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Organic Pollution and Its Impact on the Microbiology of Coastal Marine Environments: A Philippine Perspective

Wolfgang Reichardt*, Maria Lourdes San Diego McGlone and Gil S. Jacinto

Marine Science Institute, University of the Philippines, Diliman
11001 Quezon City, Metro Manila, The Philippines
✉ wtreichardt@pmsi.ph

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Abstract: Organic pollution has changed marine coastal environments in both metropolitan and rural regions of the Philippines. This is documented for metropolitan Manila Bay and rural Lingayen Gulf with mariculture zones in Bolinao Bay. After less than a decade of intensive milk fish farming, organic feed and waste inputs apparently triggered negative feed back responses. These culminated in a devastating mass kill of cultivated as well as wild fish stocks in February 2002. This event appeared to be the combined result of oxygen depletion and a red tide harmful algae bloom. Subsequent minor fish kills affected a limited number of net cages mainly in stratified waters at drastically reduced salinities (down to 5) during the SW monsoonal rainy season.

Mesophilic vibrios from the fish farming area showed higher resistance to antibiotics than off-shore isolates and comprised several species of opportunistic pathogens, including *Vibrio cholerae* during the outbreak of a cholera epidemic in the coastal region.

Sediment traps revealed that 1 kg of (net) dry weight m^{-2} d^{-1} (or 50% of the average daily feed input to a fish cage) contributed to the sinking flux of particulate organic matter. Sediment cores mirror enormous near-source increases of organic matter input and deposition during the last decade. As a result of roughly eight years of intensive fish farming the sea floor of Bolinao Bay is covered with a 15-30 cm thick layer of watery sulfidic sediment (Eh = –250 to –150 mV). Due to the continued production of organic matter mineralization via microbe-mediated sulfate-respiration pathways, neritic sediments of the fish farming area are void of burrowing macrofauna. Comparisons with intertidal sediments of similar texture and redox potential reveal two orders of magnitude higher activities of key enzymes involved in organic matter recycling such as scleroproteases. This is at least partially attributable to abundant macrofaunal bioturbation in sulfidic intertidal sediments of the Bay. The extraordinary recycling potential of bioturbated and vegetated intertidal sediments remains a challenge to biogeochemical management options to circumvent the predominance of H_2S-producing sulfate-respiration in organic matter remineralization.

Key words: Marine fish farming, organic pollution, recycling, microorganisms, Vibrio cholerae, sulfidic sediments, biogeochemical pathways.

Introduction

Management of coastal marine resources in South East Asia is confronted with a multitude of human activities affecting the marine environment. Where basic infrastructures absorbing the effects of a rapid economic development and human population increases are lacking, quality and functionality of coastal marine environments are at risk. During the last decade, certain coastal regions of the Philippine archipelago have seen a stormy deployment of intensified net cage mariculture of finfish. In other areas, tourism as attracted by coral reefs and recreational water use has further augmented the health risks that accompany increasing population densities in the absence of a proper sanitary infrastructure.

*Corresponding Author

Organic pollution can be identified as common denominator of several environmental and human health risks that predominate in coastal marine environments. Water and sediment analyses in metropolitan Manila Bay and rural Bolinao Bay (Pangasinan) provide evidence for substantial increments in organic loads entering coastal waters during the last decade. Detrimental effects of this trend are evident from mass fish kill events accompanied by increasing hypoxia and anoxia, more frequent blooms of harmful microalgae, and, most recently an outbreak of cholera. The latter affected human populations near the mariculture area of Bolinao Bay for almost half a year.

Organic pollution shifts the equilibrium between autotrophic processes (primary production) and heterotrophic processes (as dominated by respiratory remineralization) toward heterotrophic functions. There is also growing evidence for a significant contribution of heterotrophic nutrient uptake among phytoplankton (Kirchman, 2000). New paradigms challenge the classic linkage of primary production to eutrophication as triggered by an excessive input of inorganic nutrients. Organic matter can drive primary production not only through mixotrophic assimilation processes, but also via short-circuited remineralization and regeneration of inorganic nutrients in "microbial loops" (Azam, 1998).

