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Assessment of sediment quality indicators

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1. INTRODUCTION

Excess nutrients derived from anthropogenic activities are a problem in many marine near shore water bodies. Nutrient concentrations increased above background levels may lead to increased production of pelagic phytoplankton communities and increased sedimentation of highly labile phytoplankton detritus on the surface of sediments [1]. In very eutrophic environments the sedimentation of organic matter may exceed the assimilative capacity of sediments causing low oxygen concentrations or anoxia in bottom waters and a severely reduced diversity of flora and fauna [1-2].

Organic matter in sediments is degraded by the combined action of aerobic and anaerobic sediment associated bacteria. In organic poor sediments most organic matter is degraded by aerobic heterotrophic bacteria depending on oxygen supplied from the overlying water by diffusion or by irrigation driven active transport performed by bioturbating macrofauna [3]. The macrofaunal diversity is high and dominated by large individuals capable of stimulating the metabolite exchange between sediment and water [3-4]. In sediments with an intermediate content of organic matter a larger proportion of total benthic metabolism is performed by anaerobic heterotrophic bacteria, and a large proportion of sediment oxygen uptake (SOU) is used for reoxidation of metabolites from the anaerobic heterotrophic degradation processes [5]. The diversity of macrofauna may be somewhat compromised and a shift towards more tolerant species occur [6]. In very enriched sediments the demand for oxygen can no longer be met by transport from the overlying water column and sediments turn anoxic. The dominating heterotrophic pathway is sulfate reduction, the sediment surface may be colonized by sulfide oxidizing bacteria (*Beggiatoa*) [7], and the macrofauna community shifts towards being dominated by a few species tolerant to low oxygen concentration [8].

The environmental status of sediments is usually evaluated by assessing the diversity of benthic macrofaunal assemblages [9-11]. All though this method is well established and verified, it is very time consuming and requires large amounts of site-specific knowledge if diversity is to be determined at species level. Since the diversity of macrofauna is dependent upon the environmental status of sediments, the information about sediment quality in diversity data sets must also be present in the biogeochemical parameters of sediments. If the key biogeochemical processes determining environmental status of sediments could be identified and related to the degree of environmental pressure, new easy-to-measure indicators could be developed and implemented in management procedures. This study describes the initial procedures of relating environmental pressure (as exemplified by organic enrichment gradients in the vicinity of marine fish farms) to biogeochemical processes in sediments, and assess the individual indicators most frequently used as a measure of sediment quality.

2. FISH FARMING AS A CASE STUDY

The husbandry techniques used to produce marine fin-fish are principally similar world wide. Fish are reared from small to harvestable size in finite volumes of water defined by net-pens or net-cages and are fed different kinds of commercially prepared dry food or by-products from commercial fisheries. Marine fin-fish production is energetically ineffective, meaning that large amounts of food is used to produce the fish. A modern well run farm may have a food conversion ratio (FCR) close to 1. More often poor husbandry techniques and low feed efficiency cause the FCR to be greater than 1, meaning that more than 1 T of food (dry weight) is used to produce 1 T of fish (wet weight). Thus, fish farms generate large amounts of waste that are released into the surrounding environment [12].

Fish farm waste consists of inorganic nutrients excreted directly from the fish to the surrounding environment and solid waste (primarily excess feed and faecal matter) that settle in the immediate vicinity of the farm (fig. 1) [13-14]. The direct nutrient release is usually of minor importance when compared to background levels, but the sedimentation of large amounts of highly labile organic waste within a relatively confined area may significantly alter sediment biogeochemistry and induce deleterious effects on sediment flora and fauna [9,15]. The amount of waste produced is off cause a critical parameter for total impact, but equally important are the hydrological conditions in the area of the farm, with strong water currents favoring dispersion over a wider area [16]. Many of the fish farms used in this study were placed in shallow and sheltered environments with low mean water currents (< 4 cm/s), resulting in sediments heavily enriched in organic matter directly beneath the cages [13-14].

Sediments beneath fish farms are ideal for assessing biogeochemical indicators of environmental stress, because gradients of organic enrichment are usually extending from the fish cages. Fish farms are therefore a unique opportunity to measure changes in sediment biogeochemistry and flora and fauna diversity as a function of organic matter loading at high resolution.

3. ASSESSMENT OF INDICATORS

3.1. General overview of the most frequently used indicators

The most frequently used biogeochemical indicators in evaluating the environmental effects of marine fish farms are summarized in table 1. The indicators may be divided into two categories, 1) indicators that evaluate the pressure exerted upon the environment by the fish farm (pressure indicators) and 2) indicators that evaluate the change in sediment processes resulting from changes in pressure (function indicators).

Tabel 1. The most frequently used indicators when estimating the effects of organic enrichment upon sediment biogeochemistry. Particulate organic carbon (POC), nitrogen (PON) and loss on ignition (LOI) are the most frequently used pressure indicators, whereas sediment oxygen uptake (SOU) and TCO_2-flux are frequently used estimates of total benthic metabolism. Sulfate reduction rate (SRR) is frequently used as an estimate of total anaerobic metabolism.

