

Marine habitat mapping in support of Marine Protected Area management in a subarctic fjord: Gilbert Bay, Labrador, Canada

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Abstract This paper presents an approach that allows production of benthic substrate and habitat maps in fjord environments. This approach is used to support the management of the Gilbert Bay Marine Protected Area (MPA) in southeastern Labrador, Atlantic Canada. Multi-beam sonar-derived bathymetry, seabed slope, and acoustic reflectance (backscatter) were combined using supervised classification methods and GIS with ground-truthed benthic sampling in order to derive maps of the substrates and main benthic habitats. Six acoustically distinct substrate types were identified in the fjord, and three additional substrate types without a unique acoustic signature were recognized. Ordination by multidimensional scaling and analysis of similarity generalized these to four acoustically distinct habitat types. Greatest within-habitat (alpha) diversity was found in the coralline-algae encrusted gravel habitat. Greatest between-habitat (beta) diversity was found in the management Zones 1 and 2, which have the highest level of protection. The study confirmed that the zoning plan for the MPA, which was designed to protect spawning and juvenile

fish habitat for a local genetically distinct population of Atlantic cod, afforded highest levels of protection to areas with highest habitat diversity.

Keywords Marine habitat mapping · Alpha-diversity · Beta-diversity · GIS · Atlantic cod · Iceland scallop · Marine protected area · Multibeam · Fjord

Introduction

Marine protected areas (MPAs) are frequently proposed as an approach to marine biodiversity conservation (Roberts et al. 2003). Many MPAs, however, are designed as fisheries enhancement tools with one or a few target species in mind (Sale et al. 2005). This paper examines the degree to which a small coastal MPA that was established primarily to preserve a local population of a common fishery species can also meet goals of general marine biodiversity conservation. We explore that question using acoustically-derived seafloor habitat maps and biodiversity surveys.

Seafloor mapping using multibeam echosounder (MBES) data has become an integral part of coastal marine science, especially geology, geomorphology, and more recently, habitat conservation (Todd and Greene 2008). Seafloor mapping has also been used successfully to identify potential habitat for commercial fishery species (e.g. Kostylev et al. 2001) and characterize deep-water coral reefs (e.g. Roberts et al. 2005) and other habitats important for biodiversity. Acoustic seafloor mapping can be used for marine biodiversity conservation, in a manner analogous to the use of ecological land units, e.g. land facets (Beier and Brost 2010) or bedrock geology types (Anderson and Ferree 2010) in terrestrial biodiversity conservation, based on the observation that consistent

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biological assemblages can be recognized by the acoustic signatures of the physical substrates upon which, or in which, they are found (Roberts et al. 2005; Harris and Baker 2011). On land, these methods rely on the close relationship between geomorphic landforms, bedrock geology, elevation and aspect, as physical variables, and vegetation type and associated invertebrate and vertebrate biodiversity as biological variables. Quaternary landforms and bedrock geology influence vegetation type via the chemistry, stability, and drainage properties of the soils overlying each landform type or bedrock as exemplified by specific vegetation types associated with sand dunes, eskers and moraines (e.g. Host and Pastor 1998), or serpentine soil endemics associated with blueschist facies and ophiolite sequences (e.g. Harrison et al. 2009). Underwater, the analogous geomorphic influences on benthic biology relate to substrate types and physical characteristics (especially hardness, consistency, and mobility), depth, wave or current action, and disturbance regime (Kostylev and Hannah 2007). The diversity of geomorphic features, or by analogy benthic marine substrate types, may be particularly important in conservation planning (e.g. Nichols et al. 1998; Anderson et al. 2006). Indeed, recent authors have argued that marine habitat mapping should be the “launch point” for ecosystem-based management (EBM) of marine environments, and an integral part of establishment and design of MPAs and MPA networks (Cogan et al. 2009).

This paper looks specifically at mapping benthic habitats in fjords. Fjords are particularly important habitats at high latitudes, due to their high bathymetric relief, geomorphic complexity, circulation patterns, and natural gradients in temperature, salinity, oxygenation, and other water column properties (Syvitski et al. 1987). Fjords present a number of challenges for acoustic habitat mapping that are not common in continental shelf environments. Relief and range of substrates found within fjords are generally greater than on continental shelves, where many applications of marine habitat mapping have focused (e.g. Kostylev et al. 2001). The oceanographic complexity within fjords can require the integration of water column data, such as temperature, salinity, and bottom water anoxia, or the variation in these properties into benthic habitat mapping efforts, again unlike most continental shelf environments. The major goals of this paper are to present a methodology for producing substrate and habitat maps for fjords and to explore the use of marine habitat maps for biodiversity conservation and MPA management within Gilbert Bay.

Gilbert Bay is a shallow, multiple-basin fjord in Eastern Canada (Fig. 1). The mouth of Gilbert Bay is blocked by islands, limiting water exchange with the Labrador Sea. A complex branching to the southwest from the main arm of the bay contains shallow water basins, shoals, islands and

tidal channels, in areas known as River Out and The Shinneys. These areas have been identified as important habitat for a genetically distinct population of Atlantic cod (*Gadus morhua*). Conservation of this population of fish was the primary objective of the MPA.