Recent advances in analytical techniques in environmental microbiology have been more rapid than in related disciplines, considering only phylogenetic analyses of microbial population patterns that include even "unculturable" bulk segments (Amann & Ludwig, 2000). Yet, practical implications and applications have emerged more slowly. Especially environmental monitoring and management in developing countries are still lacking the resources to make effective use of this emerging analytical potential.

On the other hand, several current issues and problems of coastal marine resource management involve microbiological clues, both as monitoring targets, and as part of intervention and mitigation options (Table 1). This paper will address selected issues of coastal marine resources management in the Philippines. It will focus on the predominant role of organic matter in coastal pollution and its (mainly microbe-mediated) turnover. Selected topics and the challenges they pose to management strategies from a microbiological perspective will be described.

Table 1: Microbiological clues in tropical coastal resource management

Issue/Problem	*Monitoring Targets*	*Intervention/Mitigation Options*
Eutrophication	Phototrophic **plankton** blooms, **benthic** vegetation	Harvest nutrient demanding biomass (e.g., as feed for mariculture) N-elimination
Organic pollution (from terrestrial sources and mariculture)	*Organic matter recycling* capacity (Biofilms, biogeochemical pathways)	Optimize recycling efficiency (enhance area of metabolically active interfaces)
Hypoxia, Anoxia (O_2 depletion)	Photosynthesis: Respiration equilibrium of *OM production and remineralization*	Reduce imbalance (enhance phototrophic processes)
Environmental health /ecotoxicity: Sediments turning sulfidic (Loss of nursery space for living resources)	Sedimentation rates of *Particulate Organic Matter (POM),* *Sediment Infrastructure* (Biofilms, bioturbating macrofauna)	Implement: Mariculture Fallow for oxidative sediment regeneration, Resettlement of bioturbating macrofauna, Enhanced vegetation: seagrasses, mangroves
Global warming in tropical waters: Elevated CO_2 emission	Temperature characteristics of enzymatic processes driving *OM Decomposition* and *Remineralization* (respiration)	Reduce (biofilm-dependent) rate-limiting processes (depolymerization) Enhance OM deposition

Toxic red tides and harmful (prokaryotic and eukaryotic) microalgae	Phytoplankton population dynamics and *nutrient uptake* kinetics	Early alert (toxin detection) Induce viral infections (?)
Microbial diseases of mariculture organisms, corals	Environmental stress factors and conditions favouring *opportunistic pathogens*	Vaccination stress alleviation favour/add antagonistic microorganisms
Human Health aspects of maricultured sea food (microbial pathogens, antibiotics)	Pathogens residing (and protected) in *biofilms* associated with living resources	Introduce pathogen antagonists Interventions in biofouling processes

Methods

Monitoring

Bolinao Bay in the NW part of Lingayen Gulf (South China Sea; 16°17′N, 119° 54′E) is a major resource base for finfish and shellfish farming. Monitoring of water and sediment quality parameters was carried out from the Bolinao Marine Laboratory (BML) situated at the seaward NW shore of Bolinao Bay.

Sediment

Sediment samples were obtained by divers using 6 cm (diameter) rubber-stoppered plexiglass cores of 25 cm or in special cases 120 cm length. Further mud cores (10-15 cm) were collected using a lead-enforced gravity core sampler with a membrane-type valve constructed at BML.

Sedimentation of Particles

Sedimentation of particles in the water column was assessed during 1-2 weeks of in situ exposure of quadruplicate unpoisoned plastic bottle assemblies at different water depths. Trap contents were assayed for volume of total solids, wet weight, dry weight, and protein contents.

Redox Potential

Redox potential values were recorded uncorrected using a Pt redox electrode with an Ag/AgCl electrode at 194 mV serving as reference. Total proteinaceous compounds in sediment samples were analyzed using a modification of the Folin/Cu method of Lowry et al. (Reichardt, 1988b).