INDICATOR	TYPE	DESCRIPTION
Sedimentation	*pressure*	Estimates waste production and dispersal
POC in surface sediments	*pressure*	Estimate the total organic carbon content of sediments
PON in surface sediments	*pressure*	Estimates the total organic nitrogen content of sediments
LOI in surface sediments	*pressure*	Estimates the total organic matter content of sediments
SOU	*function*	An estimate of total benthic metabolism as long as SOU ≤ *TCO_2-flux*
TCO_2-flux	*function*	An estimate of total benthic metabolism
NH_4^+-flux	*function*	Estimate of total benthic metabolism in heavily impacted sediments. If TCO_2-production ≤ SOU, most NH_4^+ is reoxidized within the sediment
PO_4^{3-}-flux	*function*	Estimate of total benthic metabolism as PO_4^{3-} is released in proportion to total benthic metabolism
TP	*pressure/function*	A measure of fish farm pressure when TP is considered in isolation. If iron bound P is considered valuable information about function also becomes available
SRR	*function*	Estimates the activity of SRR-bacteria. Is often used as an estimate of total anaerobic metabolism
TS	*function*	High pools of TS in sediments indicate a high activity of SRR-bacteria
PorewaterH_2 S	*function*	The toxic endpoint of anaerobic decomposition, thought to be responsible for loss of diversity

3.2. Sedimentation beneath fish farms

The sedimentation of OM, POC and PON is very much increased in the vicinity of fish farms (fig.1). The increase in sedimentation is, however, often a localized phenomena, and significant increases from background levels are generally detectable 30-100 m away from farms [14,17]. In sheltered environments a massive sedimentation of large waste particles (primarily excess feed) may occur directly beneath the cages determining the ‘farm footprint’, whereas smaller particles (faecal pellets) may be distributed over a wider area depending upon local water currents [18].

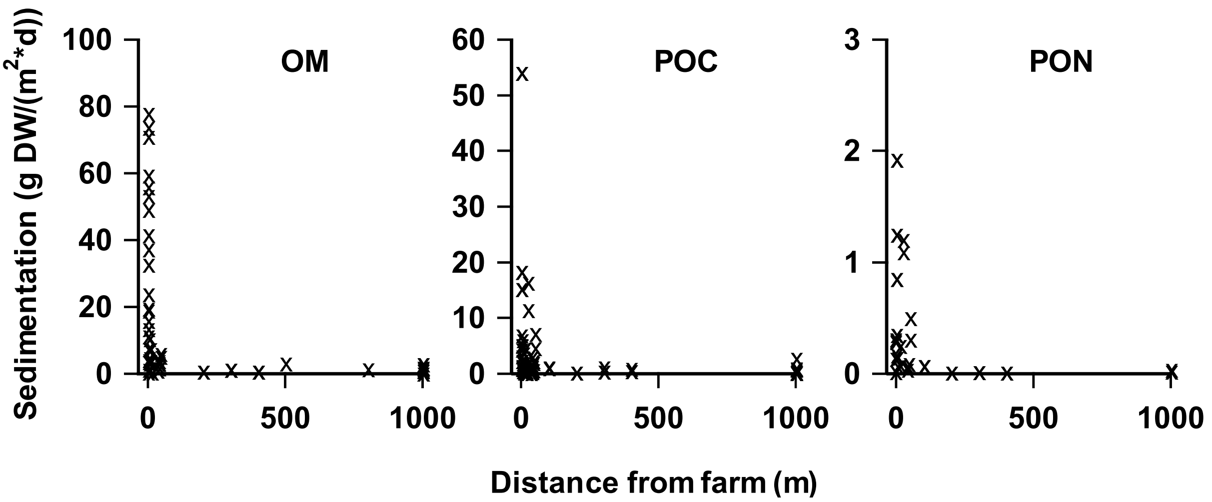

Figure 1. The sedimentation of organic matter (OM), particulate organic carbon (POC) and particulate organic nitrogen (PON) as a function of distance from fish farms (0 indicate the edge of fish cages) (sources [13,14,17,19-23]).

3.3. LOI, POC and PON in surface sediments beneath fish farms

The increased sedimentation of POM beneath and around fish farms results in increased levels of OM, POC and PON in related surface sediments (fig. 2). Significant increases can be detected up to 500 m from farms, and OM, POC and PON content seems to be more sensitive measures of fish farm impact than sedimentation. This is reflecting the fact that sedimentation estimates are subjected to large sources of error, making it difficult to discern small increases in sedimentation from background values [16].

