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Stock evaluation of giant scallop (*Placopecten magellanicus*) using high-resolution acoustics for seabed mapping

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Abstract

Survey designs in use for the evaluation of sea scallop stocks do not consider the variability of sediment type, despite strong evidence of its importance for the recruitment and survival of scallops on the sea floor. This study examines the distribution of scallops on Browns Bank, Scotian Shelf, at two test sites, in comparison to sea floor sediment distribution, with particular attention to the effects of small-scale sediment variability on the abundance of the commercially exploited scallop. Important links between scallop abundance, sediment type and habitat structure are described. Scallops are strongly associated with gravel lag deposits, which are readily distinguishable from sand-covered terrain through the use of multibeam backscatter data. There exists a highly significant correlation between scallop survey catch rates and backscatter intensity which can be used for the prediction of scallop stock abundance. Developments in underwater acoustics enable for more precise sea floor mapping and contribute to better estimates of scallop abundance.

Keywords: Multibeam backscatter; Scallops; *Placopecten magellanicus*; Habitat; Benthos; Mapping

1. Introduction

The Browns Bank sea scallop (*Placopecten magellanicus*) fishery is one of the major Canadian scallop fisheries on the east coast, in operation since the early 1970s and continuing today. Currently, the landed value of giant scallops constitutes one third of the total value of shellfish landed in the region. During the last three decades, the fishery has exploited different parts of Browns Bank (Fig. 1) with an inconsistent rate of success. It is suspected that variable survival of juvenile scallops is responsible for considerable year-to-year changes in population size and landings. While recruitment into scallop populations cannot be controlled, accurate mapping of the distribution of commercial scallops can reduce fishing effort and increase yield. The distribution of adult scallops and recruitment of juveniles on the bank is very patchy. A better identification of habitats suitable for scallop populations would likely explain the patchy distribution of this bivalve. Increasing the accuracy of scallop distribution and density estimates based on maps of bottom habitats may lead to reducing effort in scallop fisheries and could allow for better management of the resource, including planning of seed areas, marine protected

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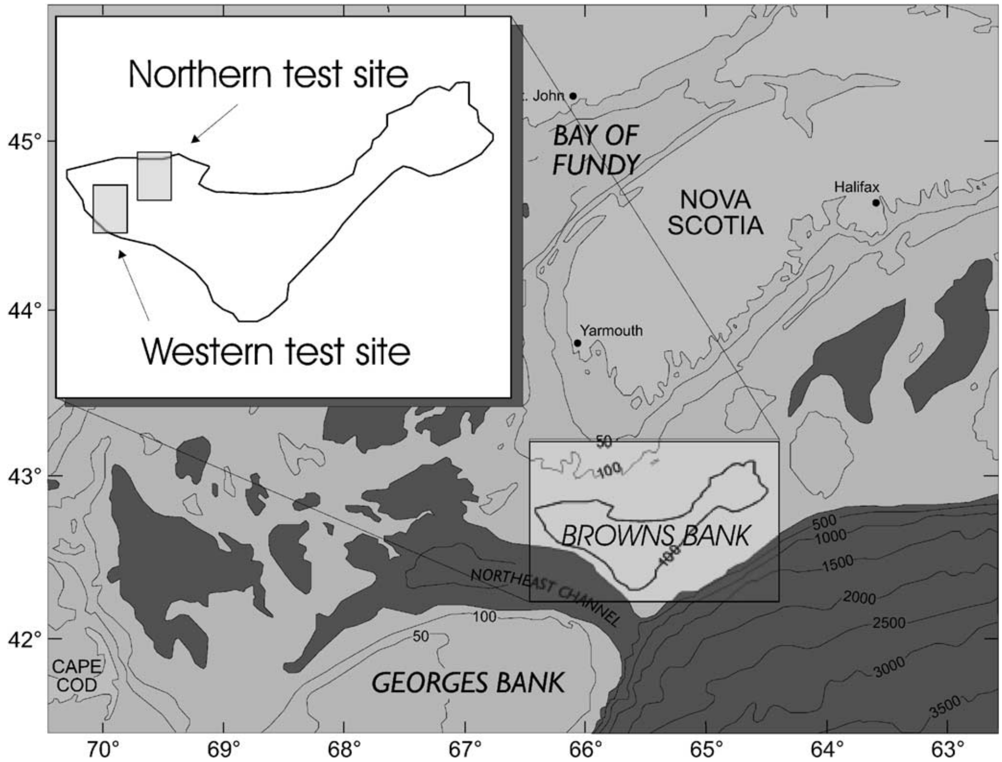

Fig. 1. Map of southern Scotian Shelf, showing the location of Browns Bank and the two test areas (rectangles).

areas, reducing impact on, and disturbance of the sea bed.

Scientific surveys of scallop distribution and abundance on the east coast of North America are conducted by Canadian and American research institutions (Serchuck and Wigley, 1986). Both countries subdivide fishing banks into strata of different abundance, and estimate the stock from average abundance of scallops and area of corresponding stratum. American surveys base their stratification on water depth while the Canadian surveys focus on the distribution of commercial effort. The logbooks of the Canadian commercial fleet in the preceding 6 or more months are analyzed to determine areas of high and low fishing intensity. Arbitrary catch per unit effort (CPUE) levels are used to establish strata of high, medium, low and very low CPUE and random sampling locations of survey tows are chosen for each stratum (Robert and Jamieson, 1986). The estimate of abundance is formed by contouring the survey catch rates and expanding the mean by the area enclosed by a given contour (Mohn et al., 1985,1987).

The current Canadian survey design strategies were derived by Caddy and Chandler (1969) who suggested that the best variable on which stratification could be based is the preceding commercial catch. The authors considered three variables—depth, commercial catch and sediment type, and the results of *t*-tests showed that the most statistically significant was the effect of commercial fishing intensity on scallop abundance, followed by depth, and non-significant, but suggestive effect of sediment type. In this analysis sediment type for each test tow was described as “gravel” or “sand” or “sand and gravel” but analyzed as two categories, “gravel” and “other”. In addition, a single sediment type was assigned to 10 min × 10 min cells, based on the sediment map of Georges Bank published by Wigley (1961). The accuracy of these sediment maps can be assessed from the following example. The sediment type “sand” is assigned to the area 34 station 9 (Caddy and Chandler, 1969, Table 1) and, at the same time, the comment for this station is "too rocky to fish" (Caddy and Chandler, 1969, Table 3).

