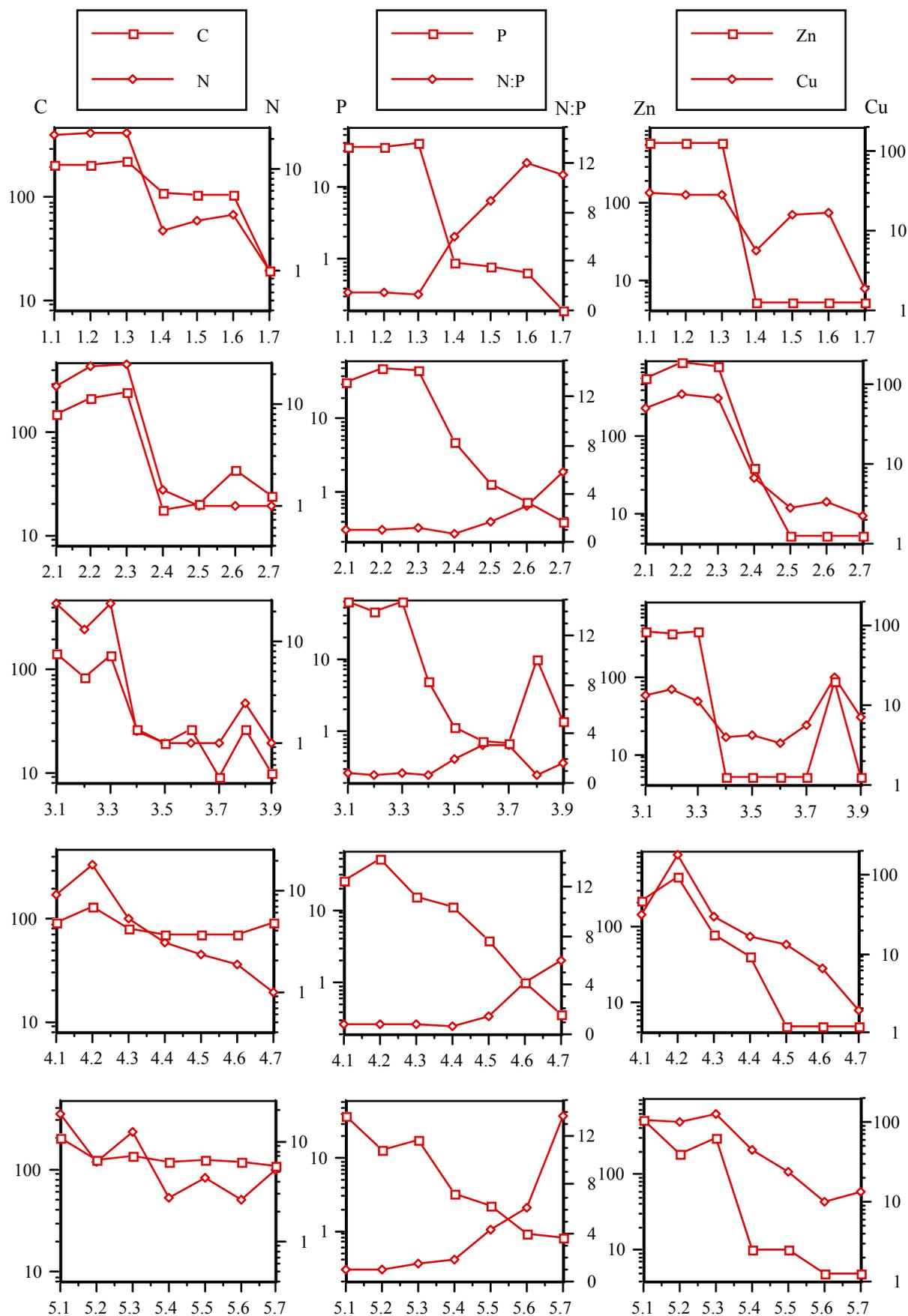
Fig. 8. Concentrations of total C, N and P (mg/g), N:P atom ratios and concentrations of Zn and

Cu (µg/g) in the top 0-1cm layer of sediments at 6-8 stations sampled at farms 1 (upper row) to 5 (lower row). Note abandoned sites 3.8 and 3.9 (midrow).

detection limit. Moderate Zn enrichments were observed in cores 2.4, 4.4, 5.4 and the abandoned site 3.8.

