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Acoustic detection of organic enrichment in sediments at a salmon farm is confirmed by independent groundtruthing methods

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ABSTRACT: Acoustic backscatter contrast in depositional sediments under salmon farm cages in the Bay of Fundy, Canada, was correlated with localized changes in (unknown) sediment geotechnical properties, as indicated by 4 independent measures of organic enrichment. Sediment total sulfides and redox potentials, enzyme hydrolyzable amino acids, sediment profile imaging and macrofaunal samples, taken at mid-cage positions, each rejected the null hypothesis that salmon cage footprints, defined acoustically as high backscatter areas, were indistinguishable from nearby reference areas. Acoustic backscatter imaging appears capable of mapping organic enrichment in depositional sediments caused by excessive inputs of salmon farm wastes associated with intensive aquaculture.

KEY WORDS: Organic enrichment · Multi-beam acoustics · Sedimentary sulfides · Sediment profile imaging · Aquaculture

INTRODUCTION

Organic enrichment in sediments results from an enhanced supply of dissolved and particulate organic matter, which usually instigates a proportionate microbial response. The organic matter supply may be of natural origin, e.g. from phytoplankton or a whale carcass reaching the seabed, or from anthropogenic sources (e.g. municipal and industrial effluents, fish plant processing, agriculture and mariculture wastes). Many aspects of the ecology of organic enrichment in sediments are relatively well known, e.g. microbiology (Poole et al. 1978), macrofaunal responses (Pearson & Rosenberg 1978, Gowen & Bradbury 1987, Gray et al. 2002) and pelagic–benthic coupling (Cloern 2001).

One area of organic enrichment studies which has remained problematic and unresolved is the determination of the geographic (=spatial) extent of organic enrichment effects in sediments. This arises because of inherent problems in classical sampling with grab or corer, even if a few radial transects from the organic enrichment source are used. Grab samplers are remote devices of relatively small sampling area (<0.5 m^2) whose sampling position is usually not accurately known. The high cost in time and expertise required for processing samples, e.g. for macrofaunal identification, limits the number of samples that can be analyzed. This means that the area that can be accurately mapped, according to the 4 levels of organic enrichment gradient of Pearson & Rosenberg (1978), is therefore very limited. By contrast, acoustic methods offer comprehensive spatial coverage of sizeable areas (>40 km^2 d^{-1}) of accurately geo-referenced data.

During preliminary, multibeam acoustic surveys at salmon farming leases in Newfoundland (Tlusty et al. 2000) and New Brunswick (Hughes-Clarke 2001), it was noticed that backscatter images studied from the net depositional sediments showed the individual

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salmon cage 'footprint' as a contrast (white area, high backscatter) to the darker background image (low backscatter), characteristic of depositional sediments. The inference was that the high backscatter was caused by localized changes in sediment geotechnical properties, due to organic enrichment resulting from the very high inputs of salmon faeces and waste food under farms.

This work is the first step in establishing whether the acoustic methods briefly described herein can be developed further to map organic enrichment effects in soft sediments. The aim of this study was to check the inference mentioned above by testing the null hypothesis that the acoustically defined areas of high backscatter were not the direct result of organic enrichment events in sediments.

MATERIALS AND METHODS

Acoustic surveys were completed from RVs 'Mary-O' and 'Heron' on 27 July 2001 and 9 October 2002 around a farm site in Lime Kiln Bay, which opens to the Bay of Fundy (Fig. 1). In October 2002, RV 'Heron' was equipped with a 300 kHz multibeam sonar (vertically mounted Simrad EM3000), and in July 2001, RV 'Mary-O' deployed a 200 kHz pole-mounted sidescan (Knudsen 320B/.P with Airmar staves). Both systems produce estimates of bottom backscatter strength, correcting for source level, beam patterns, spherical spreading and attenuation, ensonified area and grazing angle (Hughes-Clarke 1994, Hughes-Clarke et al. 1996). Due to imperfect knowledge of absolute calibration levels, the backscatter strength estimates at the reference and farm sites have been assumed to be the same, and the 200 kHz data-bulk shifted to match the 300 kHz results. The data obtained were processed digitally to produce a map of bottom backscatter strength in which high backscatter was indicated by a lighter colour. A gross correction for grazing angle was applied, but this did not remove all the residual ship-track parallel stripes, which reflects both variations in the shape of the angular response and imperfections in the beam-pattern model used. The mean backscatter strength is dependent on the exact grazing angle, where in the cage footprint it is measured, and on the absolute calibration. Backscatter strength was measured in a 5 × 5 m area near the centre of the cage footprint, aided by graphical software (SwathEd, developed at the University of New Brunswick) to select the highest values. The value in decibels (dB) for each pixel was averaged. The mean for each location was found to be reproducible within 0.2 dB. High backscatter (white) is indicated by less negative values, and low backscatter (dark) by more negative values.