Relatively few studies have measured both sedimentation and organic enrichment of surface sediments. The two measures of fish farm pressure are expected to be linearly correlated, and the few available data confirms this expectation to some degree (fig. 3). Various factors may cause

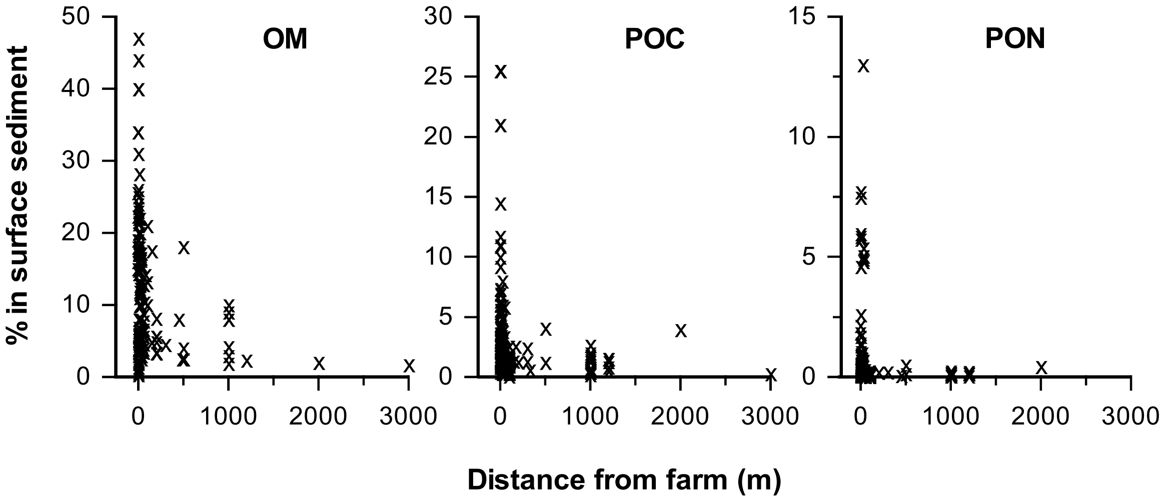

Figure 2. The organic matter content (OM) (estimated as LOI), particulate organic carbon content (POC) and particulate organic nitrogen content (PON) in surface sediments beneath and around fish farms (sources [10-11,13-14,17,19-23,27-41]).

disruptions of the linear correlation, especially factors like resuspension of sediment particles [17,24], aggregations of wild fish in the vicinity of fish farms feeding on sinking waste particles [25] and amelioration of sediments by wild fish populations [26].

Measurements of organic enrichment are extremely important measures of fish farm impact, since organic matter input is ultimately the driver of sediment quality. They estimate the direct enrichment resulting from farming practices and integrate factors such as dispersion by water

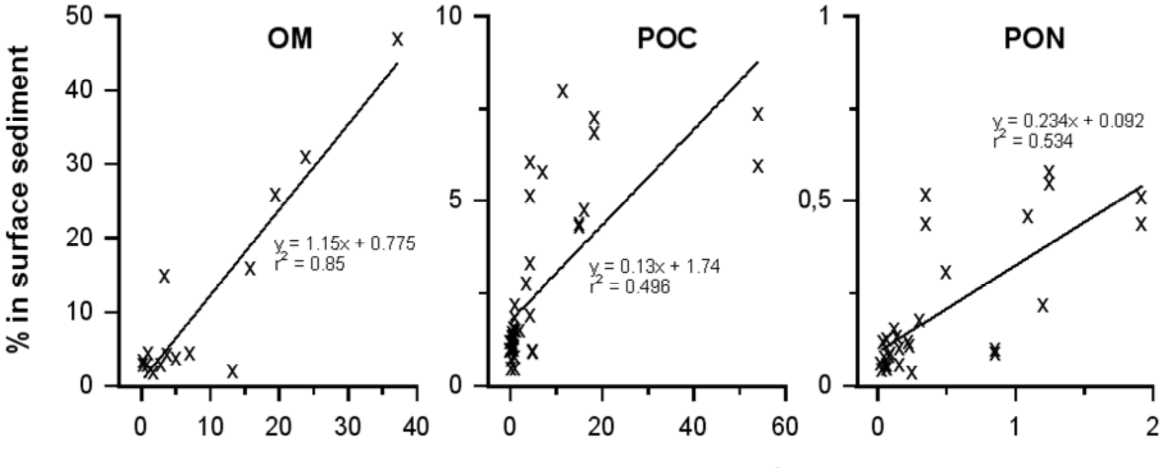

Figure 3. Relationships between sedimentation and organic enrichment of surface sediments (sources [13,17,20,22-23])

currents. Furthermore, estimates of organic enrichment are relatively stable through time meaning that they are sampling extensive.

3.4. Benthic metabolism beneath fish farms

Organic matter in sediments is degraded by both aerobic and anaerobic bacteria [3,42]. Aerobic decomposition occur where O_2 is available, which is primarily in the upper parts of sediments and aerobic zones extending alongside macrofauna burrows, where O_2 diffuses from the water phase into the sediments. Adjacent to the aerobic zones we find the suboxic zones where respiration occur though Fe-, Mn- and NO_3^--respiration, and in the deeper parts of sediments we find the anoxic zones where the dominating heterotrophic pathways are sulfate reduction and fermentation [3].