At the reference locations, the concentration of cupper ranged 1.9-13 µg/g. Beneath the cages, the concentrations ranged 11-180 µg/g. Whereas N, P and Zn were fairly consistent showing the higher impact levels at farms 1, 2 and 3, Cu was more abundant beneath the cages at farms 4 and 5. This may indicate different management practice with regard to antifouling agents. Compared to the background levels of less than 5 µg/g observed at locations 1, 2 and 4, the Cu-gradients from the farms tend to confirm the wider dispersal effects indicated by the N:P ratio. Both appeared to be very sensitive indicators on low level impacts, but it is interseting to note that whereas N:P ratio indicated some effect at stations 2.5-2.7 but no effect at 5.7, Cu indicated some effect at 5.7 but no effect at 2.5-2.7. Again, this demonstrated the different sources and pathways of the antifouling agents and organic detritus.

Ranking cage sites from chemical analyses

Mean element abundancies in the three cores sampled beneath each of the five cage sites are shown in table 4. The ranking of the pollution level at the cage sites: 2>1>3>5>4 was adopted from the result of the electrode measurements in table 3. Nitrogen was clearly higher at locations 1, 2 and 3 as compared to locations 4 and 5. Also C, P and Zn was generally more abundant at the three northernmost locations. C and Zn was particularly high at both farms 1 and 2 whereas pH and pS were particularly low only at farm 1.

Table 4. Total C, N and P (mg/g dry sed.) and Zn, Cu (µg/g dry sed.) within the 0-1cm sediment layer beneath cages at farms no 1-5. The table gives the mean value and standard deviations of three core samples. The table is sorted by ascending degree of pollution, as indicated by the electrode measurements (see table 1).

Farm	C		N		P		Zn		Cu	
	mean	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
2	208	50	21.5	5.3	43.4	9.2	787	179	66	13
1	215	14	22.4	.3	36.2	3.3	629	11	29	1
3	124	35	20.3	6.2	55.9	10.2	397	6	13	3
5	153	44	12.6	6.4	23.3	13.1	330	167	110	13
4	101	27	10.7	6.5	30.7	18.2	247	181	80	86

Thus, the analyses shown in table 4 gave no reason to change the rank derived from pH and pS measurements (table 3). On the contrary, the distribution of Zn gave exactly the same rank as the pH, and the analyses of C, N and P were consistent with regard to larger deviations from background levels at farms 1 and 2 as compared to farms 4 and 5. Farm 3 was intermediate, ressembling the most affected farms with regard to N and P, but ressembling the less affected farms 4 and 5 with regard to C and Zn.

The Cu gradient, however, was somewhat different. It was consistent with the other parameters with regard to the internal ranks between the three northern farms showing 2>1>3 and the two southern showing 5>4. However the fairly consistent result that the three northern locations were more affected than the two southern were opposed by the concentrations of Cu. This result may indicate a regional difference with regard to management of antifouling agents.

Pollution indexes

In order to summarise the results of the chemical investigation, index values ranging 3, 2, 1 and 0 were assigned to, respectively, *large*, *moderate*, *small* and *no* deviations from the lower range of concentrations observed at reference stations. The criteria are given in table 5.

Table 5. Pollution index criteria.

Deviation	Index	pH	pS	pE	N	P	Zn	Cu
					mg/g		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	7.2-7.7	4-7	0-2	2-8	.5-2	5-150	5-35
No	0	>7.7	>7	>2	<2	<.5	<5	<5

In table 6, pollution indexes were assigned to the mean parameter value for the three cores sampled below cages, and to each of the cores sampled in the transects. Thus the chemical indexes are based on analyses of the top 0-1 cm section, whereas the electrode indexes are derived from the mean of the recordings at 0.5 and 2 cm. Separate indexes for electrode measurements and chemical analyses were calulated as well as a total pollution index. Corresponding to the terms introduced in table 5, the terms *large*, *moderate* and *slight* effects will be assigned to sediments with pollution indexes *2.01-*

3.00, *1.01-2.00* and *0.01-1.00*, respectively, whereas *no* effects applies to an index of *0,00*, only. Pollution index variations are shown in figs. 9 and 10.

Fig. 9 showed that the mean electrode index came out very similar to the mean index derived from total element analyses of N, P, Zn and Cu. The mean total index below cages of 2.37 ± .24 showed large effects on all cage sites. Effects declined rapidly with increasing distances from the cage sites. Thus, only 20 m off the cages the total index was down to .74 ± .31. However, both electrode and chemical indexes showed slight effects also at the 50 m stations at all farms. At the reference stations, both indexes were 0.00 at farms 1, 2 and 4, but slight effects were observed at farms 3 and 5. The fact that Cu and P contributed to raise the index at both locations (see table 6) indicated that the observed effect was not a result of natural variations only.

Table 6. Pollution index assignments. Criteria defined in table 5.