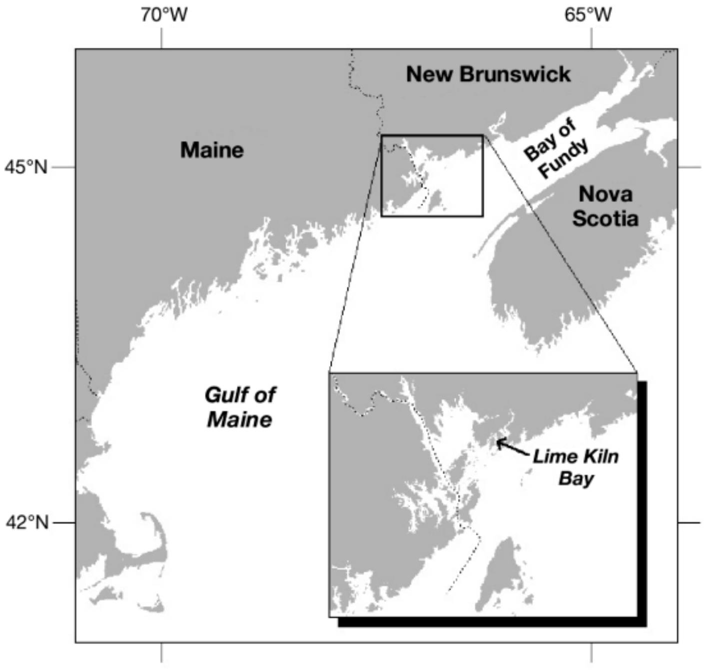

Fig. 1. Map of sampling site

Groundtruthing surveys were conducted from RV 'Pandalus III' on 26 July 2001 and 9 September 2002, at the same farm site, moored to cages (farm) or a floating pontoon 50 m from the nearest cage (reference location). The maximum permissible stocking density at New Brunswick salmon farms is 18 kg m^{-3}. The cages at the salmon farm we investigated were 50 m in diameter; the farm was 3 mo into its smolt year of production in 2001, and nearing the end of its production cycle in 2002 (market year). Thus, in 2002 a higher fish biomass was present and, consequently, feeding rates would be higher than in 2001. Five farm cages were sampled at the cage mid-point on each date, and an equal number of reference samples within a 1 m^2 quadrat 50 m away from the cages. Sampling was achieved by SCUBA divers equipped with hand-held Hargrave core samplers (Wildish et al. 2003). The 2001 and 2002 acoustic surveying were completed 1 and 30 d after the groundtruthing, respectively. Each core sampled an area of 0.0263 m^2 and a full core contained 6.2 l of sediment. Sediment characteristics in the sampled part of Lime Kiln Bay were depositional (Milligan 1994).

Each core was photographed as described in Wildish et al. (2003), and the sediment profile images (SPI) were analyzed with Optimas (Version 6.2) software using the area tool divided by the fixed corer width to give the mean sample and redox potential depths (RPD). Images were analyzed by the method of Nilsson

& Rosenberg (2000) to determine the benthic habitat quality (BHQ) index. The latter is based on predetermined values (maximum of 15) for presence/absence of infauna/epifauna and RPD depths (Table 1). Sediment interface samples (the top 0 to 2 cm of the profile) were taken for geochemical measures of redox potential (Eh, expressed in mV relative to the normal hydrogen electrode) and total sulfides in pore water (expressed as mM) as described in Hargrave et al. (1997). Geochemical data corresponding to other organic enrichment indices are shown in Table 1. Subsamples were taken from each core to measure percent water content, organic matter content as % loss on ignition at 450°C for 2 h, and organic carbon and nitrogen by CHN analyses. Subsamples from thawed sediment, kept frozen before analysis, were taken in the 2001 sampling for enzyme hydrolyzable amino acids (EHAA) by the method of Mayer et al. (1995), and for determing sediment surface area by nitrogen adsorption (Mayer 1994). Non-parametric statistics (Elliot 1977) on untransformed data were used to determine differences between farm and reference sites.