The MPA is divided into three management Zones (Fig. 1) with varying degrees of protection based on the habitat use of cod in each Zone. The MPA boundaries and management Zones were designated based on the annual movements of the cod population within the bay (Fisheries and Oceans Canada 2007). Zone 1 of the MPA is afforded the highest level of protection as it protects spawning sites and nursery habitat used by juveniles. Zones 2 and 3 are used for feeding and migration by adult cod. Some spawning also occurs in Zone 2. Commercial fishing is completely banned in Zone 1 of the MPA, and is only permitted in Zones 2 and 3 for species other than Atlantic cod (Fisheries and Oceans Canada 2007). At present the primary commercial fishery in Gilbert Bay is for Iceland scallop (*Chlamys islandica*) (Morris et al. 2002; Wroblewski et al. 2009). The MPA is not a “no-take” reserve, as recreational angling for species such as salmon, trout and Arctic char are permitted in all Zones (Fisheries and Oceans Canada 2007).

The management plan states that the regulatory conservation objective of the MPA is “the conservation and protection of the Gilbert Bay cod and its habitats” (Fisheries and Oceans Canada 2007). Many of the management issues in Gilbert Bay relate to balancing this objective with the economic benefits which are gained through fishing in the bay, particularly through the scallop fishery. Marine habitat maps of Gilbert Bay were commissioned by Fisheries and Oceans Canada to aid MPA managers’ efforts to identify and protect sensitive habitats within the MPA, particularly habitats that might be used by Gilbert Bay cod, or that might be impacted by fishing.

The paper describes the classification methods for defining and mapping substrate classes and the biota occurring within them. Next, the paper analyzes the variation in diversity of acoustically distinct substrate classes, as a means to measuring habitat heterogeneity within the bay. Finally, we discuss the implications of our findings for management of this MPA, and for the use of marine habitat mapping in MPA planning, design, and management in general.

Methods

The method used to produce the substrate and habitat maps combines multibeam acoustic data with ground-truthing samples into a supervised classification method (Fig. 2).

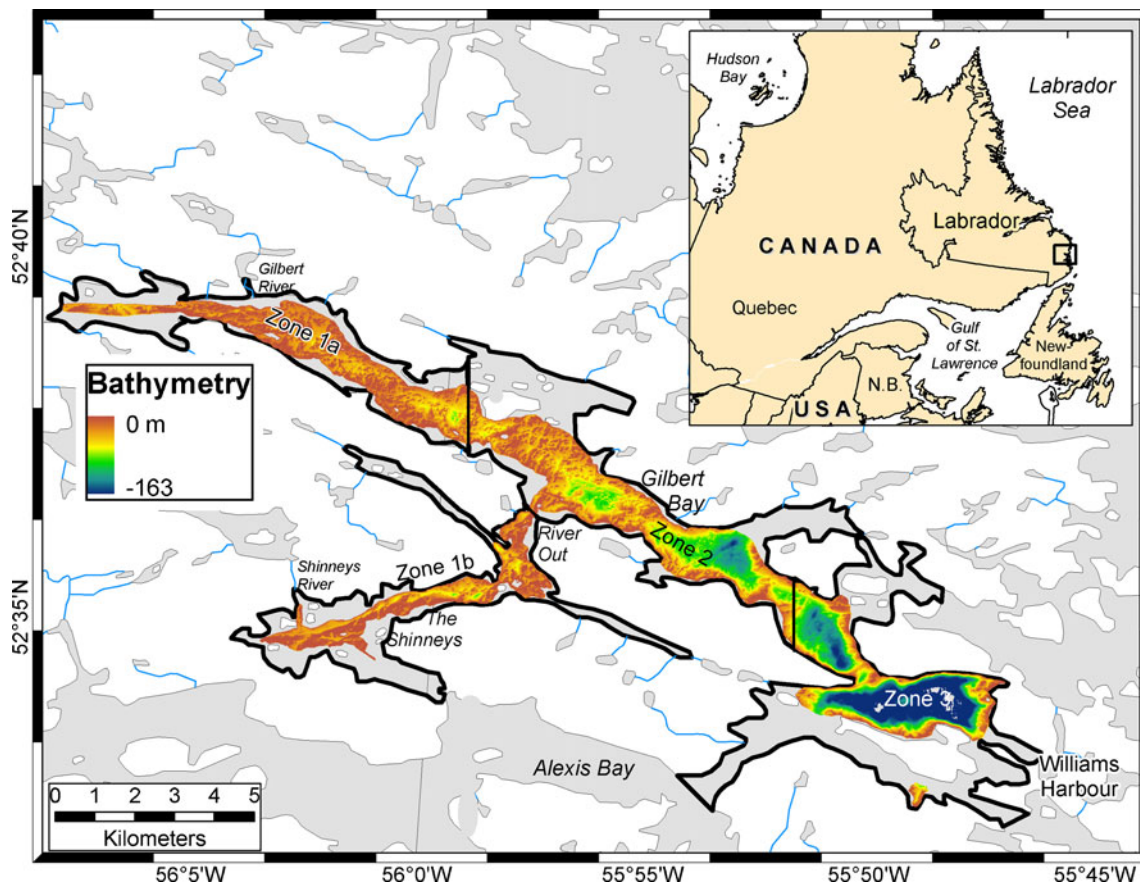


Fig. 1 Location map showing the multibeam bathymetry and the boundaries of the management Zones of Gilbert Bay MPA, southeastern Labrador