	Farm no.	pH	pS	pE	**El. index**	N	P	Zn	Cu	**Chem. index**	**Total index**
Below, Core1-3	1	3	2	3	**2.67**	3	3	2	1	**2.25**	**2.43**
	2	3	3	3	**3.00**	3	3	2	2	**2.50**	**2.71**
	3	3	3	3	**3.00**	3	3	1	1	**2.00**	**2.43**
	4	2	2	3	**2.33**	2	3	1	2	**2.00**	**2.14**
	5	2	2	3	**2.33**	2	3	1	2	**2.00**	**2.14**
Edge, Core 4	1	1	0	1	**0.67**	1	1	0	1	**0.75**	**0.71**
	2	1	2	3	**2.00**	0	2	2	1	**1.25**	**1.57**
	3	1	1	2	**1.33**	0	2	0	0	**0.50**	**0.86**
	4	0	1	2	**1.00**	1	3	2	1	**1.75**	**1.43**
	5	1	1	3	**1.67**	1	2	1	2	**1.50**	**1.57**
20 m Core 5	1	1	0	1	**0.67**	1	1	0	1	**0.75**	**0.71**
	2	0	2	3	**1.67**	0	1	0	0	**0.25**	**0.86**
	3	0	0	1	**0.33**	0	1	0	0	**0.25**	**0.29**
	4	0	0	1	**0.33**	1	2	0	1	**1.00**	**0.71**
	5	1	1	1	**1.00**	1	2	1	1	**1.25**	**1.14**
50 m Core 6	1	0	0	1	**0.33**	1	1	0	1	**0.75**	**0.57**
	2	1	1	2	**1.33**	0	1	0	0	**0.25**	**0.71**
	3	0	0	1	**0.33**	0	1	0	0	**0.25**	**0.29**
	4	0	0	1	**0.33**	0	1	0	1	**0.50**	**0.43**
	5	1	0	1	**0.67**	1	1	0	1	**0.75**	**0.71**
Ref. Core 7	1	0	0	0	**0.00**	0	0	0	0	**0.00**	**0.00**
	2	0	0	0	**0.00**	0	0	0	0	**0.00**	**0.00**
	3	0	0	1	**0.33**	0	1	0	1	**0.50**	**0.43**
	4	0	0	0	**0.00**	0	0	0	0	**0.00**	**0.00**
	5	1	0	1	**0.67**	1	1	0	1	**0.75**	**0.71**
Core 8	3	0	0	1	**0.33**	1	3	2	1	**1.75**	**1.14**
Core 9	3	0	0	1	**0.33**	0	1	0	1	**0.50**	**0.43**

The distribution of the electrode and chemical indexes (fig. 10) showed similar trends at most locations. However, at farm 2 the electrode index showed moderate effects at 20

m and 50 m, whereas the chemical index showed only slight effects. The slight effect shown by the latter index resulted from a slight enrichment of phosphorous and the N:P ratio was low (fig.8). This do confirm some presence of farm detritus in the surface layer of the sediment, but the low degree of accumulation suggest a short history of contamination.

If the difference between the two indexes at farm 2 was the result of an increased sedimentation of detritus from the adjacent farm which had just begun, the two indexes might yield an inverse relationship at abandoned locations. The only abandoned locations sampled during this survey was the two stations situated close to the present cage site at farm 3. Both cores gave a higher chemical index, and core 3.8 (table 6) did indeed yield a rather high chemical index of 1.75, which mostly resulted from the feed components P and Zn. The very slight effects shown by the chemical index of .33 should then indicate that metabolic rates had declined to low or background levels in these sediments, whereas refractory organic phases and inorganic P and metal fractions were left behind from previous operations.
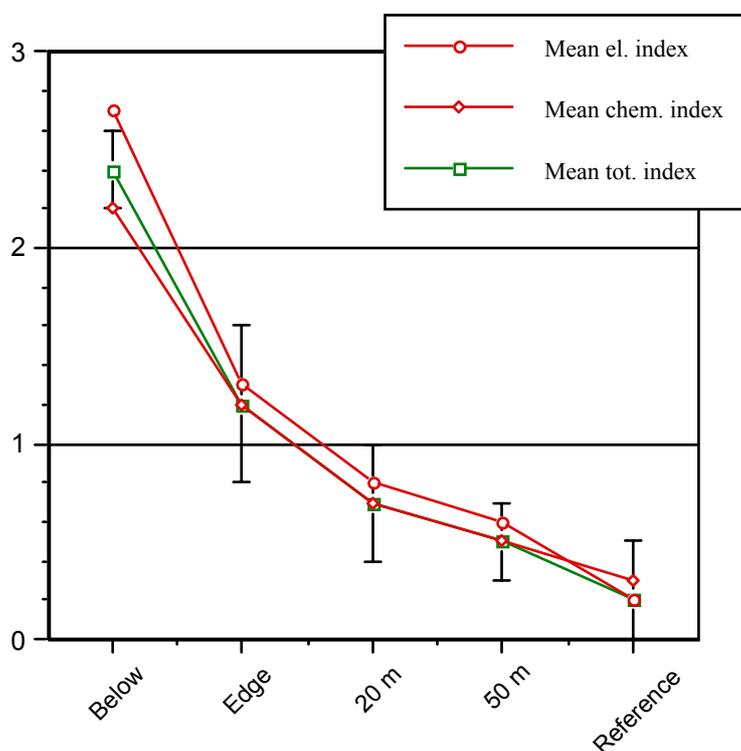
Fig. 9. Variation of mean pollution indexes at the five farms surveyed in October 1993. Vertical bars = 2 standard deviations of the total index.