Comparison of American and Canadian survey designs has shown that they are relatively equal in performance (Serchuck and Wigley, 1986). Evaluation of the relative ability of these designs to estimate the actual scallop abundance would necessitate development of a third technique against which these two designs could be evaluated (Robert and Jamieson, 1986).

General knowledge about scallop ecology and distribution matches the occurrence of scallops with sand and gravel sediments (e.g. Bousfield, 1960). The study of benthic habitats on Browns Bank (Kostylev et al., 2001), based on the analysis of underwater photographs similarly showed that scallops dwell in gravelly areas, with a smooth seabed and higher than average current speeds. Smith and Robert (1998) suggested that allocation of sediment type strata within each of the commercial catch strata would likely provide some gains in precision of stock estimates compared to random sampling design. The results were based on the analysis of Georges Bank scallop catches, and simplified map of surficial sediments from Thouseau et al. (1991). The term "surficial" means "pertaining to, situated at, or formed or occurring on a surface, especially the surface of the earth" (Gary et al., 1977).

New research evolving out of the application of multibeam bathymetric systems (Todd et al., 1999) has shown that the surficial sediment distribution on Browns Bank is more complex than previously mapped and that overly generalized maps of sediments distribution were not suitable for correlation with fishery catch statistics. Geological mapping of Browns Bank, performed by Geological Survey of Canada (Atlantic) on the basis of multibeam imagery and a suite of ground truthing methods, has been used to identify areas of sand cover and gravel lag. The mapping was carried out to an areal resolution generally less than 10 m × 10 m, an increase in resolution by a factor greater than 1000 compared to existing maps. Considering the previous knowledge about the effects of sediment type on recruitment and survival of sea scallops, it seems appropriate to re-evaluate the current survey techniques, given the new sediment information.

The current study examines the distribution of scallops in comparison to sea floor sediment distribution, as predicted using an acoustic backscatter proxy, with particular attention focussed on the effects of small-scale sediment variability on the estimation of scallop abundance. We describe links between scallop abundance, sediment type and habitat structure, and propose that sediment type should be the dominant factor in the design of research surveys of scallop stocks.

2. Methods

Multibeam bathymetric data were collected by the Canadian Hydrographic Service on Browns Bank in 1996 and 1997 using the CCGS Frederick G. Creed equipped with a 95 kHz Simrad EM1000 multibeam bathymetric system. This system produces 60 narrow beams with average rate of 5 pings per second fanning over an arc of 150° and operates by ensonifying a narrow strip of sea floor across the beam of the survey vessel and detecting the bottom echo with narrow, across-track listening beams. The swath of sea floor imaged on each survey line is typically 5–6 times the water depth in 100 m water depth. In the Browns Bank surveys, line spacing was about 3–4 times water depth to provide complete ensonification overlap between adjacent lines. Navigation was by Differential Global Positioning System, providing positional accuracy of ±3 m. Survey speeds averaged 14 knots resulting in an average data collection rate of about 5.0 km^2/h in water depths of 35–70 m.

During the survey, water depth values were inspected and erroneous values were removed using CARIS/Hydrographic Information Processing System (HIPS) software from Universal Systems Limited, Fredericton, NB. Within HIPS, the data were adjusted for tidal variation using tidal predictions from the Canadian Hydrographic Service. Multibeam bathymetric data were gridded in 5–10 m (horizontal) bins and shaded with artificial illumination using software developed by the Ocean Mapping Group at the Geological Survey of Canada (Atlantic). Relief maps, color-coded to depth were developed and displayed on a Hewlett-Packard workstation using GRASS (Geographic Resources Analysis Support System) developed at the US Army Construction Engineering Research Laboratories.

In addition to the bathymetric data, calibrated acoustic backscatter data can be logged by the Simrad

EM1000 system (see Urick (1983) and Mitchell and Somers (1989) for backscatter definition). Since the sounders illuminate the seafloor over a broad arc of up to 1500, the angular response behavior of backscatter needs to be considered (Courtney and Shaw, 2000).

For angles of incidence less than approximately 20°, the backscatter signal returned from the seabed is largely within the specular zone where a direct and coherent reflection from the seabed is recorded from objects larger than the acoustic wavelength. The amount of energy returned from a specular reflection increases with the acoustic impedance contrast across the seabed boundary (acoustic impedance is the product of density and acoustic velocity). The specular return is conversely diminished as the roughness of the seabed increases. In contrast, the energy returned at wider beam angles arises from constructive interference with roughness on the seabed (Bragg scattering) and this scattered energy increases with increasing surface roughness. There can also be an added contribution to the backscatter energy from volume heterogeneity within the subsurface at these wider-angles. The acoustic pulse does propagate to a varying extent below the surface of the seabed, dependent on the frequency of the sounding system. For general information on acoustic techniques and definition of terms see Medwin and Clay (1998).

To reduce the dynamic range of the recorded data, the Simrad EM1000 system applies a partial correction to the backscatter strength values for the varying angle of incidence by using Lambert's law for the variation with angle and assuming a flat sea floor (Simrad, 1992). Backscatter strengths are computed using calibration values for the electronics and transducers at the time of instrument manufacture (Mitchell, 1996). Unless further calibration occurs at the time of survey, backscatter strength values may be inaccurate. However, the relative signal is still useful and differences in the backscatter between different sea floor materials are clearly visible in the data. High backscatter values (dark tones) are typically −10 to −30 dB for gravel and low backscatter values (light tones) range from −30 to −60 dB for fine-grained sand (Mitchell and Hughes Clarke, 1994; Shaw et al., 1997). Because backscatter is a function of a suite of acoustical variables, it is prudent to interpret backscatter images in conjunction with other geophysical data (seismic reflection and sidescan sonar sonograms) and geological samples of sea floor materials. For comparison with the bathymetric image, Browns Bank backscatter data were processed and displayed. The amplitude of the returned signal varies from −16 to −40 dB, highlighting features not apparent in the bathymetric image.

Simrad EM1000 acoustic backscatter data collected during the 1997 and 1998 surveys were reprocessed to remove any mean angular response above the Lambert's law correction. The mean angular response function was estimated using a rolling average computed along the survey track and it was subtracted from the backscatter data, correcting all data to an angle of incidence of 45°. These data were then gridded within a GIS at a 5 m × 5 m resolution and estimates of the gridded and corrected backscatter were extracted for each of the fixes along the scallop tow track. To reflect the potential positional inaccuracy of the scallop rake behind the trawler, the median value of the backscatter within a 100 m × 100 m box was calculated for each of the tow positional fixes.