Usually the degradation of organic matter is slower in the absence of O_2, because anaerobic bacteria lack the capacity to break certain bonds in naturally occurring organic matter [43]. This is, however, not the case in fish farm sediments where labile organic matter is supplied in surplus. Thus, in heavily enriched fish farm sediments, the limiting factor for respiration becomes the supply of suitable electron acceptors.

A frequently used measure of total benthic metabolism is sediment oxygen uptake (SOU), which measures the net flux of O_2 across the sediment water interphase, and integrates both the O_2 used for direct aerobic respiration and the O_2 used for reoxidation of reduced metabolites produced by the anaerobic respiration processes (primarily sulphide produced by sulfate reducing bacteria). At low to medium degrees of organic enrichment SOU is a valid measure of total benthic metabolism, but in extreme cases (as found beneath fish farms) this measure becomes inadequate. SOU is limited to some maximum value defined by local hydrological conditions (water currents, temperature and oxygen saturation in bottom waters) [16], whereas anerobic metabolism is not limited by the same factors. When the sediment demand for oxygen can no longer be met by

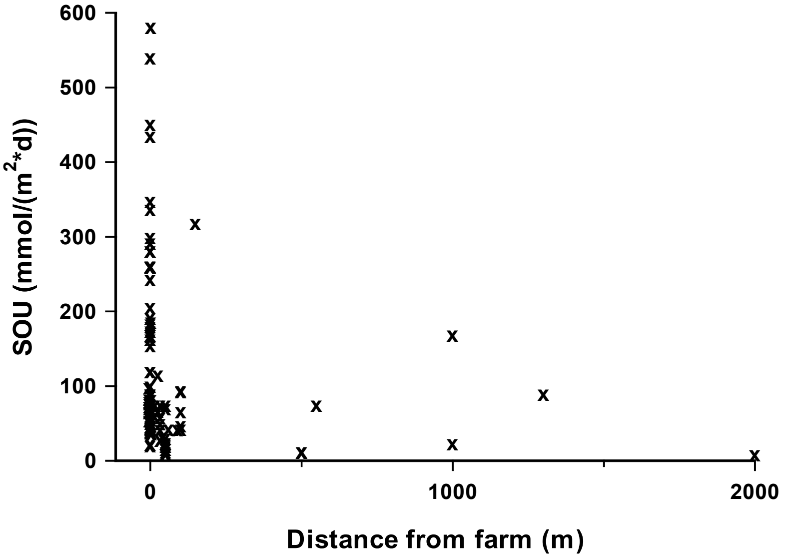

Figure 4. The SOU in sediments beneath fish farms. SOU is stimulated many fold in the vicinity of fish farms, and significant increases in benthic metabolism above background values can be detected up to 500 m from farms (sources [6,8,13,17,19,21,35,37,40,44]).

diffusion, the anaerobic metabolism is still active and SOU is no longer a valid estimate for benthic metabolism.

SOU is the most frequently measured parameter of benthic metabolism in fish farm sediments (fig. 4), and clearly shows that fish farms significantly alter the biogeochemistry of adjacent sediments. Some studies only detects minor increases in SOU in near farm sediments, which is a reflection of different hydrological conditions or better husbandry techniques determining total waste output and dispersion.

TCO_2-production is another estimate of benthic metabolism that is valid over the entire gradient of organic enrichment found in sediments adjacent to fish farms. CO_2 is the end product of heterotrophic metabolism, and the net exchange of TCO_2 ($CO_3^{2-} + HCO_3^{-} + H_2CO_3$) across the sediment-water interphase is therefore a valid measure of net organic matter being degraded in sediments. Unfortunately, TCO_2-production is rarely measured, and only five studies have, applied this parameter in fish farm sediments [14,21-22,35,37] (fig. 5). The results follow the trends of SOU, and the highest values are measured directly beneath the farm.