Even though effects were less adverse below the cages at farm 4 and 5, as compared to the three northernmost farms, relative high indexes were found at edge, 20 m and 50 m stations, and even the reference station came out with a total index as high as .71 at farm 5. However, the absence of any zinc enrichment and the fact that the N:P ratio (fig. 8) was as high as 14, which was close to the Redfield ratio, tend to suggest that the reference station at farm 5 suffered from a general eutrophication rather than direct

sedimentation of organic detritus from the fish farm. Also, the fact that a slight sulphide activity was recorded at depth below 5 cm in all cores taken at farm 5 showed a more eutrophic character of the sediment at this location. If so, the less adverse effects below the cages might indicate better management at farm 5 as compared to the other locations. Thus, farm 5 may be a good example that carefull management may allow exploitation of less ideal locations.
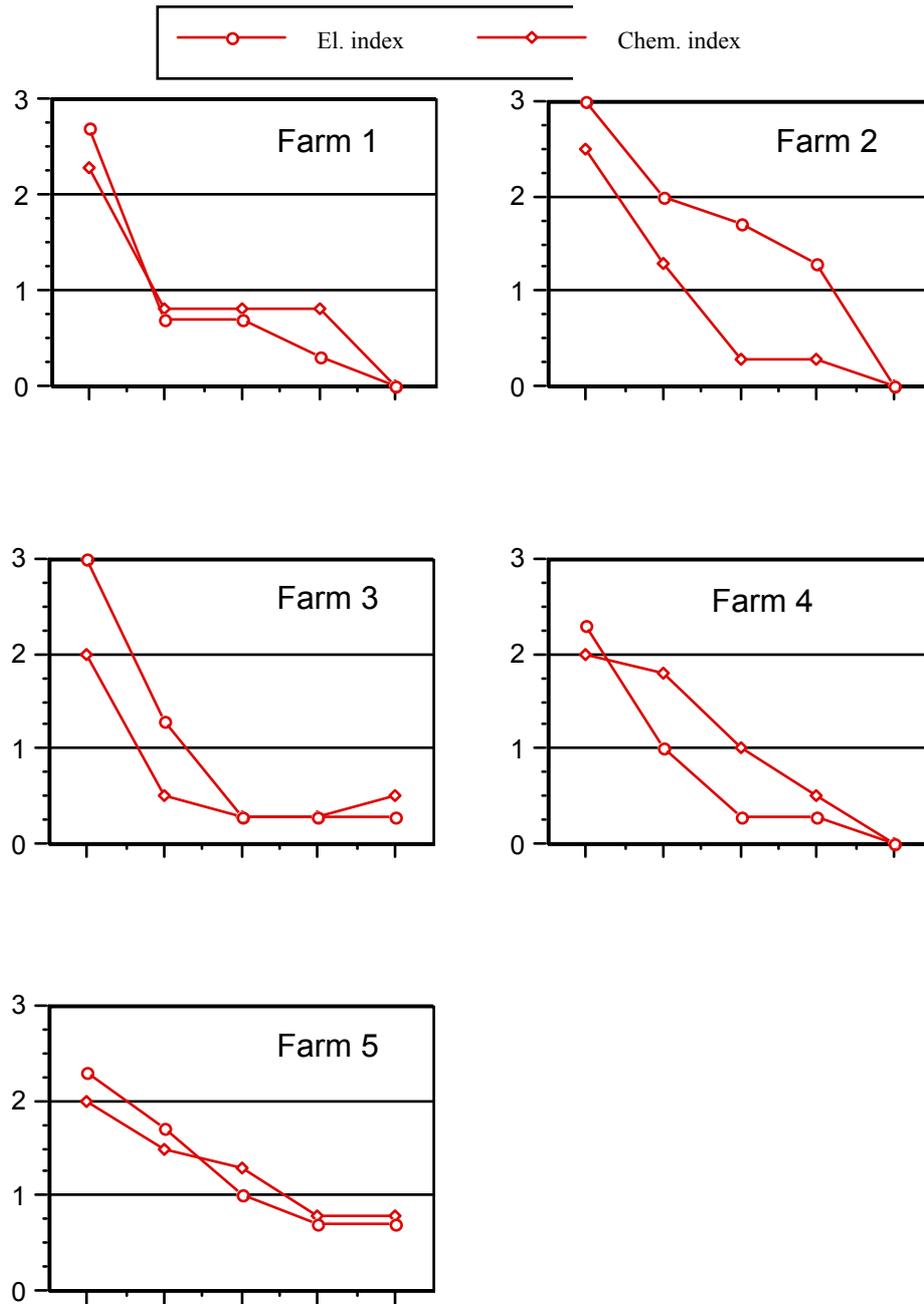
Fig 10. Variations of pollution index derived from electrode measurements (pH, pS and pE) and chemical analyses (N, P, Zn and Cu) at each farm location.