To complement the multibeam survey, 850 km of high-resolution geophysical profiles were collected over Browns Bank in 1998 (Todd et al., 1999). The systems deployed included a Huntec Deep Tow Seismic (DTS) boomer, single-channel sleeve-gun seismic reflection, and Simrad MS992 sidescan sonar (120 and 330 kHz). The geophysical survey investigated different sea floor types and features identified using the multibeam bathymetric and backscatter data.

Using a 0.75 m^3 IKU grab, 24 sea floor sediment samples were collected at strategic sites. The grab sampler penetrated the sea floor up to 0.5 m and preserved the integrity of the layering within the surficial sediments. Grain size descriptions based on the sub-samples and on sea floor photographs adhere to the Wentworth size class scheme for clastic sediments (Wentworth, 1922). Detailed descriptions of methodology and sampling for the purpose of surficial sediment mapping on Browns Bank is presented by Todd et al. (1999).

Four general sediment assemblages (gravel lag, gravel lag with thin discontinuous sand, continuous thin sand over gravel lag and thick sand bodies) were identified on the basis of multibeam backscatter, sidescan sonar and seismic profiles, and used in compiling a sediment distribution map of Browns Bank (Todd et al., 1999). To assess the relationship between scallop abundance and sediment type, two test sites were chosen on Browns Bank (Fig. 1), to reflect the diversity of interpreted bottom types. A total of 40 sampling stations (two sites × four sediment types × five tows) were conducted to test the variability of scallop abundance among sediment types.

At each of the sampling stations, an 2.38 m wide scallop dredge was towed for 10 min, covering approximately 1 nautical mile (1852 m) of sea floor, staying within a single sediment type as accurately as possible. For each of these stations, the total catch (bushels),

Table 1
Observed catches per 10 min tow with 8 ft survey rake

Tow no.	Start tow		End tow		Depth (fms)	Tow catch (#bushels)	Comments
	Latitude (N)	Longitude (W)	Latitude (N)	Longitude (W)			
Browns Bank west test site							
1	4245.364	6615.206	4244.904	6614.627	32	<0.25	Gravel lag with thin sand
2	4244.325	6613.986	4244.559	6614.791	33	<0.25	Gravel lag with thin sand
3	4244.628	6615.999	4244.212	6615.439	34	1.5	Gravel lag with thin sand
4	4243.870	6614.982	4244.203	6615.654	33	1.5	Gravel lag
5	4245.173	6617.861	4245.000	6617.671	34	1.25	Gravel lag
6	4244.036	6616.069	4243.544	6615.431	34	0.75	Gravel lag with thin sand
7	4241.940	6613.806	4242.270	6614.485	35	0.5	Gravel lag
8	4242.529	6615.972	4242.850	6616.666	36	<0.25	Thin sand over gravel lag
9	4243.586	6619.380	4244.011	6617.956	36	<0.25	Thin sand over gravel lag
10	4244.011	6620.430	4243.385	6620.520	44	0	Thick sand
11	4242.685	6618.842	4242.229	6618.335	41	0.5	Gravel lag with thin sand
12	4241.914	6617.065	4241.506	6616.485	38	0.5	Gravel lag
13	4240.745	6615.472	4240.368	6614.874	36	0.5	Gravel lag
14	4240.264	6613.377	4240.730	6614.007	34	2.25	Thin sand over gravel lag
15	4240.606	6617.069	4240.315	6617.833	38	0	Thick sand
16	4241.172	6619.641	4241.762	6619.900	47	<0.25	Thick sand
17	4242.293	6619.892	4242.100	6619.165	46	<0.25	Thick sand
18	4242.680	6617.006	4242.233	6616.476	37	<0.25	Thin sand over gravel lag
19	4241.088	6616.643	4240.622	6616.117	38	0	Thin sand over gravel lag
20	4240.149	6616.739	4240.323	6617.489	38	0	Thick sand
Browns Bank north test site							
21	4245.871	6611.996	4246.517	6611.979	29	1	Gravel lag with thin sand
22	4246.749	6611.534	4246.349	6610.936	29	1.5	Thin sand over gravel lag
23	4245.856	6608.956	4246.183	6609.665	31	<0.25	Thin sand over gravel lag
24	4246.738	6610.702	4247.218	6611.364	28	<0.25	Thin sand over gravel lag
25	4248.018	6611.432	4248.342	6610.710	27	1	Thick sand
26	4247.815	6610.077	4247.508	6610.733	31	<0.25	Thick sand
27	4247.212	6610.393	4247.494	6609.617	29	<0.25	Thick sand
28	4247.383	6609.057	4247.466	6608.250	31	0	Gravel lag with thin sand
29	4248.064	6608.273	4248.320	6608.946	32	1.75	Gravel lag with thin sand
30	4248.184	6609.424	4248.468	6610.049	33	6.5	Gravel lag
31	4248.933	6610.837	4248.791	6611.577	29	2 (seed)	Gravel lag
32	4248.167	6611.731	4248.527	6611.065	26	1	Thin sand over gravel lag
33	4248.991	6608.672	4249.353	6609.273	30	6 (seed)	Gravel lag
34	4249.780	6610.162	4250.024	6610.916	30	28 (seed)	Gravel lag
35	4250.411	6609.164	4250.431	6609.936	40	21.5 (seed)	Gravel lag
36	4250.786	6612.103	4250.612	6611.332	48	11.5 (seed)	Gravel lag with thin sand
37	4251.040	6610.414	4251.288	6609.684	58	4 (seed)	Thin sand over gravel lag
38	4251.381	6609.033	4251.536	6608.321	66	0.75	Thin sand over gravel lag
39	4251.795	6609.740	4251.439	6610.361	75	0.5	Thick sand
40	4251.669	6610.876	4252.117	6610.349	79	<0.25	Thick sand

size distribution of scallops (in 5 mm intervals of shell height), sediments and associated fauna were recorded (Table 1). The duration of tow, depth and bearing were also recorded simultaneously. Tow track coordinates were recorded in the OceanVision System. The location of tows relative to surficial sediment distribution is shown in Fig. 2. Fig. 3 shows backscatter map of Browns Bank. For each tow, a track record was started as soon as the dredge settled on the bottom after it was shot, recording the ship's position for every 3–4 s. The track record was stopped as soon as the winch was clutched in to haul back at the end of 10 min. Scallop abundance in 5 mm shell height class was prorated to a standard tow of 800 m.