Multibeam sonar data acquisition

The multibeam sonar survey of Gilbert Bay was conducted by the Canadian Hydrographic Service (CHS) between Sept. 30 and Oct. 9, 2002, using an EM 100 transducer aboard the hydrographic vessel *CCGS Matthew*, and in shallower waters, an EM 3000 transducer aboard the hydrographic launch *CCGS Plover*. The survey covered 32 km² of the total 82 km² area of the MPA (Fig. 1). Most areas not surveyed were too shallow, presenting a damage risk to the survey vessels. The multibeam sonar system recorded depth and acoustic reflectance (backscatter), adjusting for vessel motion (roll, pitch, heave, and yaw), tides, and sound velocity within the water column.

Bathymetric data were processed by the CHS using CARIS HIPS v. 7.1.¹ Raw backscatter intensity was compensated for angle of insonification, and calibrated for sensor to yield compensated backscatter values in decibels. Backscatter intensity was processed by the Geological Survey of Canada and provided as an x, y, z, text file. While the initial sonar survey yielded depth and backscatter values at approximately

2 m spacing, the data were gridded in ArcGIS² Spatial Analyst (v. 10) to 5 m spatial resolution for all subsequent analyses. Although a finer resolution may have been interesting, the resolution of the grid was defined based on the sounding density. Seabed slope was derived from the grid using the terrain analysis feature in MapInfo[®] Vertical Mapper 8.0.

Ground-truthing: field sampling

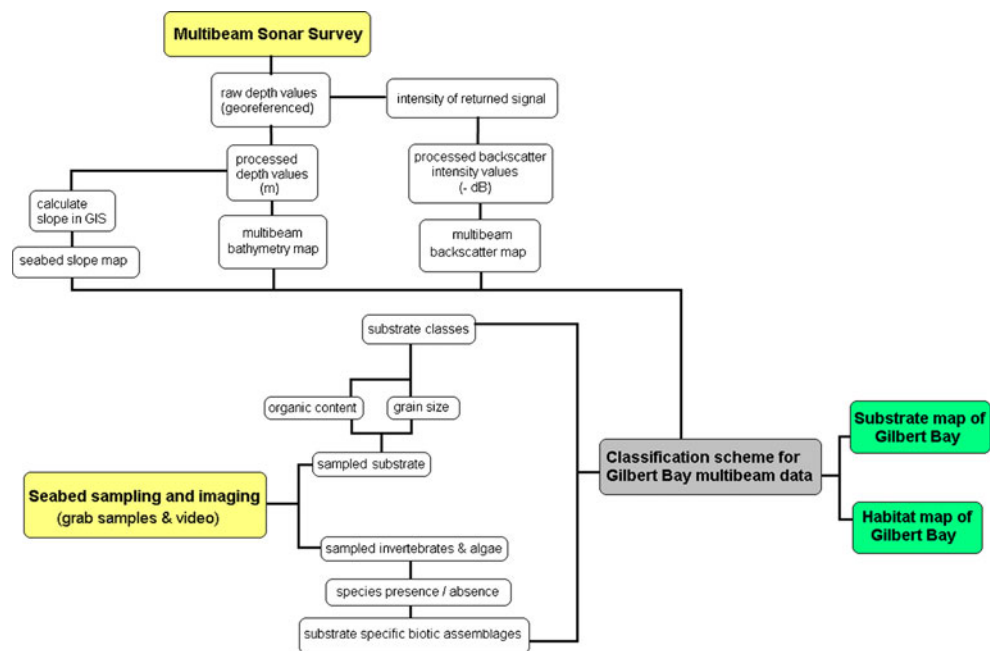
The correspondence of depth, slope, and backscatter values to bottom type and benthic biota was determined by extensive ground-truthing conducted in the fall 2006 and 2007 using benthic grab samples and bottom video imagery. Locations for ground-truthing observations were pre-determined using the multibeam sonar to maximize the variation in depth, backscatter, and slope values within the multibeam sonar dataset (cf. Copeland et al. 2007a).

Paired grab samples and drop video casts were made at 132 stations covering all parts of the bay. Benthic grab samples were collected using a Van Veen grab sampler for deeper waters in 2006 ($n=77$) and a hand-operated Petit

¹ <http://www.caris.com>

² <http://www.esri.com>

Fig. 2 Methodology developed for substrate and habitat map production



Ponar grab sampler for shallower waters in both 2006 ($n=24$) and 2007 ($n=31$). Position and depth of each grab sample were measured with a spatial accuracy better than 3 m and 0.1 m, respectively. Sites from which two successive grab sample casts returned empty were deemed hard-bottom sites, and were characterized by video transect only. Grab samples were photographed, subsampled in duplicate (~150 ml each) for sediment grain size and organic matter content, and then wet-sieved through 1 mm mesh to recover flora and fauna. The washed residue was photographed and invertebrates and algae present in it were collected and preserved in 70% ethanol.