The remaining sediment in each core was sieved through a 5 mm^2 mesh sieve and running seawater, with the smallest mesh size being 1 mm^2. Macrofauna retained were initially stored in 5% formalin in seawater, followed by 50% isopropanol. They were then identified and counted, using standard procedures adopted at the Atlantic Reference Centre, Huntsman Marine Science Centre, to the lowest possible taxon. The species/abundance data were analyzed to detect patterns by graphical, univariate and multivariate methods (Clarke & Warwick 2001) available in Primer software.

RESULTS

Backscatter maps identify the farm sites sampled in 2001 and 2002 (Fig. 2). The faint appearance of earlier cage deployments is seen most clearly in the upper panel, and the outline of an unused herring weir is present in both. The high backscatter areas clearly define the cage footprint, suggesting that waste food and faeces accumulate directly below the cages, with little spreading. The backscatter strength in each of the cage footprints appears to be higher in 2002 than 2001 (Table 2) by a mean value of 6.3 dB. Possible reasons for this are that the 2001 record was tainted with echoes and shadows from the cage structures and nets. Also, there were differences in backscatter calibration on the 2 sampling dates.

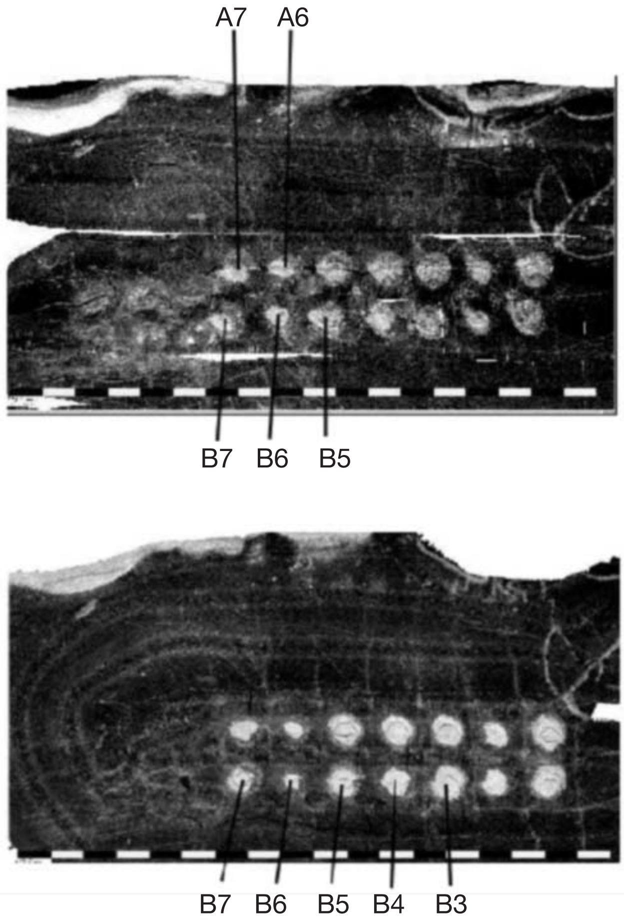

Fig. 2. Acoustic backscatter maps from 26 July 2001 (upper) determined by Knudsen sidescan and 9 October 2002 (lower) determined by a 300 kHz multibeam sonar (vertically mounted Simrad EM3000). The 2 rows of active cages, labelled A and B, are each identified by a number from 1 to 7 (some numbers not shown). Only sampled cages are identified. The remains of 2 indistinct rows of 6 cages active until 2000 appear to the left of the labeled ones, and the remains of an old herring weir is closest to A1. The reference location is just outside the frame, below the scale bar (hatched bars at bottom) where each unit = 50 m

Table 1. Summary of organic enrichment indices based on sedimentary observations for macrofauna of Pearson & Rosenberg (1978), sediment profile images (SPI) and the benthic habitat quality (BHQ) of Nilsson & Rosenberg (2000) and interfacial geochemistry of Wildish et al. (2001). Note that the degree of organicenrichment increases down the table. Eh_{NHE}: redox potential relative to the normal hydrogen electrode

Description	Macrofauna	Sediment profile imaging BHQ	Interfacial geochemistry Eh_{NHE}	Sulphide
Normal	III	>10	>100	<300
Oxic	II	5–10	0–100	300–1300
Hypoxic	I	2–4	–100–0	1300–6000
Anoxic	0	<2	<–100	>6000