An estimate of scallop biomass per standard tow was calculated from size–frequency distribution as

$$B = \sum n_i l_i^3$$

where n_i is the number of scallops in size group i, and l_i the height of the scallops (in mm) in the size group i. Allometric relationships between biomass (meat weight) and size (shell height) are usually of form $B = al^b$, where b is close to 3 and a is a biomass of unit-sized animal. The value of a was disregarded in the approximation because it does not affect the shape of the relationship.

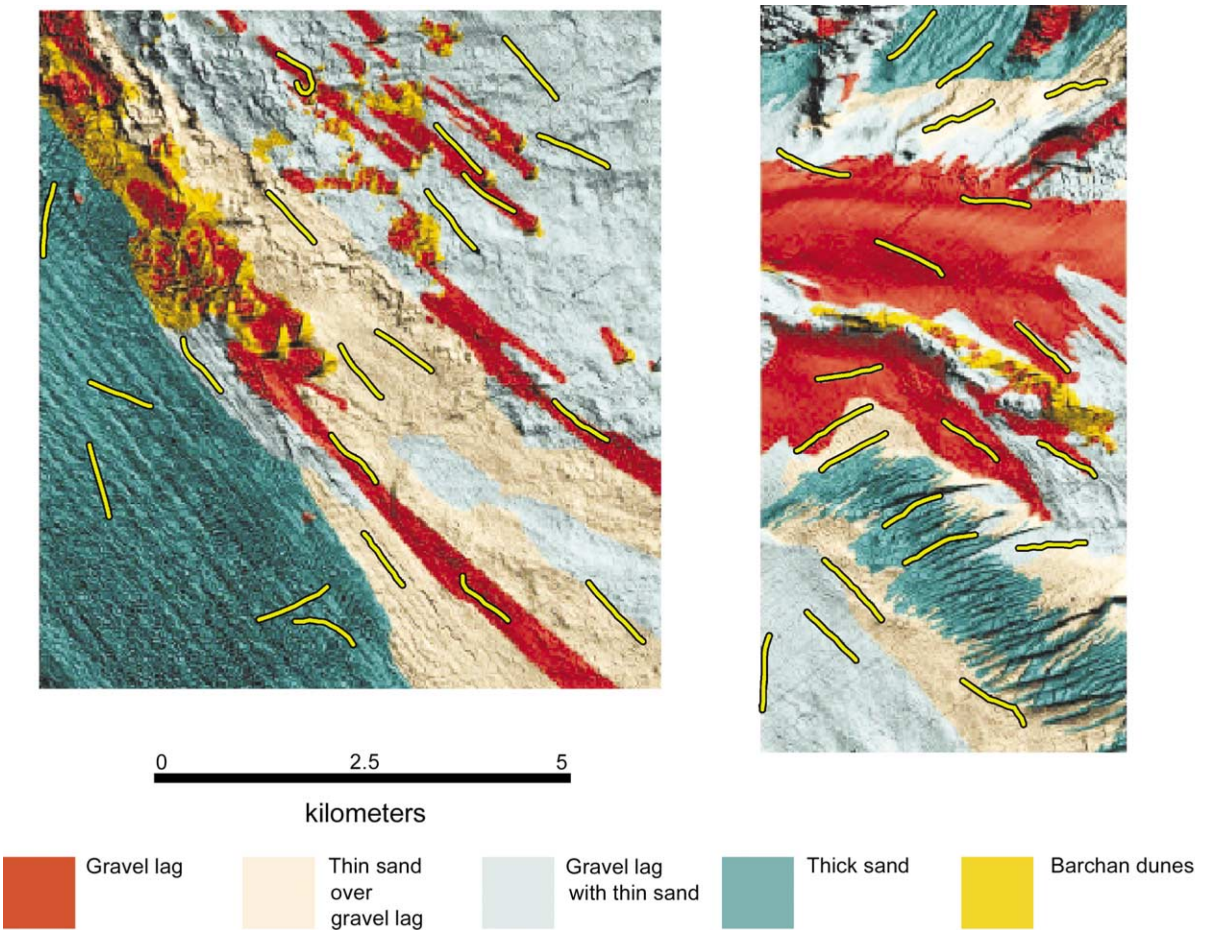

Fig. 2. Maps of the two test areas. Sediment types are overlaid on the multibeam bathymetry map. Tows are marked as yellow lines.

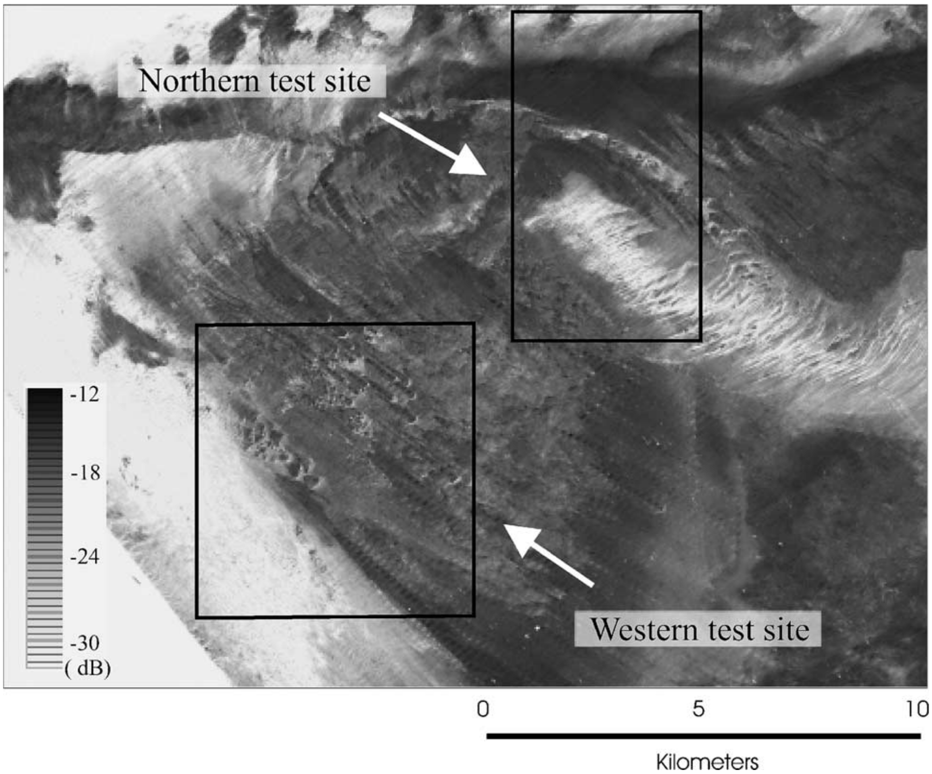

Fig. 3. Backscatter map of the western part of Browns Bank. Two test sites are indicated with rectangles.