Drop video surveys were recorded using two camera systems with transects of 4 min in length. Position and depth were recorded at the beginning and end of each drop video transect using the GPS and depth sounders. In deep-water areas, video was recorded using a Shark Marine drop-video camera with lights and two scaling lasers. In shallow water areas (<18 m) and areas too close to shore, video was recorded using an Amphibico Dive Buddy video housing with enclosed SONY TRV 38 digital video camera. Towed video surveys were recorded in 2007, using both camera systems, in shallow waters. Many of the towed video surveys in 2007 extended into shallow water areas not covered by the 2002 multibeam survey.

Positions of the grab samples and video transects were superimposed in MapInfo to ensure that the two sets of field samples for each target were in fact closely juxtaposed.

Sediment sample and biota analysis

Archived subsamples were kept frozen until date of analysis. Grain size analysis was carried out on subsamples

by wet sieving to remove the mud fraction and dry sieving to split the sand and gravel fractions. Video imagery was reviewed in the laboratory; the percentage of seabed covered by mud, sand, pebble, cobble, boulder and coralline-algae was quantified by counting the duration of each 4-min tow for which each substrate type was visible.

Grab sampled biota were identified to the lowest possible taxonomic level under a dissecting microscope. Except for polychaete worms, most taxa were identified to species level. Similarly, biota observed in video were identified visually to the lowest possible taxonomic level.

Substrate and habitat classification of samples

The results of grain size analysis were combined with observations from video imagery to form a complete description of the substrate at each sampling site. Samples were then grouped into substrate classes based on the dominant two to three size classes or unique components e.g. coralline-algae. Clasts coarser than sand, including granules, pebbles, cobbles, and boulders, but not including bedrock, were collectively termed “gravel”.

Species composition of ground-truth samples was analysed using non-metric multidimensional scaling (nMDS) and Analysis of Similarity (ANOSIM) conducted at the presence-absence level (Clarke and Warwick 2001; Copeland et al. 2007b, 2008 and 2011). Substrate classes which had statistically unique biotic assemblages were classified as discrete habitats, whereas substrate classes with statistically indistinguishable biota were combined into a habitat. The combined abiotic and biotic criteria in habitat classification minimizes the influence of behavioural, seasonal or successional changes in species composition on habitat definition.

Supervised classification and accuracy assessment

Acoustic characteristics of each station sampled by grab sampler or video transect were determined from the multibeam dataset. Depth, backscatter, and slope values for each of the classified ground-truth sampling points were extracted from the multibeam dataset using MapInfo. This allowed ranges of these three variables to be determined for each of the substrate classes, which in turn were used to classify the entire multibeam survey area based on the characteristics of the ground-truthed sites. 10% of the sampling points were randomly excluded from this training dataset, for later use in testing the accuracy of the classification (cf. Kostylev et al. 2001). Each sampling point in the training dataset was plotted in depth-backscatter-slope space. The distribution of depth, backscatter intensity, and slope values for each substrate type was determined using box-plots of each variable for each substrate type, identifying mean, median, inter-quartile range, 95% confidence limits, and outlier values.

Classification rules initially followed the interquartile ranges of depth, backscatter intensity, and slope for each of the substrate classes in the training dataset, but were then extended to maximize the proportion of the multibeam dataset classified, and to minimize the ambiguity in classification. To produce substrate and habitat maps, queries were made using the GIS to select pixels that met classification rules for depth, backscatter and slope for a given substrate class. Layers were overlaid in order of increasing specificity (most limiting acoustic criteria) to produce the substrate map.

Accuracy of the substrate maps was assessed using the 10% of the ground-truthing dataset reserved for testing, and the classified multibeam sonar raster data. Accuracy was measured in two ways: the percentage of points from the testing dataset which was unambiguously classified, and the percentage of points from the testing dataset which was misclassified. Unambiguously classified pixels fell into only 1 of the 6 acoustically distinct substrate classes, while ambiguously classified points met the depth, slope, and backscatter criteria for more than one substrate class. Misclassified points were those whose physical substrate characteristics did not match those of the acoustic class into which they were categorized in the supervised classification.

Habitats were defined based on the combination of their physical characteristics (especially depth and substrate type) and their species composition. The habitat map combined those substrates that had statistically indistinct biota into habitats, thus limiting the maximum number of habitat classes to a smaller number than the number of substrate classes

Quantification of alpha- and beta-diversity

Diversity, both within-habitat (alpha) and between-habitat (beta) were measured as species or substrate type richness.