Ecto-enzymatic Protease Activities

Ecto-enzymatic protease activities were determined for hide powder azure (Sigma) following the procedure of Reichardt (1988b).

Water Column

Plankton samples were collected by pulling a 63 µm plankton net through for approximately 100 m around a fish net cage.

Water samples taken with a 5 l- Kemmerer/van Dorn type PVC water sampler ("Niskin"-KC, Denmark) were transferred into sterile 0.3 l brown glass bottles.

Biological oxygen demand (BOD) was determined in 250 ml BOD bottles for 24 h intervals of dark incubation at 30°C. Dissolved oxygen was measured using a portable oxygen probe (Oxi 333i).

Viable counts of heterotrophic bacteria were obtained after spreading 0.1 ml aliquots of water sample or of its serial dilution on marine nutrient agar and TCBS-agar plates. Marine agar plates contained 5 g/l of nutrient broth (Himedia, India) and 15 g/l of agar in ¾ strength aged seawater and were incubated for up to one week at 30 °C. TCBS-agar (Himedia, India) plates for the enumeration of presumptive vibrios were incubated for one day at 30 °C and 37 °C.

Antibiotic resistance among vibrio populations toward oxytetracline was estimated from the difference of CFUs on plain TCBS-agar and TCBS-agar coated with 16 mg/l of the antibiotic.

Sources and Effects of Organic Matter Inputs

Metropolitan Manila Bay

Organic Pollution Causing Oxygen Depletion

Waters of Manila Bay (with an area of 1700 km^2) and an average depth of 17 m have a residence time of about one month. The bay receives drainage from two major river systems with considerable sewage discharge functions. Bioavailable organic carbon (i.e., remineralizable via O_2-consuming microbial respiration) follows a slightly increasing trend, whereas the aerobic respiration capacity is steadily decreasing (Jacinto and Velasquez, 2004). In the vicinity of major sources of organic pollution, dissolved oxygen concentrations measured during 24 h periods fall below a threshold value for hypoxic water bodies of 2.8 mg/l in stratified water layers during SW monsoon periods (Wu et al., 2002). Water quality improves again after complete mixing during NE monsoon periods.

Only 15% of the population of 16 million inhabitants in the drainage area of Manila Bay are connected with a sewerage system. Rapid population increments from the 1980s onward are mirrored in a steep decline of dissolved oxygen that is depleted by the aerobic respiratory mineralization of increasing organic loads (McGlone et al., 2004). Based on a model to estimate the time required to reach complete depletion of a given amount of dissolved oxygen (DO) in the water column, calculated DO levels reveal an inverse relationship with population growth of Metro Manila.

Sedimentation Record

Another approach to identify trends of organic pollution employs marine coastal sediment cores. Sedimentation records mirror the combined heterotrophic and photoautotrophic biomass production in the water column. Based on ^{210}Pb dating, certain sections of Manila Bay indicate an abrupt five-fold increase in sedimentation rates about a decade ago (Sombrito et al., 2004). As cysts of harmful dinoflagellates such as *Pyridininum bahamense* are preserved in the sediments, limited but useful records of past red tide blooms can serve as indicators of pollution of the more recent past.

Rural Lingayen Gulf

Hydrography

Rural Lingayen Gulf with Bolinao Bay (Figure 1) covers an area of 2100 km^2 with an average water depth of 46 m, and an average residence time of one month. About one tenth of the area are coral reefs in the vicinity of Bolinao. Since 1997 parts of the Gulf including Bolinao Bay have become mariculture zones for intensive year-round milkfish cultivation in cages and pens. Discharge of freshwater and suspended solids from surrounding slopes and agricultural land (amounting to 10 km^3 and 2.8 million t a^{-1}, respectively) peaks during the SW monsoonal wet season (May–October) (Talaue-McManus et al., 1999). Resulting stratification of the water column can reduce salinity in surface water layers to values below 5. A multitude of (approximately 1100) fish cages is anchored along the Bolinao Bay channel connecting the fish farming area to the open South China Sea. These structures are not only exposed to a wide range of current velocities, but can themselves effectively slow down existing currents. This leads to reduced water exchange and accelerated O_2 depletion on small scales (Udarbe-Walker & Magdaong, 2003).