3. Results

3.1. ANOVA with sediments

The effects of interpreted sediment type and fishing area on the total number of scallops were analyzed in two-way ANOVA (Table 2). Due to the low range of depth variation between the tows, this factor was not included in the analysis. Data were log-transformed prior to the analysis and generally satisfied normality assumption after transformation. For the total abundance of scallops and for commercial scallops Box–Cox transformation displayed minimum sum of squares error at the values of lambda equal to 0, meaning that the best required data transformation is logarithmic. For juvenile scallops the loss function was minimal at lambda values of −0.3, suggesting that only marginal gain would be obtained from reciprocal square root transformation compared to log-transformation. The results show that the number of commercially sized scallops per standard tow is significantly dependent on both test area and sediment type ($p < 0.0001$). While the distribution of commercially sized scallops (shell height over 100 mm) is significantly related to the sediment type, there were also significantly more scallops in the northern test area than in the west. The total catch of juvenile scallops (shell height under 75 mm) per tow as well as the total scallop catch (expressed in numbers of individuals) were dependent on sediment type with high significance ($p = 0.0001$). Residual analysis shows that in all three analyses residuals are independent of predicted values, and variance is homogeneous in the total abundance of scallops and in the abundance of commercial scallops. Weak heteroscedasticity of variance is present in the distribution of juvenile scallops across factors. Fig. 4 shows size–frequency distributions of scallops in the two test areas and across four sediment types.

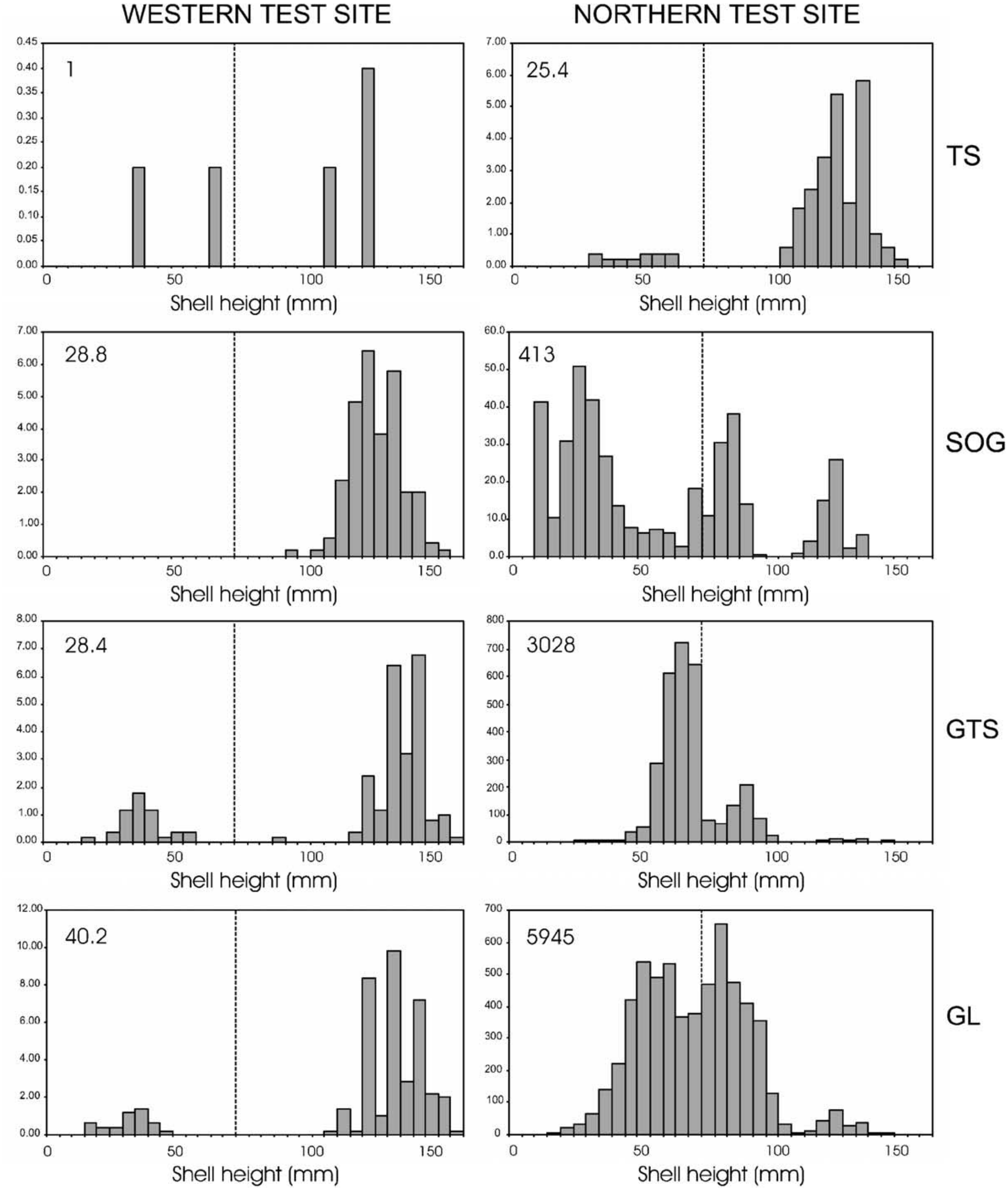

Fig. 4. Frequency distribution of scallops in two test areas of Browns Bank. TS: thick sand, SOG: sand over gravel lag, GTS: gravel lag with thin sand, GL: gravel lag. Bars indicate average number of scallops within each size class per standard tow. Numbers in the top left corner of each graph indicate average total number of scallops per standard tow. Note large differences in average abundance between areas and sediment types. Vertical dashed lines divide juvenile and commercial size classes.