Alpha-diversity was quantified in two ways. First, the average number of species per video tow or per grab sample was compared among substrate and habitat groups using 1-way ANOVA. Second, the species-sampling curve for each substrate type was calculated using a species presence-absence matrix for all samples. Separate species-sampling curves were calculated for grab samples and video transects.

Beta-diversity was quantified as the number of different substrate types present in a moving circular area of 1 ha in size centred on each pixel. Substrates were used instead of habitats as they carried more information than the latter, habitats resulting from the combining of biologically similar substrate classes. A majority filter was first applied to the substrate map in order to reduce the noise resulting from the backscatter data. ArcGIS focal statistics tool was then used to calculate the number of different substrates in the given radius. The resulting substrate diversity map was then normalized to the number of classified pixels within that circular area to correct for edge effects. Beta-diversity was compared among the Gilbert Bay management Zones.

Results

Substrates mapped in Gilbert Bay

In 2006 and 2007, eight substrate types were described in Gilbert Bay: muddy gravel, sandy gravel, coralline-algae encrusted gravel, gravelly sandy mud, gravelly mud, mud, nearshore gravel, and current-swept gravel. The last two substrates did not have acoustically distinct signatures and were distinguished based on video alone. The general trend in the distribution of substrates in Gilbert Bay was that muddy gravel, sandy gravel and gravelly sandy mud occurred on the sills that separate the main basins, whereas gravelly mud and mud were found on the floors of the basins (Figs. 3 and 4). A more detailed description of the distribution of substrates is provided in Copeland et al. (2011).

Accuracy analysis of the substrate map showed that about 69% of the testing dataset (10% of the ground-truthing points) were correctly classified, while 17% were misclassified, and 14% remained unclassified. Classification ambiguity was similar with about 61% of the pixels in the 5 m grid uniquely classified, while 22% were ambiguously classified into 2 or 3 substrate classes and 16% of the pixels remained unclassified. Details of classification accuracy and ambiguity assessments are presented in Copeland et al. 2007b and 2008.

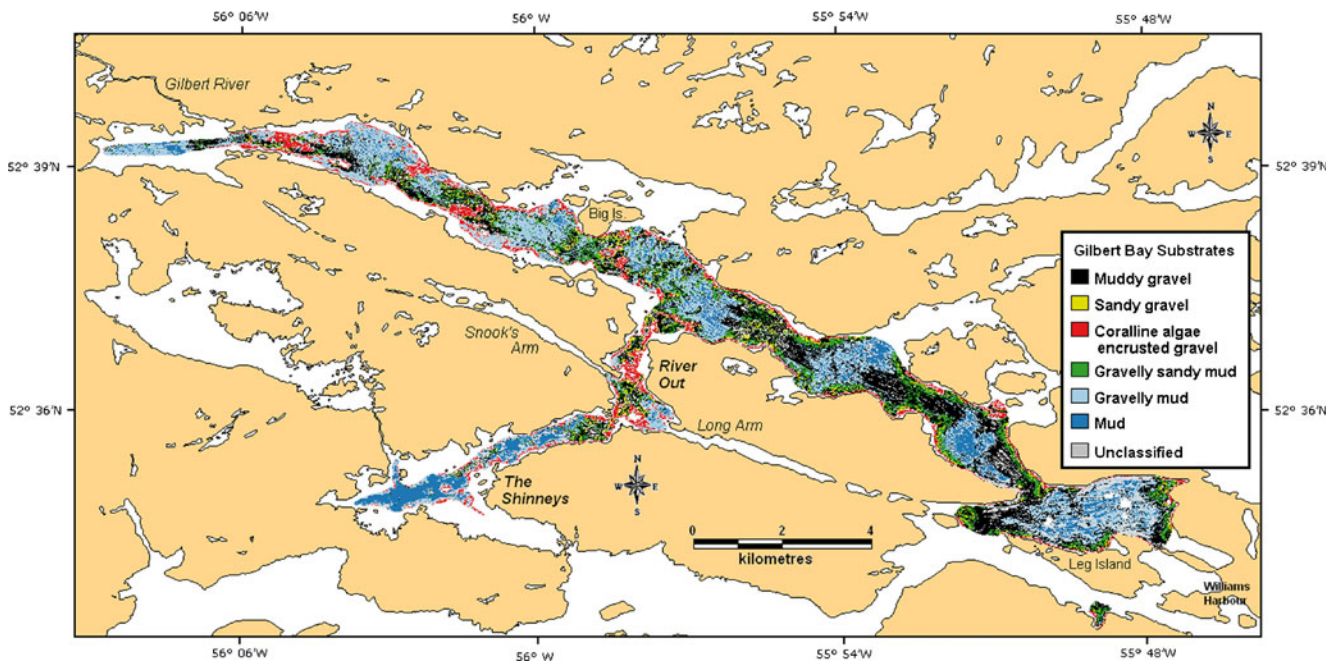


Fig. 3 Benthic substrate map of Gilbert Bay created by supervised classification of multibeam sonar data from ground-truth samples collected in 2006. The map only includes the six substrate types surveyed by the multibeam data