Figure 1: Bolinao Bay.

Sedimentation Rates

Sediment traps deployed at an operating fish cage and at the margin of the fish cage zone in Bolinao Bay suggest that net sedimentation of particles in the immediate vicinity of a cage was five times greater than outside the cage area. Near bottom traps linked to a fish cage at 18 m water depth revealed a sedimentation rate of 1001 g dry weight m^{-2} d^{-1}(Table 2). This corresponds to roughly half of the estimated daily feed input of 2 kg m^{-2}. Proteinaceous compounds analyzed by a modified method of Lowry et al. (Reichardt, 1988a) were six times more abundant near the cage than at the margin of the cage area. Increments of organic C:N ratios from 8.0 to 9.5 suggest moderate N losses of sinking particles once deposited on the seafloor (T. Jennerjahn, ZMT, personal communication).

Sediment cores obtained from the fish cage area (at Guiguiwanen Point in Bolinao Bay) were characterized by more than 40 cm thick unconsolidated top layers of anoxic sulfidic mud with nearly double the water content of the more compacted sediment below 40 cm sediment depth (joint sampling trip with N. Kadil, IES, UPD, September 2004). Preliminary estimates indicate annual sediment deposition rates of approximately 4 cm.

Sedimentation rates reported previously by Holmer et al. (2002), were also extremely high, but referred to

Table 2: Impact of intensive finfish mariculture on sediment trap data in Bolinao Bay (7 –19 April, 2004)

	A 16° 23.002 N, 119° 54.933 E			*B* 16° 18.899 N, 119° 55.417 E		
Water depth	*10 m*	*15 m*	*24 m*	*8 m*	*13 m*	*18 m*
Net Input						
by volume	1089	1720	2201	2117	4385	5504
[ml m^{-2} d^{-1}]	+/- 123	+/- 158	+/- 131	+/- 376	+/- 598	+/- 892
by dry weight	102	190	270	247	602	1001
[g m^{-2} d^{-1}]	+/- 25	+/- 15	+/- 13	+/- 31	+/- 65	+/- 207
by protein	621	1817	1790	3146	7716	6543
[mg $m^{-2}d^{-1}$]	+/- 177	+/-762	+/- 840	+/- 851	+/- 1473	+/- 1283

(*n* = 4 replicate traps per depth) at cage (A) and off cage (B) area

shallow water fish pen areas only where resuspension effects are often beyond control.

Microbial Water Quality Aspects

Red Tides

Fish cages constitute nearly permanent point sources of organic pollution. Small scale hydrography augments the accelerated depletion of dissolved molecular oxygen by (predominantly microbial) respiratory processes. Fish feeds are most likely to affect existing equilibria between photoautotrophic and heterotrophic processes in the euphotic water layer, and can eventually also favour the formation of mixotrophic or even phagotrophic phytoplankton blooms (Kirchmann, 2000). A massive fish kill in 2002 suggested a collusion of both those impacts as its cause. O_2 depletion in the euphotic zone had approached minima of < 2 mg/l when red tide plankton blooms of fragile raphidophyte flagellates and more robust dinoflagellates (*Prorocentrum minimum*) became visible (Reichardt et al., 2003).

Increasing frequencies of mostly mixotrophic blooms of harmful microalgae in coastal waters of the Philippines seem to concur with organic pollution from either sewage disposal (Manila Bay) or from marine aquaculture in the Lingayen Gulf (Sombrito et al., 2004). Apparently organically polluted waters confer a competitive advantage on mixotrophic microalgae that have the capacity to shift between photoautotrophic and heterotrophic modes of energy generation.