Table 2
Summary of all effects of ANOVA, performed on abundances of size groups in the total catch[a]

	d.f. effect	MS effect	d.f. error	MS error	*F*	*p*-level
Total number of scallops per standard tow						
Test site	1	12.6801633	32	0.6537382	19.396392	0.000111
Sediment	3	6.32045412	32	0.6537382	9.6681728	0.000107
Interaction	3	1.00208318	32	0.6537382	1.5328508	0.224910
Number of commercial size scallops per standard tow						
Test site	1	8.25006294	32	0.5114458	16.130863	0.000334
Sediment	3	5.34637737	32	0.5114458	10.453456	0.000059
Interaction	3	0.72987085	32	0.5114458	1.4270734	0.253019
Number of juvenile scallops per standard tow						
Test site	1	18.4019241	32	0.7148605	25.741977	0.000015
Sediment	3	4.07664299	32	0.7148605	5.7027106	0.003031
Interaction	3	2.64774751	32	0.7148605	3.7038657	0.021479

[a] The ANOVA model accounted for 62.4% variability in total catch of scallops, 61.8% in abundance of commercial scallops and 62.8% in abundance of juvenile scallops. Sediment type explained 34% of variance in total abundance of scallops, 38% in abundance of commercial scallops and 20% in juvenile scallops.

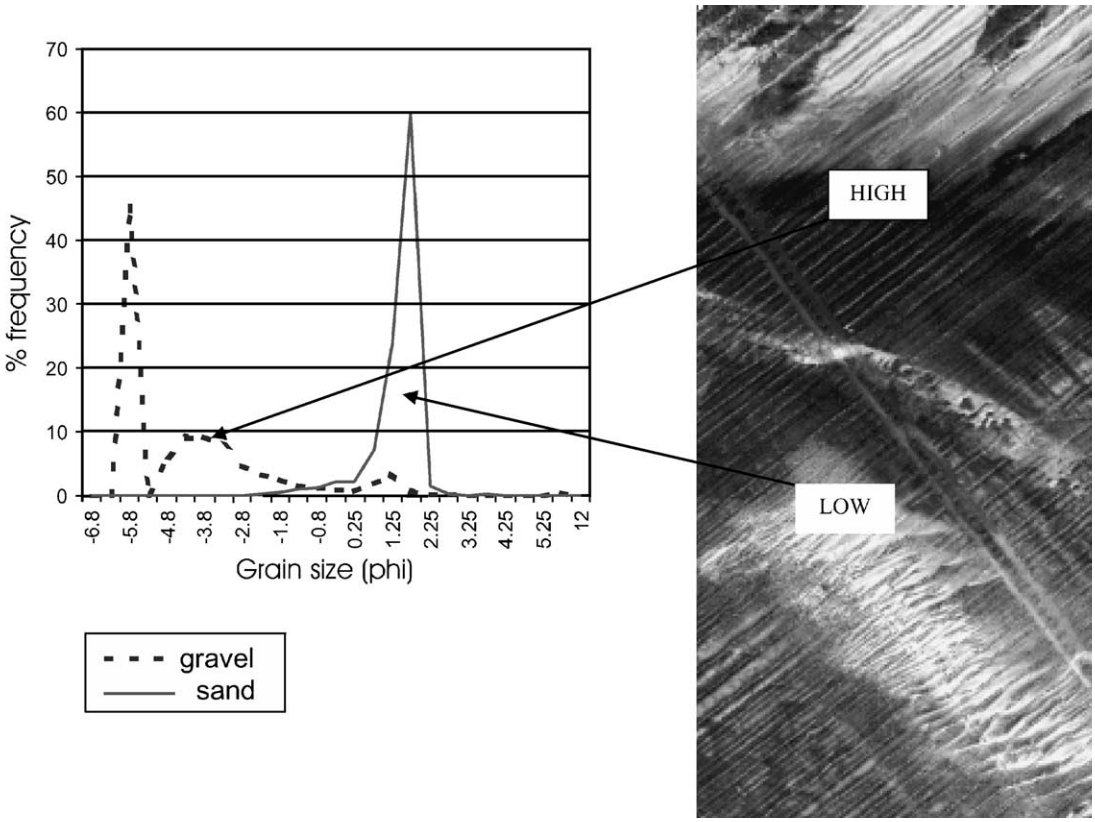

Fig. 5. Particle size distribution for two samples, representative of sandy and gravelly habitats. Plots of backscatter intensity for the northern test area on Browns Bank shows areas corresponding to high (gravel) and low (sand) backscatter intensity.

3.2. Backscatter and sediment particle size

The sediment distribution mapping was largely based on the acoustic backscatter of sea floor, which makes it possible, among other things, to distinguish between coarse-grained and fine-grained sediment. Seafloor sediment samples allowed the correlation of particle size distribution to backscatter values. Fig. 5 shows typical particle size distributions for gravel and sandy habitats and their relation to backscatter intensity. The dark tones in Fig. 5 correspond to high backscatter (gravel) and the light tones to low backscatter (sand). We interpret backscatter maps to represent continuous variation in sediment structure, and the current study is the first precedent of the use of backscatter values for numerical analysis of scallop distribution. The use of backscatter strength for correlation with scallop catch allowed to avoid unaccounted variability in ANOVA, related to the occasional lack of precision in the positioning of tows within distinct sediment types.

The total catch of scallops is positively related to the backscatter strength (Fig. 6) with exponential relationship. Therefore, scallop abundance was log-transformed for the purpose of the analysis. The relationship between backscatter and abundance of scallops in standard tows is different in different size groups (commercial and juvenile). The number of juvenile scallops per tow was significantly related to the backscatter strength. The results show that logarithm of juvenile abundance is linearly related to backscatter ($N = 40$, $R = 0.531$, $R^2 = 0.282$, $F = 14.912$, $p < 0.0001$) (Fig. 7).