Table 2. Backscatter strengths, as mean dB, in farm footprint and reference locations

Location	27 July 2001	9 October 2002
Farm A7	−19.5	
Farm A6	−18.4	
Farm B7	−17.1	−12.2
Farm B6	−18.0	−11.8
Farm B5	−19.4	−12.0
Farm B4		−12.0
Farm B3		−12.9
Reference	−35.0	−35.0

Confirmation that the faint appearance of cage footprints in Fig. 2 represents an earlier cage deployment, which terminated in 2000, is shown in Fig. 3. The upper and lower panels are backscatter maps for the same area of Lime Kiln Bay in November 2000 and July 2001, respectively (the same as in the upper panel of Fig. 2). The new 2001 cage deployment saw the cages moved closer to the old herring weir, but with considerable overlap with the earlier deployment. This and other evidence with aerial photographs and backscatter maps (Hughes-Clarke et al. 2002) suggest that the areas of high backscatter may persist for 1 to 4 yr in the sedimentary environments of Lime Kiln Bay.

All of the geochemical variables in Table 3 were examined by comparing the medians between farm and reference sites, followed by testing for differences by the Mann-Whitney *U*-test (Elliot 1977). Significant differences at $p < 0.05$ were found for porosity, organic matter, carbon, nitrogen, EHAA, Eh and $S^=$ (sulfide) for both sampling dates shown in Table 3.

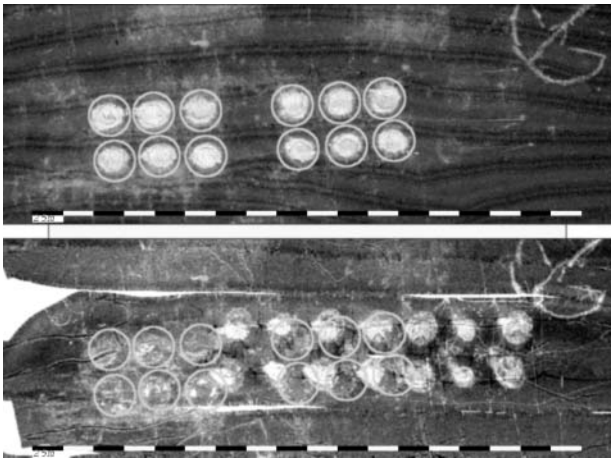

Fig. 3. Acoustic backscatter maps of November 2000 (upper), determined by a 300 kHz multibeam sonar (vertically mounted Simrad EM3000), and 26 July 2001 (lower) determined by Knudsen sidescan. Circles indicate the position of individual cages for the earlier (1999 to 2000) deployment. Each unit of the scale bar = 25 m

Eh is lower and $S^=$ higher in 2001 than 2002. This was unexpected because a larger volume of wastes was produced by the larger biomass of salmon in the market year (2002). It is possible that the anaerobic bacteria present in the sediment had undergone a self-poisoning event (due to high H_2S) earlier in the summer of 2002, as found by Poole et al. (1977) and Marvin-DiPasquale & Capone (1998). High porosity, organic matter, carbon and nitrogen contents of sediments at the farm site, coupled with relatively low sulfide levels, supports the view that the wastes were accumulating in 2002 at rates much greater than the rate of decomposition by anaerobic sulfate-reducing bacteria.

A typical SPI obtained in 2002 (Fig. 4) shows considerable build-up of non-biodegraded salmon faeces/waste food at the sediment surface of the farm site. This layer had a median depth of 13 cm (range 8.8 to 16.1 cm for all 5 cores) compared to 6.7 cm (range 5.2 to 10.4 cm) in 2001 (not shown). Most farm images for 2002 were distinguished by white bacterial mats (*Beggiatoa* sp.) within this layer, suggesting that oxic/anoxic interfaces were present within it. The benthic habitat-quality indices and RPD depths for farm and reference sites (Table 4) are significantly different for both dates, based on Mann-Whitney *U*-tests.