Discussion

All sediment properties presented in figs. 7 and 8 showed that deviations from the conditions at the reference stations increased when approaching the cage site of all five fish farms surveyed. The magnitude of the deviations varied between locations and some parameters deviated stronger than others.

The metal contaminations were moderate and apart from possible effects of cupper contamination on certain sensitive species, the metal enrichments will not have accute effects on biological processes in the sediment. Neither should the large enrichments with regard to phosphorous have any significant impact on sedimentary processes. The rationale for performing such element analyses might be the assessment of metal contamination levels and the amount of fish farm debris in a given sediment sample.

Sedimentation of carbon and nitrogen, however, provide energy and nutrient substances for bacterial processes and the benthic fauna. However, a considerable fraction of the organic matter settling on the sediment surface is not easily degradable. Thus aged deposits may be enriched with organic C and N without showing a correspondingly stimulated metabolic activity.

Because of physical and chemical reactions operating to restore the normal pH values and reduce the concentrations of hydrogen sulphide, observed deviations of pH and pS should be considered short term impacts resulting from enhanced bacterial activities in the sediment. Thus, the pH and the pS deviations are good indicators on enhanced sediment metabolism and recent effects. A sustained enhancement of sediment metabolism is probably one of the most important factors preceding changes of community structure.

High concentrations of Zn and P were very characteristic features of the composition of farm detritus. Elevated concentrations of Cu were more variable and probably dependent on the use of antifouling agents.

Thus, the chemical pollution index derived from the N, P, Zn and Cu concentration deviations, may require a certain amount of accumulation before showing significant response. On the other hand, the chemical index should remain elevated for a longer time after stopping the input. The electrode index derived from pH, pS and pE deviations, should respond rapidly to the metabolic activity which is momentarily stimulated by sedimentation of farm detritus and it may decrease more rapidly upon stopping the input. Some indications were found to confirm the faster response and normalisation of the electrode index.

In general pollution indexes may help conceiving major trends from complex sets of data. However, the risk is that a few properties with high problem relevance may be masked by contributions from many properties with low problem relevance. With regard to the effects from fish farms, high concentrations of hydrogen sulphide, values of pH below the critical level of 6.9 and perhaps the concentration of cupper, might be considered to have a higher problem relevance than organic carbon and nitrogen, whereas zinc and phosphorous have little problem relevance, but a mere quantitative statement of deviations from background conditions.

Litterature

1. Frogh, M., Å.Mohus, T.Sagen, K.Sivertsen og S.Skreslet, 1985. Forurensing i fiskeoppdrett i Herøy. *Nordlandsforskning, Rapport nr. 3 1985.*

2. Schaanning, M., 1991. Effekter av fiskeoppdrett på marine sedimenter. Jordforsk-rapport 212.409-1, 44pp. ISBN 82-7467-024-8.

3. Frogh, M. and M. Schaanning, 1991. Bentisk Nedbryting av Organisk Materiale i et Sjøområde Påvirket av Fiskeoppdrett Nordlandsforskning, Report no 1, 1991, 40pp. ISBN 82-7321-156-8.

4. Dragsund, E. og M.T. Schaanning, M.T., 1993. Sammenhengen mellom strømforhold og sedimentkjemi på oppdrettslokaliteter. NIVA/OCEANOR report no. OCN R-93051. ISBN 82-7427-113-0. 44pp.