Opportunistic Bacterial Pathogens and Mesophiles

Apart from mixotrophic microalgae, organic-rich marine water bodies are also the domain of copiotrophic (heterotrophic) bacteria. This group is characterized by its preference for high concentrations of easily accessible organic nutrients. Most copiotrophic bacteria exhibit life cycles with attached, biofilm-forming stages and detached suspended phases. *Vibrio*, the arguably best studied copiotrophic marine bacterial genus are permanent associates of marine macroflora and macrofauna (Simidu & Tsukamoto, 1985). As copiotrophic constituents of the intestinal microflora of marine invertebrates and fishes, *Vibrio* spp. have been dubbed the "coliforms of the sea". Members of this group were the first providing us insight into starvation survival mechanisms. These involve attachment of starved, metabolically altered cells to nutrient providing solid surfaces. Ensuing formation of bacterial biofilms associated with nutrient exuding macroorganisms (such as seaweeds and macroinvertebrates) is very common and presumably a case of mutual advantage (Kjelleberget al., 1987).

Yet, copiotrophic, biofilm-forming bacteria also possess genetically regulated mechanisms to activate exoenzymes with the capacity to dissolve plant and animal tissues. Correspondingly, diverse polysaccharases including agarase and chitinase as well as protease enzymes may confer the potential of opportunistic pathogens on a number of copiotrophic marine bacteria (Jass et al., 2002; Wingender & Jaeger, 2002).

The abundance of opportunistic pathogens is expected to peak in coastal waters of the tropics. Whereas bulk ocean water is permanently less than 5 °C cold and contains adequately adapted psychrophilic and psychrotrophic bacteria, coastal and surface waters in the tropics with temperatures approaching 30 °C will select for "mesophilic" bacteria. As copiotrophic bacteria with maximum nutrient demands, certain mesophilic vibrios can reveal their pathogenic potential in nutrient-enriched marine environments (e.g., Bruno et al., 2003).

The group of mesophilic vibrios also includes human pathogens such as the causative agent of cholera, *Vibrio cholerae* (Harvell et al., 1999). A recent outbreak of cholera along the coasts of the Lingayen Gulfin 2004 has directed public awareness to the potential risk of stimulating potential pathogens in coastal fish cage mariculture. At the peak of the epidemic, we found enhanced presumptive *Vibrio cholerae* counts in the water near fish cages, particularly, where freshwater inflow and stratification had caused an extreme decrease in salinity values down to 5. Fish cages in these waters showed high fish mortality, most probably linked with the predominance of non-sucrose-fermenting, fish-pathogenic vibrios (Table 3).

As fish and shellfish farmers apply antibiotics to ward off vibriosis diseases, one can expect elevated levels of acquired antibiotic resistance among pelagic bacteria in the mariculture zone. Preliminary tests have confirmed this for oxytetracycline at a minimum inhibitory concentration of 16 mg/l (Table 4).

Microbe-Driven Sediment Biogeochemistry

Deposition of Proteins

Proteins constitute predominant components of commercial fish feeds used in Bolinao Bay. Overfeeding causes grossly enhanced sinking fluxes of particulate organic matter and deposition of roughly half of the feed input on the sediment beneath the fish cages. In near-bottom sediment traps protein concentrations were 3-4 times higher in the presence of cages than in the absence of nearby cages (Table 2). Once deposited, protein concentrations remained relatively stable at different sediment depths. Corresponding proteolytic enzyme activities measured with hide powder azure (Sigma Chemicals) as particulate scleroprotein substrate (Reichardt, 1988b) were quite low at the sediment surface, yet detectable down to a sediment depth of 40 cm (Table 5).

Experimental trials with sulfide additions revealed inhibitory effects of H_2S on proteolytic activities. These proved, however, insufficient to account for the extremely low decomposition of proteins observed *in situ.* While regulation of exo-enzymatic protein degradation in marine sediments comprises at least three levels of complexity, a predominance of direct inhibitory effects on the protease molecules is most likely.