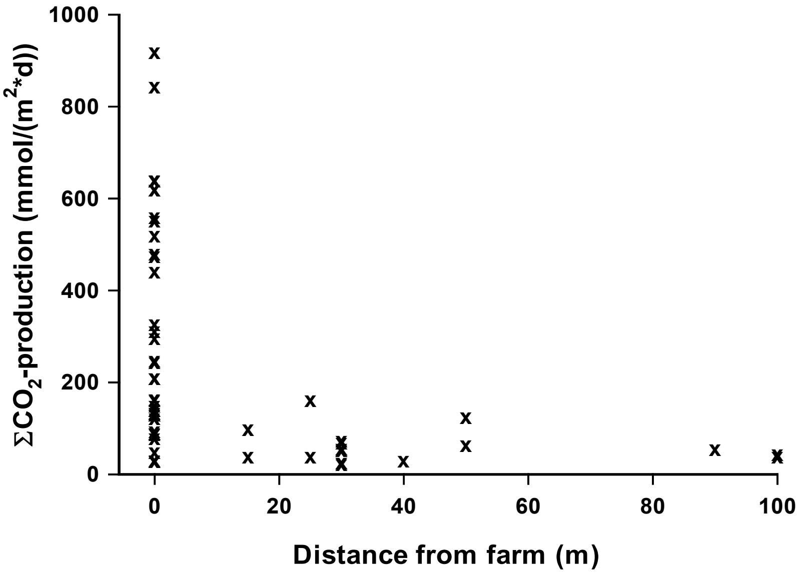

Figure 5. The $\sum CO_2$-production in sediments beneath fish farms. $\sum CO_2$-production is stimulated many fold in the vicinity of fish farms, and significant increases in benthic metabolism above background values can be detected up to 50 m from farms (sources [14,21-22,35,37]).

Both TCO_2-production and SOU should be related to organic matter content, since organic matter is the driver of bacterial decomposition processes. A few studies have simultaneously measured organic content and total sediment metabolism (fig. 6) but there is no significant correlation between POC content and SOU or TCO_2-production. There is, however, a tendency of increasing benthic activity as organic matter content increases. Furthermore, it is evident that

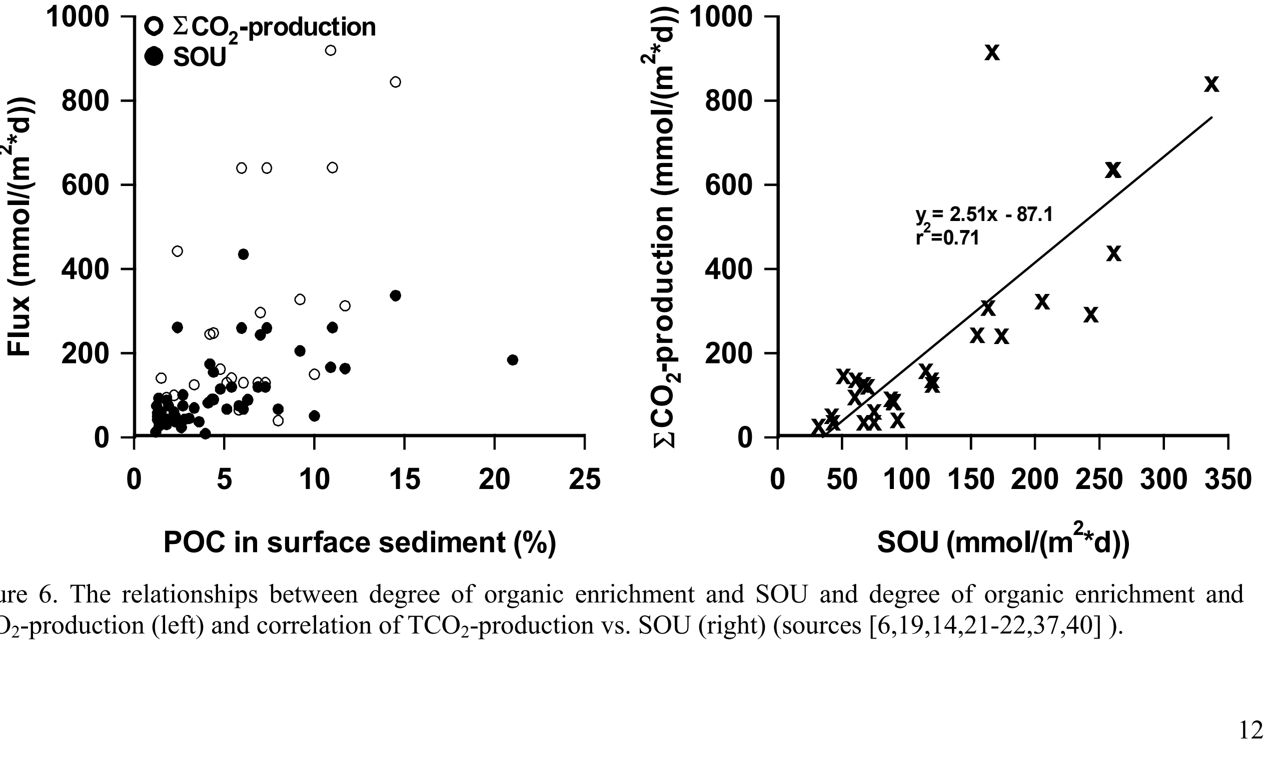

Figure 6. The relationships between degree of organic enrichment and SOU and degree of organic enrichment and TCO_2-production (left) and correlation of TCO_2-production vs. SOU (right) (sources [6,19,14,21-22,37,40]).

sediment TCO_2-production is able to reach much higher values than SOU at similar levels of enrichment. Since TCO_2-production and SOU are essentially expressing the same thing, namely benthic metabolism, the two parameters are expected to be linearly correlated (auto correlated). This tendency is verified by the present data (fig. 6).