5. Ben-Yaakov, S., 1973. pH buffering of pore water of recent anoxic marine sediments. *Limnol. Oceanogr.* 18, 86-94.

6. Boulegue, J., 1978. Electrochemistry of reduced sulfur species in natural waters - I. The H2S-H2O system. *Geochim. Cosmochim. Acta*, 42:1439-1445.

7. Zehnder,A.J.B. and W.Stumm, 1988. Geochemistry and biogeochemistry of anaerobic habitats. *In* A.J.B.Zehnder (Ed.), Biology of Anaerobic Microorganisms, John Wiley and Sons, Inc.. pp.1-35.

8. Lumb, C.M., 1989. Self-pollution by Scottish Salmon Farms? *Marine Pollution Bulletin*, Volume 20, No. 8, pp. 375-379.

9. Braaten, B.J., J.Aure, A.Ervik og E.Boge, 1983. Pollution problems in Norwegian fish farming. *ICES C.M. 1983/F.26*, 11pp.

10. Aller,R.C., 1978.Experimental studies of changes produced by deposit feeders on pore water, sediment, and overlying water chemistry. *American Journal of Science*, Vol. 278, 1185-1234.

11. Millero, F.J., T.Plese and M. Fernandez, 1988. The dissociation of hydrogen sulfide in seawater. *Limnol. Oceanogr.* 33, 269-274.

12. Mehrbach,D., C.H.Culberson, J.E.Hawley and R.M.Pytkowicz, 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnol. Oceanogr.*, 18: 897-907.

13. Petterson, K., 1986. Betydelsen av fiskfoders fosforsammansättning för fosforläckage till vatten från foderspill och fekalier. Slutrapport november 1986, LIU B: 18, Uppsala universitet, Norrtälje.

14. Uotila, J., 1990. Fiskodlingssedimentets metallhalter och spridning i sydvestra Finlands skärgård. I E.Hoffmann, R.Persson, E.Gaard og G.S.Jonsson eds. Havbrug og miljø. Nordisk Ministerråd, *Nord* 1991:10, pp67-73.

15. Myhr, K., 1989. Fish-farm waste material for fertilization of barley for silage. *Norsk Landbruksforskning* 3: 71-78. ISSN 0801-5333.

16. Lemm, C.A., 1983. Growth and Survival of Atlantic Salmon Fed Semimoist or Dry Starter Diets. *Prog. Fish-Cult. 45(2)*, pp 72-75.

17. Knutzen, J. og J.Skei, 1990. Quality criteria for water, sediments and organisms and preliminary proposals for classification of environmental quality. NIVA report no 2540.

18. Jørgensen,B.B., M.Bang and T.H.Blackburn, 1990. Anaerobic mineralisation in marine sediments from the Baltic Sea-North Sea transition. *Mar.Ecol.Prog.Ser.*, 59:39-54.

Appendix 1

Tables of results

Table A1. pH, redox potentials (E_h or pE) and concentration of H_2S (pS) determined during the fieldwork.

Location	Depth (cm)	pH	Eh (mV)	pE	pS
1.1	0.5	6.42	-126	-2.14	1.94
1.1	2	7.10	-182	-3.08	2.51
1.2	0.5	7.02	-153	-2.59	2.42
1.2	2	7.21	-171	-2.90	2.11
1.3	0.5	6.32	-98	-1.66	2.82
1.3	2	6.41	-160	-2.71	2.20
1.4	0.5	7.56	23	0.39	8.21
1.4	2	7.34	32	0.54	8.30
1.5	0.5	7.59	26	0.44	8.68
1.5	2	7.49	10	0.17	8.43
1.6	0.5	7.83	50	0.85	8.91
1.6	2	7.94	-31	-0.53	8.85
1.7	0.5	7.98	201	3.41	9.45
1.7	2	7.88	147	2.49	9.39
2.1	0.5	6.80	-142	-2.41	3.27
2.1	2	6.80	-148	-2.51	2.32
2.1	4	6.80	-152	-2.58	1.47
2.2	0.5	6.35	-203	-3.44	0.13
2.2	2	6.24	-199	-3.37	0.01
2.2	4	6.41	-202	-3.42	0.40
2.2	7	6.32	-219	-3.71	0.18
2.3	0.5	5.24	-167	-2.83	-0.41
2.3	2	5.47	-166	-2.81	-0.19
2.3	4	6.00	-194	-3.29	-0.01
2.3	7	6.15	-219	-3.71	0.13
2.4	0.5	7.07	-177	-3.00	2.10
2.4	2	7.40	-131	-2.22	3.11
2.5	0.5	7.81	-172	-2.92	3.40
2.5	2	7.69	-120	-2.03	3.57
2.6	0.5	7.73	-71	-1.20	6.12
2.6	2	7.69	-113	-1.92	6.22
2.7	0.5	7.92	156	2.64	7.21
2.7	2	7.85	150	2.54	7.27
3.1	0.5	6.70	-206	-3.49	1.39
3.1	2	6.50	-200	-3.39	0.95
3.2	0.5	7.35	-129	-2.19	4.82
3.2	2	7.34	-184	-3.12	2.50
3.2	4	7.52	-140	-2.37	3.49
3.2	6	7.47	-104	-1.76	3.26
3.3	0.5	6.81	-218	-3.69	1.14
3.3	2	6.64	-188	-3.19	0.83
3.3	4	6.52	-216	-3.66	0.68
3.3	6	6.49	-240	-4.07	0.60