Recycling Capacity of Neritic vs. Intertidal Sediments

A comparison of aphotic neritic sediments with their intertidal counterparts from Bolinao Bay revealed striking differences in their organic matter recycling capacities. Intertidal sulfidic sediment with extremely high

Table 3: Milkfish mortality in Cages

Position (°)	*Water Depth (m)*	*Transparency (m)*	*Salinity *SW *BW*	*CFU/ml (TCBS)*	*NF/F-Ratio***	*Specimen containing TCBS-Vibrio spp. [CFU/g wet weight]*
Sampling in Bolinao Bay on 2 August 2004						
N 16 22.237 E 119 56.652	7	3	SW 25	150	0.1	Mussel *(Perna viridis)* 690,000
N 16 18.047 E 119 54.956	14.5	1	SW 20	1030	3.8	Milkfish, intestine: 4,200000 ***
Sampling in Bolinao Bay on 30 August 2004						
N 16 17.272 E 119 55.208	7	0.9	SW 5 BW 29	2000	0	Mussel *(Perna viridis)* 3200,000 Milkfish, intestine: 4,800000
N 16 17.994 E 119 54.967	14.5	1.2	SW 6 BW 30	1800	0	Milkfish, intestine: 4,200000
N 16 18.887 E 19 55.409	17.5	1.5	SW 11 BW 16	220	0.8	Milkfish, intestine: 3,800000
N 16 23.093 E 119 55.086	17	1.5	SW 15 BW 32	>160	0.2	n.d.

*SW = Surface water, *BW= bottom water (core sampler),
**NF/F-Ratio: [Sucrose-non-fermenting: sucrose-fermenting CFU on TCBS-Agar, 38 ^{o}C]
*** Vibrio cholerae serotype non-01 confirmed

Table 4: Acquired antibiotics resistance in planktonic populations of *Vibrio* spp.

Effect of Oxytetracycline on Viable Counts on TCBS-Agar (30°C)

Concentration (mg/l)	*Colony-forming Units (CFUs)*
Zero (Control)	206 +/- 65
16	63 +/- 31
80	19 +/- 6
400	0
2000	0

Impact of vicinity to fish cages on oxytetracycline susceptibility of planktonic vibrios

Source	Recovery (CFU / ml) [*n* = 8 replicates]
Near fish cage	76 +/- 7
Off mariculture zone	30 +/- 12

Table 5: Total Protein content and protease activities in core no. 2 from Bolinao Bay (N16°23.057, E119°54.884) near cages at 20 m depth

Depth [cm]	*Water per cm^3*	*E_h [mV]*	*Protein mg cm^{-3}*	*Protease (30°C) [abs. units/cm^3.h]*
0-1	-	-168	1356	4.24
1-3	817.7	-188	1910	1.99
7-9	-	-201	1801	2.06
11-13	824.5	-191	1766	0.53
15-17	-	-189	1818	0.41
21-23	-	-150	1958	0.46
31-33	716.8	+10	1875	-
37-39	-	+13	-	0.25

deposition rates for organic deposits had two orders of magnitude lower proteolytic enzyme activities than their neritic counterparts which contained twice the amount of proteins. Despite similar texture and high organic matter deposition, intertidal sediments were by far more effective than their neritic counterparts in terms of their recycling capacities (Table 6). Main differences between the two types of sediment were exposure to light and macrofaunal bioturbation in the intertidal zone. Bioturbation seemed instrumental in extending the metabolically most active surface of the seafloor into the (internal) subsurface layers of irrigated and aerated macrofaunal burrows. Biofilms covering these macrofaunal burrows proved to be hot spots of organic matter recycling. Neritic sediments from the mariculture zone of Bolinao Bay, on the other hand, were usually lacking macrofaunal bioturbation.