The logarithm of abundance of commercial size scallops is also linearly related to backscatter strength ($N = 40$, $R = 0.724$, $R^2 = 0.524$, $F = 41.748$, $p < 0.0001$) (Fig. 7). The results suggest that catches

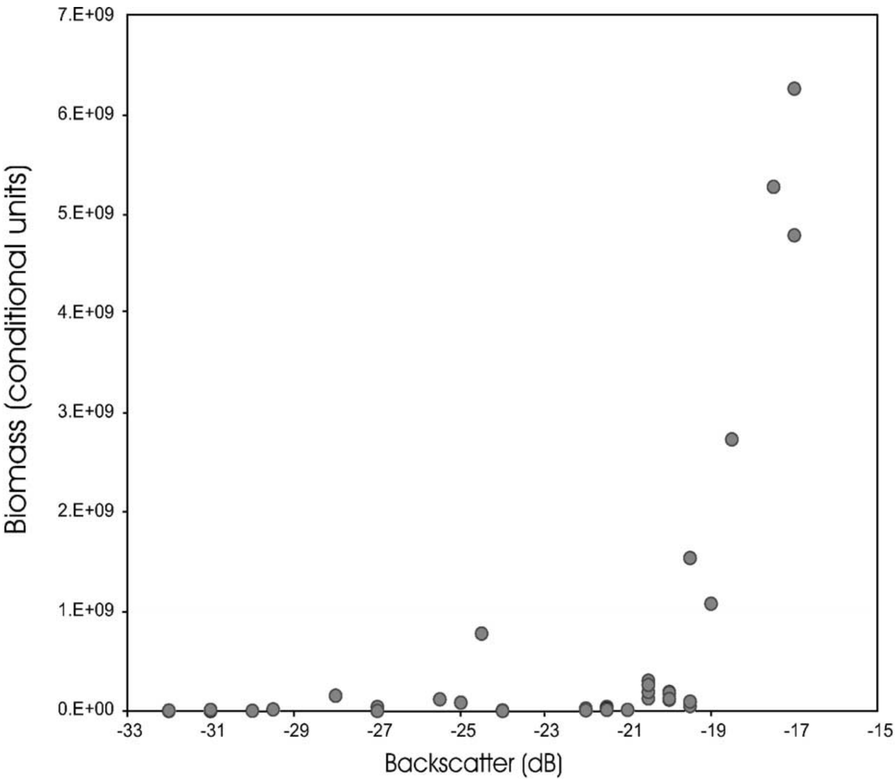

Fig. 6. Scallop catch in conditional biomass units plotted versus the mean backscatter strength.

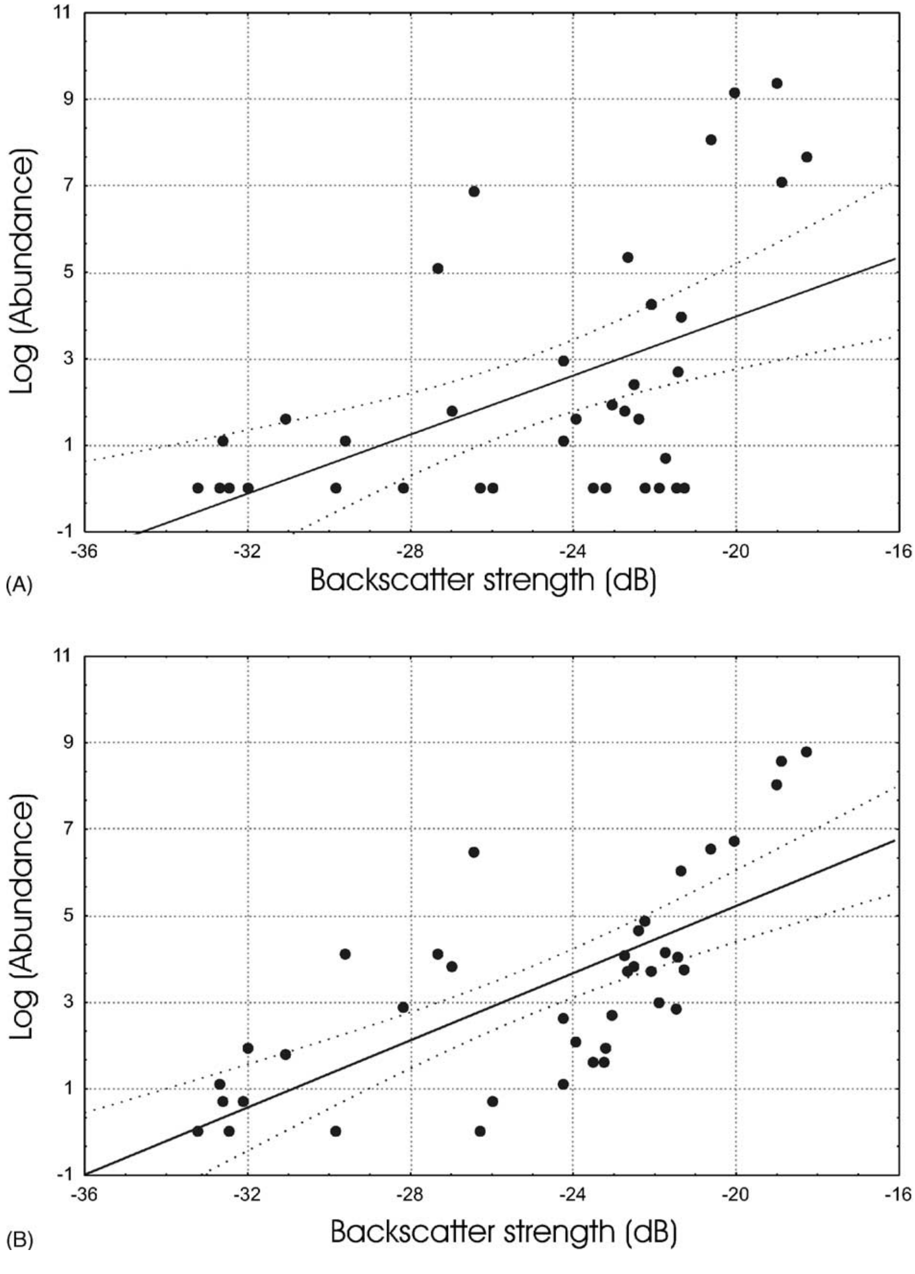

Fig. 7. Relationship between log-transformed abundance of juvenile (A) and commercial (B) scallops with backscatter strength.

of commercial size scallops can be predicted from the backscatter values with more confidence than catches of juveniles (backscatter explains 52.4% of variability in logarithm of commercial scallop catches, compared to 28.2% for juveniles).