Both SOU and TCO_2-production are excellent measures of fish farm impact since they respond to changes in organic matter loading, they are relatively easy to measure and have a high degree of reliability. Ideally both parameters should be measured simultaneously together with some measure of organic enrichment, as both indicators become hard to interpret if used singly.

3.6. S - cycling in fish farm sediments

Sulfate reduction is usually the dominating anaerobic degradation process, whereas Fe- and Mn-reduction may be of significant importance in Fe- and Mn-rich sediments [5]. The process is performed by sulfate reducing bacteria that use SO_4^{2-} as the terminal electron acceptor for the oxidation of organic matter, while sulfide is concomitantly released to the surrounding sediment [3]. The highly toxic sulfide is found primarily as HS^-, and is usually confined to the anoxic part of

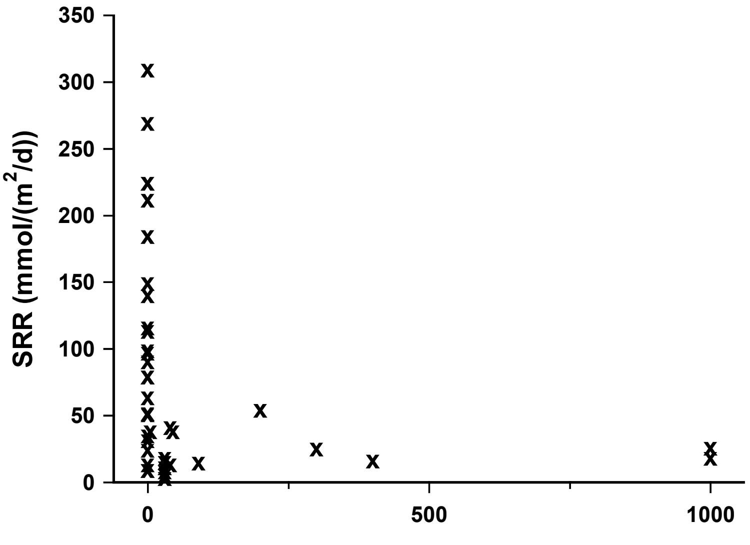

Figure 7. Sulfate reduction rates (SRR) in sediments adjacent to fish farms (Sources [21,23,35,37]).

sediments because sulfide is rapidly oxidized back to SO_4^{2-} by sulfide oxidizing bacteria in the oxic sediment layers or immobilized as FeS or FeS_2 [3]. In organically enriched sediments the capacity for reoxidizing and immobilizing HS^- may be severely impaired, and sulfide may accumulate to high concentrations in the upper sediment layers or escape to the overlying water column [31]. High HS^--concentrations are responsible for the formation of bacterial mats on the surface of sediments (*Beggiatoa* sp.) [3,31] and have been partly responsible for fish kills in fish farms [45-46].

Several authors suggest that HS^- may be the controlling factor for sediment associated flora and fauna, and has been able to relate changes in fauna diversity or dieback of flora to increases in pore water sulfide concentrations [[8,16,27]. The number of investigations of S-dynamics in fish farm sediments are, however, very limited, but the results clearly show that SRR may be very stimulated in fish farm sediments (fig. 7). The exact consequences of this increase is difficult to interpret since parameters like organic enrichment, pore water concentrations of sulfide and solid S content of sediments were not measured in the same studies.

4. CONCLUSIONS

Two types of indicators, pressure indicators and function indicators, are used to asses the impact of marine fish farms on the biogeochemistry of adjacent sediments. Whereas pressure indicators estimate the pressure (organic enrichment) exerted by the farm upon the environment, they tell very little about the environmental quality. Function indicators, on the other hand, describe changes in some specific biogeochemical pathway or total benthic metabolism resulting from changes in pressure. The most frequently used pressure indicators are surface content of OM, POC and PON, and they correlate well with estimates of sedimentation. The most frequently used function indicators are measurements of total benthic metabolism (SOU and TCO_2-production), that respond well to increases in pressure. SRR is another function indicator that measures the impact upon a specific biogeochemical pathway.