Table A1. Continued.......................

Location	Depth (cm)	pH	Eh (mV)	pE	pS
3.4	0.5	7.55	20	0.34	5.28
3.4	2	7.58	-92	-1.56	5.35
3.5	0.5	7.93	22	0.37	7.69
3.5	2	7.81	-3	-0.05	7.63
3.6	0.5	8.14	177	3.00	8.79
3.6	2	7.96	42	0.71	8.40
3.7	0.5	7.91	67	1.14	8.59
3.7	2	7.84	82	1.39	8.44
3.7	4	7.73	-21	-0.36	8.73
3.7	6	7.71	-115	-1.95	8.58
3.7	8	7.72	-160	-2.71	8.21
3.8	0.5	7.77	56	0.95	8.00
3.8	2	7.74	21	0.36	8.30
3.8	4	7.67	-110	-1.86	7.72
3.8	6	7.60	-159	-2.69	6.15
3.9	0.5	8.01	123	2.08	8.39
3.9	2	7.93	33	0.56	8.47
4.1	0.5	6.95	-187	-3.17	2.59
4.1	2	6.86	-193	-3.27	2.40
4.1	4	6.87	-178	-3.02	2.38
4.1	7	6.86	-212	-3.59	2.10
4.2	0.5	6.97	-178	-3.02	2.55
4.2	2	6.74	-187	-3.17	2.20
4.2	4	6.70	-190	-3.22	2.31
4.2	7	6.73	-200	-3.39	2.35
4.3	0.5	7.56	-148	-2.51	4.95
4.3	2	7.62	-125	-2.12	4.21
4.3	4	7.70	-13	-0.22	4.19
4.3	7	7.66	-67	-1.14	5.13
4.4	0.5	7.91	-54	-0.92	7.50
4.4	2	7.82	-101	-1.71	5.88
4.4	4	7.80	-82	-1.39	7.22
4.5	0.5	7.78	202	3.42	7.94
4.5	2	7.74	-93	-1.58	6.85
4.5	4	7.75	-77	-1.31	5.50
4.6	0.5	7.82	152	2.58	7.75
4.6	2	7.78	12	0.20	7.80
4.6	4	7.77	25	0.42	8.23
4.6	7	7.79	31	0.53	8.32
4.7	0.5	7.92	178	3.02	8.94
4.7	2	7.91	87	1.47	8.69
4.7	4	7.90	64	1.08	8.81
4.7	7	7.94	46	0.78	8.85

Table A1. Continued.........................

Location	Depth (cm)	pH	Eh (mV)	pE	pS
5.1	0.5	6.77	-187	-3.17	2.14
5.1	2	6.74	-194	-3.29	2.23
5.1	4	6.92	-202	-3.42	2.45
5.2	0.5	7.30	-162	-2.75	3.27
5.2	2	7.37	-151	-2.56	3.25
5.2	4	7.45	-152	-2.58	3.20
5.3	0.5	7.06	-192	-3.25	3.04
5.3	2	7.09	-203	-3.44	2.74
5.3	4	7.12	-205	-3.47	2.74
5.3	7	7.15	-187	-3.17	2.75
5.4	0.5	7.66	-128	-2.17	4.66
5.4	2	7.61	-131	-2.22	3.86
5.4	4	7.55	-102	-1.73	4.03
5.4	7	7.53	-166	-2.81	3.67
5.5	0.5	7.61	76	1.29	6.54
5.5	2	7.56	20	0.34	6.41
5.5	4	7.54	-53	-0.90	6.63
5.5	7	7.53	-56	-0.95	6.34
5.6	0.5	7.60	145	2.46	7.20
5.6	2	7.55	42	0.71	7.08
5.6	4	7.53	-60	-1.02	6.24
5.6	7	7.52	-109	-1.85	5.72
5.7	0.5	7.55	164	2.78	7.52
5.7	2	7.53	45	0.76	7.36
5.7	4	7.51	-63	-1.07	7.10
5.7	7	7.53	-108	-1.83	6.89

Table A2. Analyses of water content and specified elements (total concentrations), and calculated atomic ratios in the top 0-1cm sediment layer.