We interpret the macrofauna present at the farm site (Table 4) to partly reflect recent falls from the luxuriant fouling community present on the cage structures above the sediment. The fauna is able to live in the partly re-oxygenated build-up of un-decomposed organic wastes. Multivariate analysis of macrofaunal abundance, in combination with environmental variables such as redox potential, using non-metric multidimensional scaling (nMDS), indicated that farm and reference sites clustered separately (Fig. 5) and that the bubbles were significantly larger at the farm sites. Other variables, such as sulphide, BHQ and RPD, tested in this way suggested that the bubbles were also significantly larger at farm sites (not shown). Analysis of similarities (ANOSIM) testing revealed that samples from the farm site were significantly different ($p < 0.01$) from reference sites in both years tested. Univariate tests (not shown) including the total number of taxa (Table 4), Shannon-Wiener and Pielou's eveneness, all indicated lower diversity and evenness at the farm site compared to the reference site. Graphical analysis (not shown) with *k*-dominance curves (Clarke & Warwick 2001) suggested that biological stress was elevated at the farm site in both years. The most abundant taxon at the farm was the sludge worm *Capitella capitata* (Table 4), which is indicative of enriched conditions. By contrast, *C. capitata* was nearly absent at the reference site.

Table 3. Summary of Lime Kiln Bay groundtruthing for interfacial geochemical variables at farm and reference sites on 2 dates. EHAA: enzyme hydrolyzable amino acids; Eh$_{\text{NHE}}$: redox potential relative to the normal hydrogen electrode

Variable	26 July 2001		9 September 2002	
	Farm	Reference	Farm	Reference
Sediment grain size				
% <63 µm -median	99.13	99.41	99.11	98.79
-range	98.79–99.60	98.76–100	97.27–99.68	98.59–99.46
% <5 µm -median	42.57	34.00	40.59	28.56
-range	38.14–47.86	33.27–36.93	36.42–47.96	28.44–32.39
Modal size-median	9.19	13.03	11.34	16.15
-range	8.00–13.93	10.56–13.93	8.00–13.93	13.93–18.38
N	5	4	4	4
Surface area (m^2 g^{-1})				
Median	24.8	18.7		
Range	20.7–43.3	13.2–27.5		
N	9	15		
Porosity (%)				
Median	79.79	68.48	82.74	66.15
Range	72.99–83.47	61.14–77.89	78.32–85.19	65.21–69.71
N	9	12	4	4
Organic matter (%)				
Median	37.73	8.88	37.49	8.63
Range	22.76–40.53	7.94–10.64	34.02–43.57	8.52–8.82
N	5	12	4	4
Organic carbon (%)				
Median	22.73	2.47	22.58	2.23
Range	13.71–24.42	2.00–2.75	21.02–25.74	2.16–2.41
N	5	12	4	4
Nitrogen (%)				
Median	2.21	0.33	2.39	0.28
Range	1.34–2.38	0.25–0.37	1.68–2.51	0.26–0.31
N	5	12	4	4
EHAA (mg g^{-1})				
Median	22.35	1.47		
Range	13.98–60.38	0.93–1.91		
N	9	15		
Eh$_{\text{NHE}}$ (mV)				
Median	–148	158	–111	100
Range	–183 to 25	83 to 183	–156 to –17	53 to 200
N	15	15	15	15
Sulfide (µM)				
Median	30 000	1300	2500	350
Range	13 000–40 000	240–5000	2180–8130	209–813
N	9	15	15	15

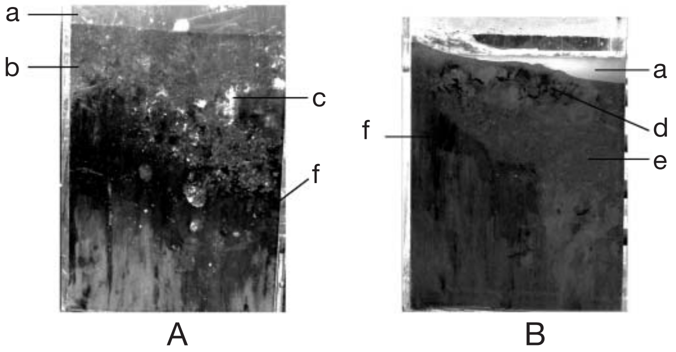

Fig. 4. Sediment profile images on 9 September 2002 for Farm B5 (A) and Reference Stn R2 (B). a: Seawater; b: undecomposed food and faecal wastes; c: white reflecting body, possibly *Beggiatoa* sp.; d: feeding voids and aerobic sediment above the redox potential discontinuity; f: black sulfide layer