5. REFERENCES

1. Paerl H. W. (2006) Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: Interactive effects of human and climatic perturbations. Ecological Engineering 26(1), 40-54.
2. Diaz R. J. (2001) Overview of hypoxia around the world. Journal of Environmental Quality 30(2), 275-281.
3. Kristensen E. (2000) Organic matter diagenesis at the oxic/anoxic interface in coastal marine sediments, with emphasis on the role of burrowing animals. Hydrobiologia 426, 1-24.
4. Aller R. C. and Aller J. Y. (1998) The effect of biogenic irrigation intensity and solute exchange on diagenetic reaction rates in marine sediments. Journal of Marine Research 56(4), 905-936.
5. Canfield D. E., Jørgensen B. B., Fossing H., Glud R., Gundersen J., Ramsing N. B., Thamdrup B., Hansen J. W., Nielsen L. P., and Hall P. O. J. (1993) Pathways of organic carbon oxidation in three continental margin sediments. Marine Geology 113, 27-40.
6. Nickell L. A., Black K. D., Hughes D. J., Overnell J., Brand T., Nickell T. D., Breuer E., and Harvey S. M. (2003) Bioturbation, sediment fluxes and benthic community structure around a salmon cage farm in Loch Ceran, Scotland. Jornal of Experimental Marine Biology and Ecology 285-286, 221-233.
7. Christensen P. B., Rysgaard S., Sloth N. P., Dalsgaard T., and Schwærter S. (2000) Sediment mineralization, nutrient fluxes, denitrification and dissimilatory nitrate reduction to ammonium in an estuarine fjord with sea cage trout farms. Aquatic Microbial Ecology 21(1), 73-84.
8. Hargrave B. T., Duplisea D. E., Pfeiffer E., and Wildish D. J. (1993) Seasonal changes in benthic fluxes of dissolved oxygen and ammonium associated with marine cultured Atlantic salmon. Marine Ecology Progress Series 96, 249-257.
9. Karakassis I. and Hatziyanni E. (2000) Benthic disturbance due to fish farming analyzed under different levels of taxonomic resolution. Marine Ecology Progress Series 203, 247-253.

10. Katavi'c I. and Antoli'c B. (1999) On the impact of sea bass (Dicentrarchus labrax L.) cage farm on water quality and macrobenthic communities. Acta Adriatica 40(2), 19-32.

11. Karakassis I., Hatziyanni E., Tsapakis M., and Plaiti W. (1999) Benthic recovery following cessation of fish farming: a series of successes and catastrophes. Marine Ecology Progress Series 184, 205-218.

12. Islam, M.S., 2005. Nitrogen and phosphorous budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. Marine Pollution Bulletin 50: 48-61.

13. Hansen P. K., Pittman K., and Ervik A. (1990) Effects of organic waste from marine fish farms on the seabottom beneath the cages. ICES Council Meeting 34, 1-14.

14. Hall P. O. J., Anderson L. G., Holby O., Kollberg S., and Samuelson M. (1990) Chemical fluxes and mass balances in a marine fish farm. I. Carbon. Marine Ecology Progress Series 61, 61-73.

15. Delgado O., Grau A., Pou S., Riera F., Massuti C., Zabala M., and Ballesteros E. (1997) Seagrass regression caused by fish cultures in Fornells Bay (Menorca, Western Mediterranean). Oceanologica Acta 20(3), 557-563.

16. Findlay R. H. and Watling L. (1997) Prediction of benthic impact for salmon net-pens based on the balance of benthic oxygen supply and demand. Marine Ecology Progress Series 155, 147-157.

17. Findlay R. H., Watling L., and Mayer L. M. (1995) Environmental impact of salmon net-pen culture on marine benthic communities in Maine: a case study. Estuaries 18(1), 145-179.

18. Stucchi D., Sutherland T. A., Levings C., and Higgs D. (2005) Near-Field Depositional Model for Aquaculture Waste. In Environmental Effects of Marine Finfish Aquaculture (ed. B. T. Hargrave), pp. 157-179. Springer-Verlag.

19. Hall P. O. J. and Holby L. H. (1985) Environmental impact of marine fish farming - sedimentation and benthic solute in situ fluxes under a fish cage culture in Bohuslan. Svenska Havsforskningsforeningens Medd. 20, 141-159.

20. Hall P. O. J., Holby O., Kollberg S., and Samuelson M. (1992) Chemical fluxes and mass balances in a marine fish cage farm. IV. Nitrogen. Marine Ecology Progress Series 89, 81-91.

21. Holmer M., Duarte C. M., Heilskov A., Olesen B., and Terrados J. (2003) Biogeochemical conditions in sediments enriched by organic matter from net-pen fish farms in the Balinao area, Phillipines. Marine Pollution Bulletin 46, 1470-1479.

22. Holmer M., Marba N., Terrados J., Duarte C. M., and Fortes M. D. (2002) Impacts of milkfish (Chanos chanos) aquaculture on carbon and nutrient fluxes in the Balinao area, Philippines. Marine Pollution Bulletin 44, 685-696.

23. MedVeg, 2005. Effects of Nutrient Release from Mediterranean Fish Farms on Benthic Vegetation in Coastal Ecosystems. Progress Report Year 3.

24. Cromey C. J. and Black K. D. (2005) Modelling the Impacts of Finfish Aquaculture. In Environmental Effects of Marine Finfish Aquaculture (ed. B. T. Hargrave), pp. 129-155. Springer-Verlag.