Locat-ion	Water (%)	C	N	P	C:N	C:P	N:P	Al	Zn	Cu	Al:Cu
			(mg/g)			(atomic ratio)			µg/g		(at.ratio)
1.1	85.9	203	22.1	34.70	10.7	15.1	1.41	2710	630	30.0	213
1.2	86.9	211	22.6	33.90	10.9	16.1	1.47	1950	640	29.0	158
1.3	88.1	230	22.6	39.90	11.9	14.9	1.25	1370	618	29.0	111
1.4	50.5	111	2.4	0.88	54.0	325.5	6.03	2870	<5	5.6	1207
1.5	53.4	106	3.1	0.77	39.9	355.3	8.91	4490	<5	16.0	661
1.6	56.4	105	3.5	0.64	35.0	423.4	12.10	4760	<5	17.0	659
1.7	22.1	19	<1.0	<0.2	22.4	247.8	11.06	3150	<5	1.9	3905
2.1	79.1	154	15.4	32.80	11.7	12.1	1.04	2020	590	52.0	91
2.2	85.5	218	23.7	49.40	10.7	11.4	1.06	1150	940	77.0	35
2.3	85.9	252	25.3	48.00	11.6	13.5	1.17	330	830	69.0	11
2.4	29.6	18	1.4	4.71	14.9	9.8	0.66	2640	40	6.9	901
2.5	26.5	20	<1.0	1.25	23.3	41.3	1.77	2650	<5	2.8	2229
2.6	27.1	44	<1.0	0.72	51.3	157.7	3.07	3120	<5	3.3	2227
2.7	18.6	24	<1.0	0.38	27.9	162.3	5.82	3280	<5	2.3	3359
3.1	82.3	147	23.9	60.70	7.2	6.3	0.87	1860	400	13.0	337
3.2	65.2	84	13.1	44.20	7.4	4.9	0.66	4490	390	16.0	661
3.3	78.7	142	23.9	62.70	6.9	5.8	0.84	2320	400	11.0	497
3.4	25.2	26	1.3	4.85	23.3	13.8	0.59	3390	<5	4.0	1996
3.5	25.9	19	<1.0	1.19	21.7	40.3	1.86	3430	<5	4.3	1879
3.6	20.2	26	<1.0	0.73	30.8	93.3	3.03	3670	<5	3.4	2542
3.7	27.4	9	<1.0	0.71	10.3	32.0	3.12	3540	<5	5.5	1516
3.8	36.3	27	2.4	9.59	13.0	7.2	0.55	3190	90	22.0	342
3.9	23.6	10	<1.0	1.40	11.4	18.1	1.58	2970	<5	6.9	1014
4.1	62.2	92	9.0	25.60	11.9	9.3	0.78	2640	220	31.0	201
4.2	76.5	132	17.8	51.00	8.7	6.7	0.77	2320	440	180.0	30
4.3	53.9	80	5.2	15.60	17.9	13.2	0.74	2640	80	30.0	207
4.4	43.1	70	3.1	11.30	26.5	16.1	0.61	2440	40	16.0	359
4.5	44.9	70	2.3	3.75	35.6	48.2	1.36	2930	<5	13.0	531
4.6	48.0	72	1.9	0.99	44.3	188.2	4.25	3300	<5	6.4	1214
4.7	33.4	95	<1.0	0.37	110.6	661.3	5.98	1780	<5	1.9	2207
5.1	84.0	204	19.0	38.10	12.5	13.8	1.10	1290	510	106.0	29
5.2	72.2	122	6.3	13.20	22.6	23.9	1.06	1700	180	99.0	40
5.3	83.4	134	12.6	18.50	12.4	18.7	1.51	3060	300	124.0	58
5.4	50.7	119	2.8	3.36	49.6	91.4	1.84	1120	10	45.0	59
5.5	58.2	122	4.3	2.25	33.1	139.9	4.23	1850	10	24.0	182
5.6	61.1	121	2.6	0.94	54.3	332.2	6.12	1270	<5	9.9	302
5.7	60.2	109	5.2	0.84	24.5	334.9	13.69	3870	<5	13.0	701