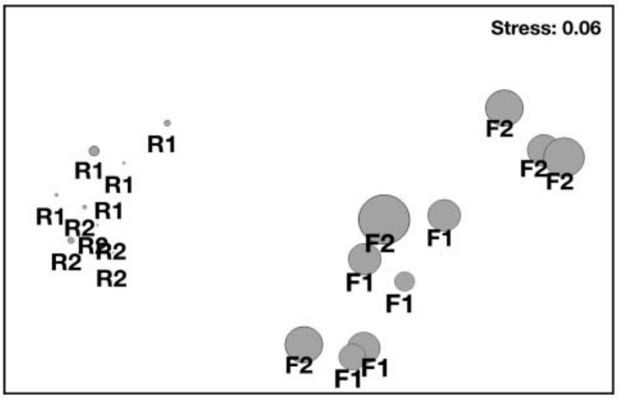

Fig. 5. Community structure non-metric multidimensional scaling (nMDS) bubble plot of farm (F) and reference (R) sites; 1 = 2001 and 2 = 2002 samplings. N = 5 for each site. Size of the superimposed circles is proportional to redox potential negativity

Table 4. Summary of Lime Kiln Bay groundtruthing for sediment profile imaging and macrofaunal species and density variables at farm and reference sites on 2 dates. BHQ: benthic habitat quality index; RPD: redox potential discontinuity depths

Variable	26 July 2001		9 September 2002	
	Farm	Reference	Farm	Reference
BHQ				
Median	0	8	0	9
Range	–	6 – 9	–	8 – 10
N	5	5	5	5
RPD, cm				
Median	0	9.9	0	11.7
Range	–	8.8 – 13.7	–	6.9 – 14.7
N	5	5	5	4
Macrofauna				
Total species	9	37	12	30
Range/core	2 – 6	13 – 18	2 – 8	14 – 17
N	5	5	5	5
Capitella capitata				
Median	30	0	1	0
Range	5–85	0–2	0–25	–
N	5	5	5	5

DISCUSSION

The results allow us to establish that at the mid-point of each salmon cage, which we investigated in 2001 and 2002 by conventional benthic groundtruthing methods, was highly organically enriched (see Table 1). All 3 established methods used to characterize Stage 0 organic enrichment (Table 1), i.e. macrofaunal, geochemical and sediment profile imaging, indicate that this farm site had reached the most advanced organic enrichment stage. The results for EHAA (for 2001 only) suggest that the farm site had 15 times more readily available amino acids for deposit feeders than the reference site. Differences in porosity, organic matter, carbon and nitrogen also support the view that the farm interfacial sediments are highly organically enriched.

The acoustic results allow us to reject the null hypothesis that areas of high backscatter directly under salmon farm cages are not causally related to organic enrichment events. The causal evidence between the area of high backscatter and independent measures indicating organic enrichment is circumstantial. The work presented is a necessary, but not sufficient, step in establishing that acoustic backscatter can accurately map organic enrichment. Further research needed to reach this goal includes determining (1) the geotechnical mechanism responsible for the characteristic acoustic response, e.g. acoustic reflection from methane gas bubbles within enriched sediments, increased surface roughness due to accreting wastes, or increased water content of sediments; (2) whether acoustic responses can distinguish a gradient of organic enrichment, and not just the gross changes that we have recognized here. If the geotechnical property that acoustics recognizes in enriched sediments is methane bubbles, it is likely that the method developed from it will be limited to areas of gross changes of organic enrichment. This is because methanogenesis represents a final stage in the organic enrichment process, and is associated with only the grossest changes. The observation that acoustic patterns persist over a few years, after the organic enrichment inputs cease, suggests that the methods can be used to temporally monitor recovery rates; and (3) whether backscatter contrasts apply in both depositional and erosional sediments. It is of interest that MacDougall & Black (1999), using acoustic methods in a net erosional sediment, found no evidence of acoustic responses indicating organic enrichment.

Depending on the answers to these questions, it may be possible to develop acoustic methods as an organic enrichment mapping tool. The fieldwork involved in acoustic mapping can be achieved at rates of 5 km^2 h^{-1}, with additional computer processing time required to finalize acoustic maps. This method should be cost-effective in time compared to classical macrofaunal sampling. The acoustic method can be used sublittorally throughout the coastal zone and for other sources of organic enrichment in sediments, and so may be of importance in integrated coastal zone management.

Efforts are already underway in many laboratories to use acoustic mapping as a more general means of defining macrobenthic communities and their typical habitats on the continental shelf (e.g. Magorrian et al. 1995, Wildish et al. 1998, Kostylev et al. 2001).

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