25. Dempster T., Sanchez-Jerez P., Bayle-Sempere J. T., Gimenez-Casalduero F., and Valle C. (2002) Attraction of wild fish to sea-cage fish farms in the south-western Mediterranean Sea: spatial and short-term temporal variability. Marine Ecology-Progress Series 242, 237-252.

26. Katz T., Herut B., Genin A., and Angel D. L. (2002) Gray mullets ameliorate organically enriched sediments below a fish farm in the oligotrophic Gulf of Aquaba (Red Sea). Marine Ecology Progress Series 234, 205-214.

27. Delgado O., Ruiz J., Pérez M., Romero J., and Ballesteros E. (1999) Effects of fish farming on seagrass (Posidonia oceanica) in a Mediterranean bay: seagrass decline after organic loading cessation. Oceanologia Acta 22(1), 109-117.

28. Karakassis I., Tsapakis M., and Hatziyanni E. (1998) Seasonal variability in sediment profiles beneath fish farm cages in the Mediterranean. Marine Ecology Progress Series 162, 243-252.

29. Kaspar H. F., Hall G. H., and Holland A. J. (1988) Effects of sea cage salmon farming on sediment nitrification and dissimilatory nitrate reduction. Aquaculture 70(333-344).

30. Johnsen R. I., Grahl-Nielsen O., and Lunestad B. T. (1993) Environmental distribution of organic waste from a marine fish farm. Aquaculture 118, 229-244.

31. Krost P., Chrzan T., Schoman H., and Rosenthal H. (1994) Effects of a floating fish farm in Kiel Fjord on the sediment. Journal of Applied Ichthyology 10, 353-361.

32. Macleod C. K., Crawford C. M., and Moltschaniwskyj N. A. (2004) Assesment of long term change in sediment condition after organic enrichment: defining recovery. Marine Pollution Bulletin 49, 79-88.

33. Dominguez L. M., Calero G. L., Martin J. M. V., and Robaina L. R. (2001) A comparative study of sediments under a marine cage farm at Gran Canaria Island (Spain). Preliminary results. Aquaculture 192, 225-231.

34. McGhie T. K., Crawford C. M., Mitchell I. M., and O'Brien D. (2000) The degradation of fish-cage waste in sediments during fallowing. Aquaculture 187(3-4), 351-366.

35. Holmer M. and Kristensen E. (1992) Impact of marine fish cage farming on metabolism and sulfate reduction of underlying sediments. Marine Ecology Progress Series 80, 191-201.

36. Maldonado M., Carmona M. C., Echeverria Y., and Riesgo A. (2005) The environmental impact of Mediterranean cage fish farms at semi-exposed lacations: does it need a re-assesment? Helgoland Marine Research 59, 121-135.

37. Heilskov A. C. and Holmer M. (2003) Influence of benthic fauna on organic matter decomposition in organic-enriched fish farm sediments. Vie Milieu 53(4), 153-161.

38. Karakassis I., Tsapakis M., Hatziyanni E., Papadopoulou K.-N., and Plaiti W. (2000) Impact of cage farming of fish on the seabed in three Mediterranean coastal areas. ICES Journal of Marine Science 57, 1462-1471.

39. Porrello S., Tomassetti P., Manzueto L., Fionia M. G., Persia E., Mercatali I., and Stipa P. (2005) The influence of marine cages on the sediment chemistry in the Western Mediterranean Sea. Aquaculture 149, 145-158.

40. Pereira P. M., Black K. D., McLusky D. S., and Nickell T. D. (2004) Recovery of sediments after cassation of marine fish farm production. Aquaculture 235, 315-330.

41. Dimech M., Borg J. A., and Schembri P. J. (2000) The effects of a marine fish-farm on the species richness and abundance of molluscs, decapods and echinoderms associated with a Posidonia oceanica meadow in Malta (Central Mediterranean). Biologia Marina Mediterranea 7(2), 357-360.

42. Kristensen E., Devol A. H., and Hartnett H. F. (1999) Organic matter diagenesis in sediments on the continental shelf and slope of the Eastern Tropical and temperate North Pacific. Continental Shelf Research 19, 1331-1351.

43. Canfield D. E. (1994) Factors influencing organic matter preservation in marine sediments. Chemical Geology 114, 315-329.

44. Lam R. S. S., MacKay D. W., T.C. L., and Yam V. (1994) Impact of marine fish farming on water quality and bottom sediment: a case study in the sub-tropical environment. Marine Environmental Research 38, 115-145.

45. Bagarinao T. and Lantin-Olaguer I. (1999) The sulfide tolerance of milkfish and tilapia in relation to fish kills in fish farms and natural waters in the Philippines. Hydrobiologia 382: 137-150.

46. Black K. D., Kiemer M. C. B., and Ezzi I. (1996) The relationships between hydrodynamics, the concentration of hydrogen sulphide produced by polluted sediments and fish health at several marine cage farms in Scotland and Ireland. Journal of Apllied Ichtyology 12, 15-20.