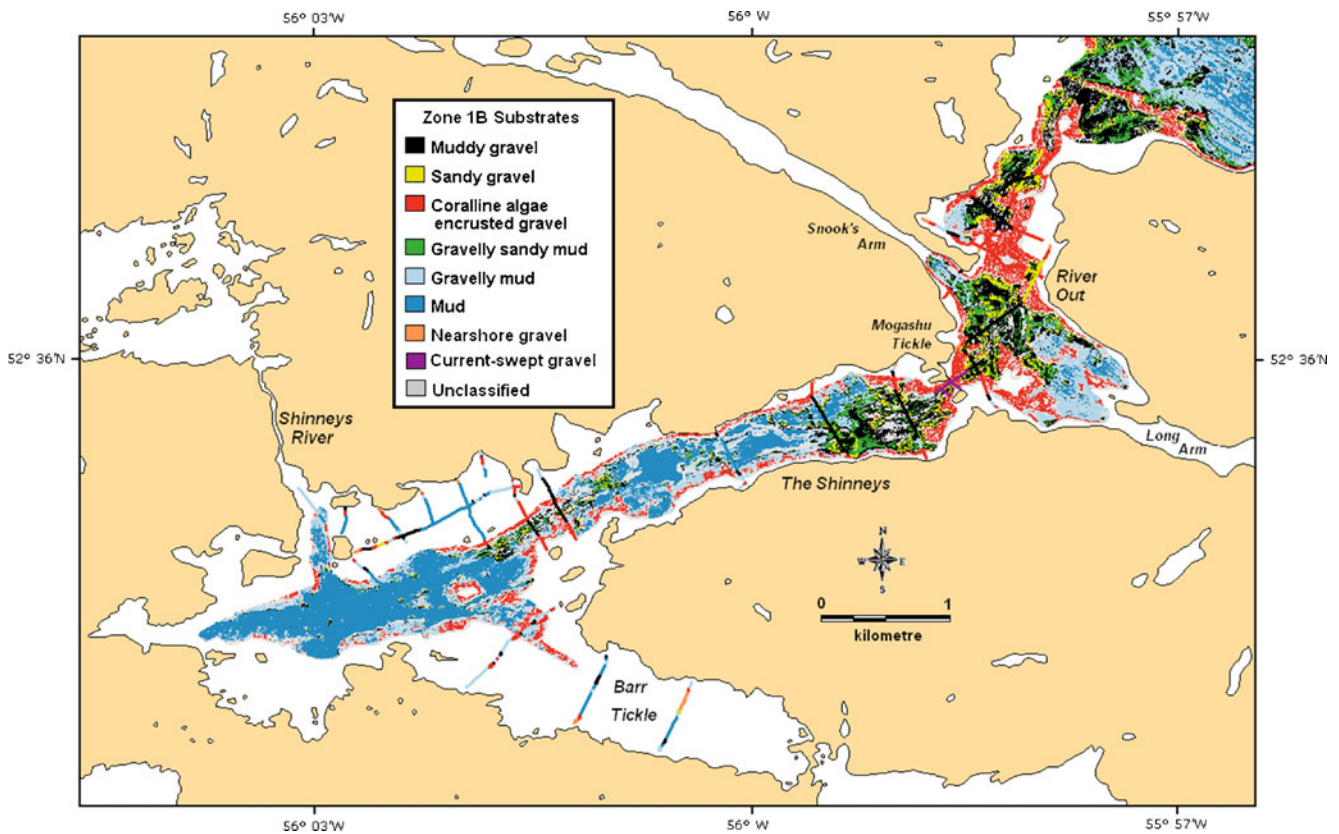


Fig. 4 Substrate map of MPA management Zone 1B with classified video transects collected in 2007 overlaid on the multibeam-derived substrate map from 2006. The map includes the two substrate types – nearshore gravel and current-swept gravel – not covered by the multibeam survey

Habitats mapped in Gilbert Bay

Analysis of the sampled biota using ANOSIM identified five statistically distinct habitats in Gilbert Bay (Fig. 5): (1) gravel bottom habitat, (2) coralline-algae encrusted gravel, (3) soft bottom habitat, (4) nearshore gravel and (5) current swept gravel (Copeland et al. 2008). Characteristic biota of each substrate type, and the statistical results comparing them, are presented in Copeland et al. (2011).

Gravel bottom habitat was composed of the muddy gravel and sandy gravel substrate classes. The coralline-algae encrusted gravel substrate supported a statistically unique suite of biota, and therefore was mapped as a distinct habitat type. The mud, gravelly mud and gravelly sandy mud substrates contained a similar biotic assemblage and thus were mapped together as soft bottom habitat. The nearshore gravel in Zone 1B was also a statistically distinct habitat, with much lower within-habitat species richness than the other habitats. The current-swept gravel in the tidal rapids was a biologically unique habitat that hosted biota rarely sampled elsewhere in Gilbert Bay, but did not have a unique acoustic signature and could not be mapped by classification of the multibeam sonar data.