Table 6: Protein content and protease activity in intertidal and neritic (aphotic) coastal silty sediments (Bolinao, Pangasinan)

	Intertidal (silt)	*Neritic (Aphotic)*
Protein [mg/l]	1011	2187
Protease [Abs.Units cm^{-3} h^{-1}]	162	1.7

Mitigation Options

Alternative Biogeochemical Pathways to Sulfate Respiration

Cores from Bolinao Bay contained 10-30 cm top layers of sulfidic sediment at redox potential values of –210 to –150 mV (Table 5). This indicated that sulfate-respiration had governed most of the mineralization of deposited organic matter as a kind of biogeochemical "default" pathway due to sufficient supply of sulfate as terminal electron acceptor. Predominance of this biogeochemical pathway is linked with widespread ecotoxic effects. Permanent hydrogen sulfide production can wipe out most of the benthic macroorganisms, unless microbe-mediated and chemical re-oxidation allow to carve out oxidized, hydrogen sulfide-free microhabitats for benthic life. This was observed in the euphotic intertidal sediments of Bolinao Bay, not, however, in its neritic counterparts at 15-25 m water depth.

Initial stages in the reoxidation of the sulfidic sediments of the mariculture area were accompanied by the growth of microbial S-oxidizing mats dominated by large *Beggiatoa* spp. These were most abundant toward the end of the SW monsoonal rainy season (August - September) in heavily polluted sediment below stratified water columns. Implementation of fallow periods by periodic removal of fish cages in certain areas resulted in a partial reoxidation of the sediment surface and its re-colonization by small burrowing invertebrate macrofauna within less than six months.

Despite this detoxification by partial re-oxidation of sulfides, neritic sediments of Bolinao Bay were lacking the type of bioturbate structures that are characteristic of the shallow, intertidal zones of the bay. Animal burrows as well as the root surfaces of mangroves and sea grasses are covered by complex microbial biofilms. The latter can enhance the capacity of the sediment to circumvent the "ecotoxic" pathway of organic matter remineralization via sulfate-respiration. The most important alternative is based on bacterial ferric iron reduction (Fe^{3+}- respiration). It seems to predominate in sediments that can rapidly regenerate (re-oxidize) the ferrous iron product. Irrigated rice fields, but also mangrove swamps, satisfy these requirements for Fe^{3+}-respiration to predominate organic matter recycling in anoxic soils and sediments (Lu et al., 2002; Kostka et al., 2002).

Furthermore, bioturbate sediment structures covered with microbial biofilms harbour a second key function in sediment biogeochemistry. The exopolymeric matrix of microbial biofilms can be viewed as a kind of immobilizing and “slow release”- agent for ecto-enzymes. These enzymes (including cellulases, chitinases, proteases) are instrumental in the first steps of (extracellular) decomposition of organic detritus particles (Smith et al., 1992). Hence, as illustrated by an extremely effective enzymatic degradation of organic matter in intertidal, thoroughly bioturbated sediments, macrofaunal bioturbation ought to be seen as key factor governing organic matter recycling in marine sediments.

Contribution of this factor to “natural” organic waste management in intertidal coastal zones of the tropics has yet to be quantified. Its potential to enhance organic matter recyling is presumably much higher than in limnic or terrestrial environments, the widely predominant resource bases of organic waste management. In comparison to freshwater environments, marine sediments exhibit by far greater depths of macrofaunal bioturbation (Ziebis et al., 1996; Webb & Eyre, 2004). Moreover, the great diversity of natural organic compounds in marine systems ought to trigger an equally high diversity of enzymatic decomposition pathways. Hence, the endogenous organic matter recycling capacity of intertidal soft bottom sediments in the tropics can be viewed as a valuable, but so far neglected, asset. Here, management interventions to enhance biogeochemically reactive interfaces can find promising targets: bioturbation, and biofilm-supporting below-ground vegetation in mangrove forests or sea grass beds (Table 1).

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