4. Discussion

Our findings show the highly predictive capability of backscatter for the estimation of scallop abundance at different sites on Browns Bank. The most likely reason of this high correlation is the life history traits of juvenile scallops, namely the requirements of scallop larvae for metamorphosis, which is a critical event in a molluscan life history. The transition from a pelagic to a benthic existence is accompanied by changes in diet and morphology (disappearance of the velum and attachment by byssus). Settlement is a pre-requisite for metamorphosis and if a suitable substrate is not found then the larva may die. Scallop larvae have a strong tendency to settle on the underside of pebbles and shell hash (Culliney, 1974). Settling under such conditions would offer some safety for the larva against predators. Scallop also settle on biogenic structures such as red algae, hydrozoa and bryozoa. The shallow part of Browns Bank is primarily a lag gravel, often covered with hydroids and bryozoans (Kostylev et al., 2001), making this habitat particularly suitable for juvenile scallops.

The relative proportion of commercial scallops was higher in the western test site, where the recruitment is impeded by the lack of available substrate. It is likely that a large area with sandy substrates makes it difficult for seed to attach. On thick sand, in the northern test site, the commercial size scallops are more abundant than juveniles. This may be explained by the very strong current in this area, which could sweep away or bury the smaller scallops in the sand. While the adult scallops are also found mostly on gravel, they are probably able to disperse to a certain extent and survive in sandy habitats better than juveniles are. Thus, changes in relative proportions of juvenile and commercial scallops can be easily explained by the preference of juvenile scallops to settle on gravelly sediments.

The scallop habitat of Browns Bank is generally poor in other megafauna species. Typical species associated with scallops are hydroidea, especially *Sertularella* sp., which is common and often attached to scallop shells (Kostylev et al., 2001). Carnivores such as whelks and hermit crabs are common and probably derive food supply from damage to benthic species damaged by scallop dredging (Caddy, 1970).

The wide applicability of the relationship between backscatter and scallop abundance has to be tested in consideration to other important environmental factors that would certainly influence scallops distribution. Water depth, food supply, temperature range, predation pressure, disturbance by fishing activities—all can influence the resulting pattern of scallop distribution. On Browns Bank, scallops were found in highest densities on gravel substrate on the western part of the bank. The presence of strong currents for larval dispersion and gravel for larval settlement (Bousfield, 1960), combined with optimum shallow water depths (Miner, 1950), make this area ideal for scallop recruitment. Water masses over the western part of the bank provide scallops with abundant phytoplankton, which is a primary source of scallop food (Cranford and Grant, 1990). In contrast, the deeper eastern part of the bank, with the presence of fine-grained sediments and possibly periodic resuspension of detritus is less suitable for scallop recruitment and establishment of large populations. Scallop spat is highly susceptible to siltation (Dickie and Medcof, 1956) and silt can cause adult mortality, in part through the clogging of cilia on the gills (Larsen and Lee, 1978; Cranford and Gordon, 1992). In addition, inorganic sediment reduces the energetic quality of ingested food thus limiting productivity of the population. The maximum densities of scallops on the bank were generally found at depths of 70–90 m on gravel lag or gravel lag with thin, discontinuous sand (Kostylev et al., 2001).

There exists no direct and simple relationship between the backscatter amplitude and surficial sediment texture. Generally for angles outside the specular range, there does exist a general correspondence between backscatter amplitudes and surficial sediment roughness that can be used for cursory mapping and sediment identification. Coarse gravels and cobbles tend to be locally rough and return high-amplitude, wide-angle backscatter signals, whereas sands and fine-grained materials can be locally smooth with a much lower backscatter. Care must be taken to look at the complete angular response of backscatter in some cases. Flat or polished bedrock, e.g., is locally smooth and thus can have a very low wide-angle backscatter response, which could be confused with clay or other smooth, fine-grained deposits. The near nadir response would, in this instance, be needed to differentiate the two possibilities. Coincident seismic data and seabed samples are often collected to aid the backscatter interpretation. Meanwhile, backscatter strength may serve as a proxy for a variety of dynamic factors taking place at seabed surface. Indeed, the sediments are often indicative of the dynamics of near-bottom flows, which may define both sediment grain size and benthic community structure (Jumars, 1993; Wildish and Kristmanson, 1997).

Current stock assessment techniques underestimate spatial trends in environmental variables, such as sediment type. In Canadian scallop surveys sampling intensity is disproportionate, and presumed areas of high scallop abundance are sampled with very high intensity (Serchuck and Wigley, 1986). It appeared that in CPUE-based stratified sampling 40% of the total samples were taken within 12% of the total survey area (Robert and Jamieson, 1986). Additionally, the distribution pattern of CPUE indicates the contiguous distribution pattern of commercial size scallops, and raises questions as to the usefulness of an average value for any extensive standardized area (e.g. 10 min^2) of the bank (Robert and Jamieson, 1986).

Scallop stock evaluation through research surveys could be significantly improved by the use of sediment or backscatter maps. Instead of averaging scallops abundance over a total area of a bank, the known distribution of sediment types should be taken into account, and the stock recalculated correspondingly, thus avoiding unnecessary and often unrealistic interpolations. Our results suggest that survey design stratification based on areas of different sediment types would reduce the inherent variances of abundance estimates.

5. Conclusion

This work shows that sediments exert a strong influence on the distribution of scallops. Maps of surficial sediment distribution have traditionally been produced from widely spaced geophysical and ground truth data and, therefore, could not delineate the small-scale variability in sediment type. Since the geology of Browns Bank is relatively simple, comprising an underlying gravel lag deposit covered with varying thicknesses of sand, multibeam backscatter data can be used to effectively produce complete coverage, high-resolution maps of seafloor sediment variability. The new maps have enough detail to provide meaningful correlations with scallop abundance data.

Results of this study open new perspectives for the scallop fishery. The most important finding is that scallop abundance and fishing success can be confidently predicted from the multibeam backscatter data. The high correlation between survey catch and backscatter values can serve as a firm foundation for management decisions both in fisheries and habitat protection. Equipped with precise information on scallop habitats, the commercial fishery may focus its harvesting of the resource over a smaller area of the fishing bank. It is good fishery management strategy to limit dredging activities to the most productive areas while saving on gear and fuel costs. At the same time, the new fishery operations allow for some ecosystem considerations. The better selection of areas to fish for scallops will decrease the adverse impacts on bystander and bycatch species. Gravel lag habitat is also important for spawning of cod and herring (Auster et al., 1996). Mapping of such habitats can only benefit all the species that share a common ground.

Information about scallop density per unit area serves as a main guideline for establishing fishing quotes and, consequently, sustainable long-term fishery. The strong links between bottom type and scallop abundance reported here would permit the development of more precise ways to estimate scallop stock, and will require re-evaluation of old survey designs and implementation of new ones that will account for close habitat–animal relationship.

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