Alpha and beta-diversity

Although the video transects sampled much more area than the grab samples, average species richness observed in

the grab samples was higher than that observed in the video transects ($F_{(1,247)}=56.5$, $p<0.0001$). Comparing among substrates, highest species richness in grab sampled biota was observed in the sandy gravel and coralline-algae encrusted gravel substrates, followed by the muddy gravel, while the muddy substrates (gravelly sandy mud, gravelly mud, and mud) had lower mean species richness (Fig. 6, $F_{(5,97)}=3.27$, $p<0.01$). Among the video transects, highest species richness per transect was observed in the current-swept gravel in Mogashu Tickle in the Shinneys (Fig. 4), followed by the coralline-algae encrusted gravel, sandy gravel, and muddy gravel. Lowest species richness in video transects was observed in the mud substrate and in the nearshore gravel substrate ($F_{(6,139)}=13.08$, $p<0.001$).

Similarly, species-sampling curves showed the greatest species richness in the coralline-algae encrusted gravel, muddy gravel, and gravelly mud, with the lowest diversity in mud and the nearshore gravel (Fig. 7). The species-sampling curves for the mud, gravelly-sandy mud, and sandy gravel all approached horizontal asymptotes at lower diversity than the muddy gravel, gravelly mud, and coralline-algae encrusted gravel, indicating that the highest within-habitat heterogeneity in species presence-absence was found in the muddy gravel and to some extent also in the gravelly mud substrate.

Figure 8 highlights the spatial heterogeneity of beta-diversity within each management Zone. Generally, basins filled by mud or gravelly mud were more homogeneous and had lower beta-diversity, whereas sills, eskers, narrow

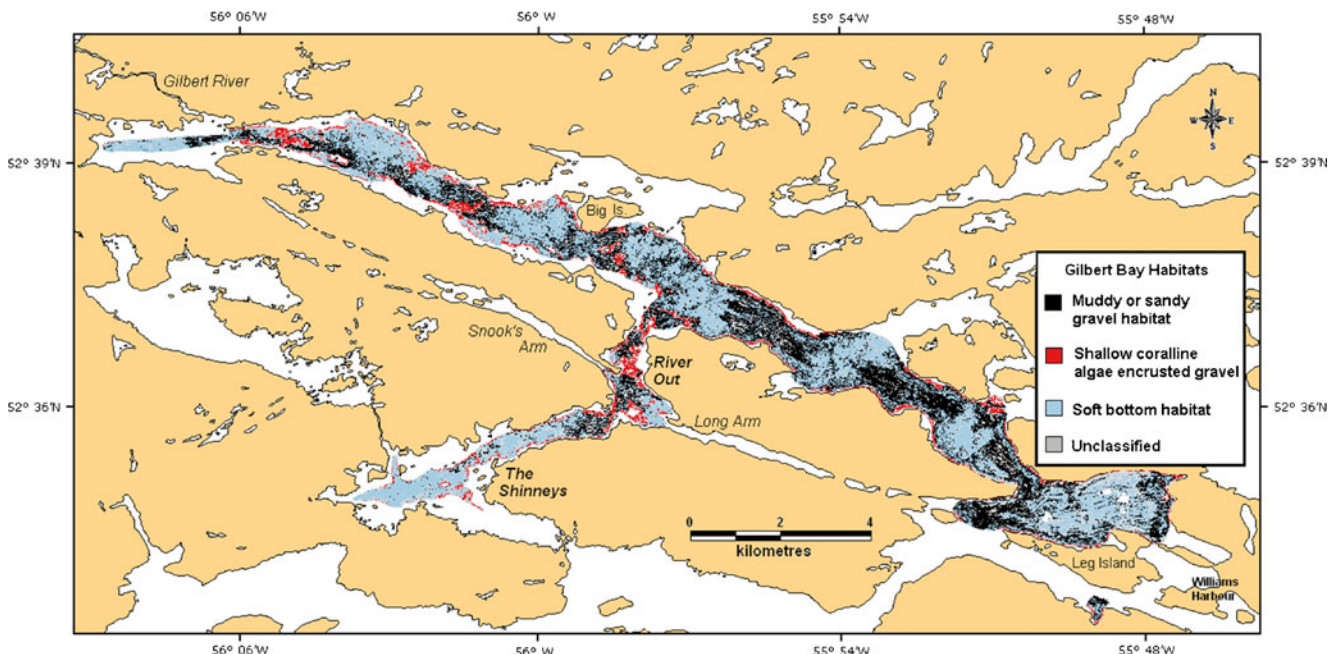
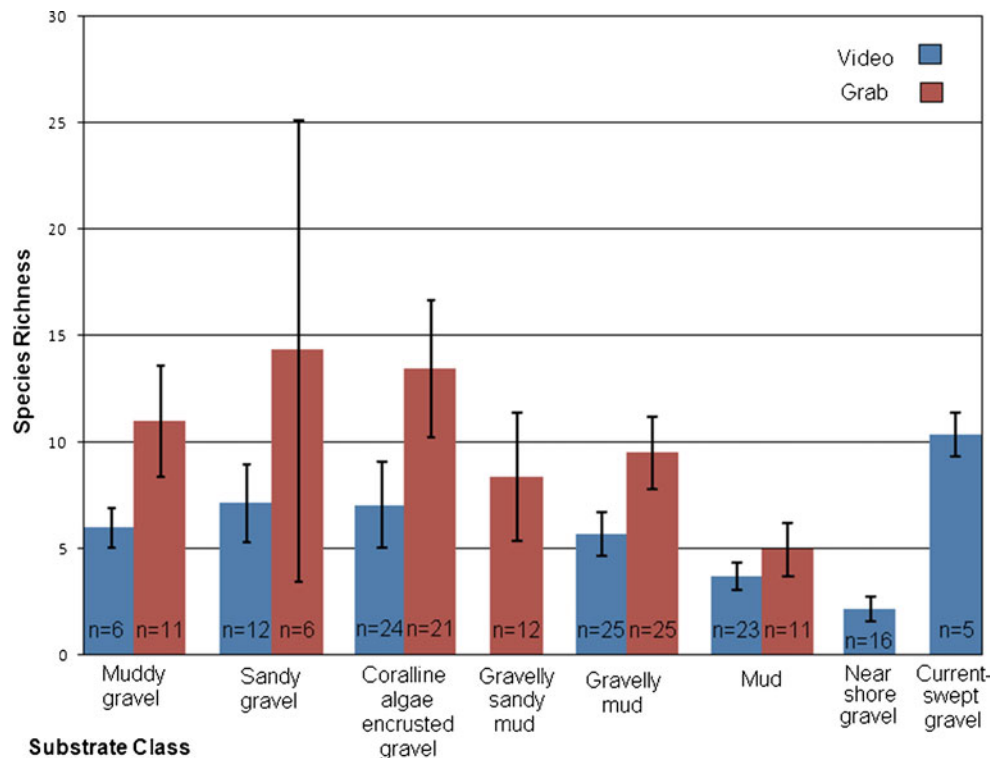


Fig. 5 Benthic habitat map of Gilbert Bay created by supervised classification of multibeam sonar data from ground-truth samples collected in 2006. The map results from the classification of the six substrate types surveyed by the multibeam system

Fig. 6 Average species richness of substrates sampled in Gilbert Bay in 2006 and 2007. Means \pm 95% confidence interval



channels, and shorelines with coralline-algae, muddy gravel, gravelly sandy mud and gravelly mud had higher beta-diversity.

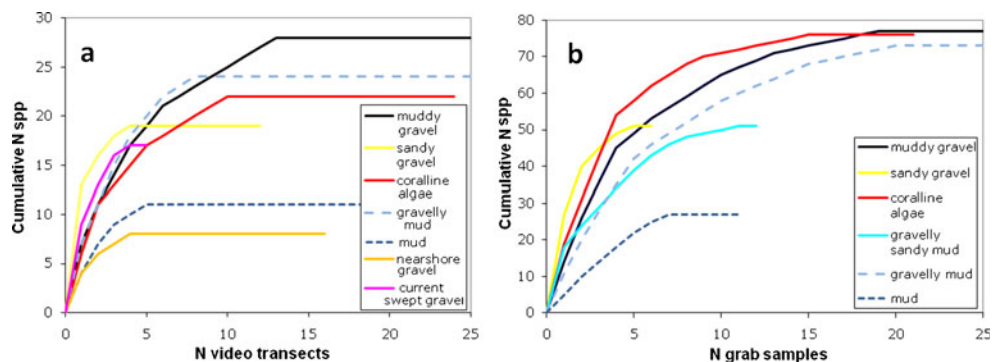
The rim of high beta-diversity in the outer edge of the multibeam coverage is mostly due to a higher substrate diversity along the edges of the bay, resulting from steeper bathymetric gradients and from the decision rules used for the supervised classification, although there was also some analytical edge effect. The average beta-diversity estimated from the diversity of substrate classes within 1 ha circles was the highest in the management Zone 1B (average: 0.084; standard deviation: 0.136), followed by the Zone 2 (0.069; 0.148), the Zone 3 (0.050; 0.095) and finally by the Zone 1A (0.040; 0.103). Beta-diversity values are dimensionless due to the standardization done to account for the number of pixels considered in the calculation.

Discussion

Alpha-diversity, beta-diversity and MPA zoning

Protected area planning for biodiversity conservation often aims to protect the greatest number of species, by focusing for instance on hotspots of high biodiversity, and congruence of diversity among higher taxa (e.g. Roberts et al. 2002; Moilanen et al. 2009; Trombulak and Baldwin 2010), and by seeking complementarity of habitats through maximizing habitat diversity (e.g. Fernandes et al. 2005). It may be possible to meet these goals simultaneously in designing and zoning a given MPA through the use of marine habitat maps. Maps of alpha and beta species diversity have been proposed as useful elements in marine conservation planning (e.g. Lourie and Vincent 2004; Harborne et al. 2006). Measures of alpha-diversity are

Fig. 7 Species-sampling curves for video transects (a), and grab samples (b). Note change in Y-axis scale



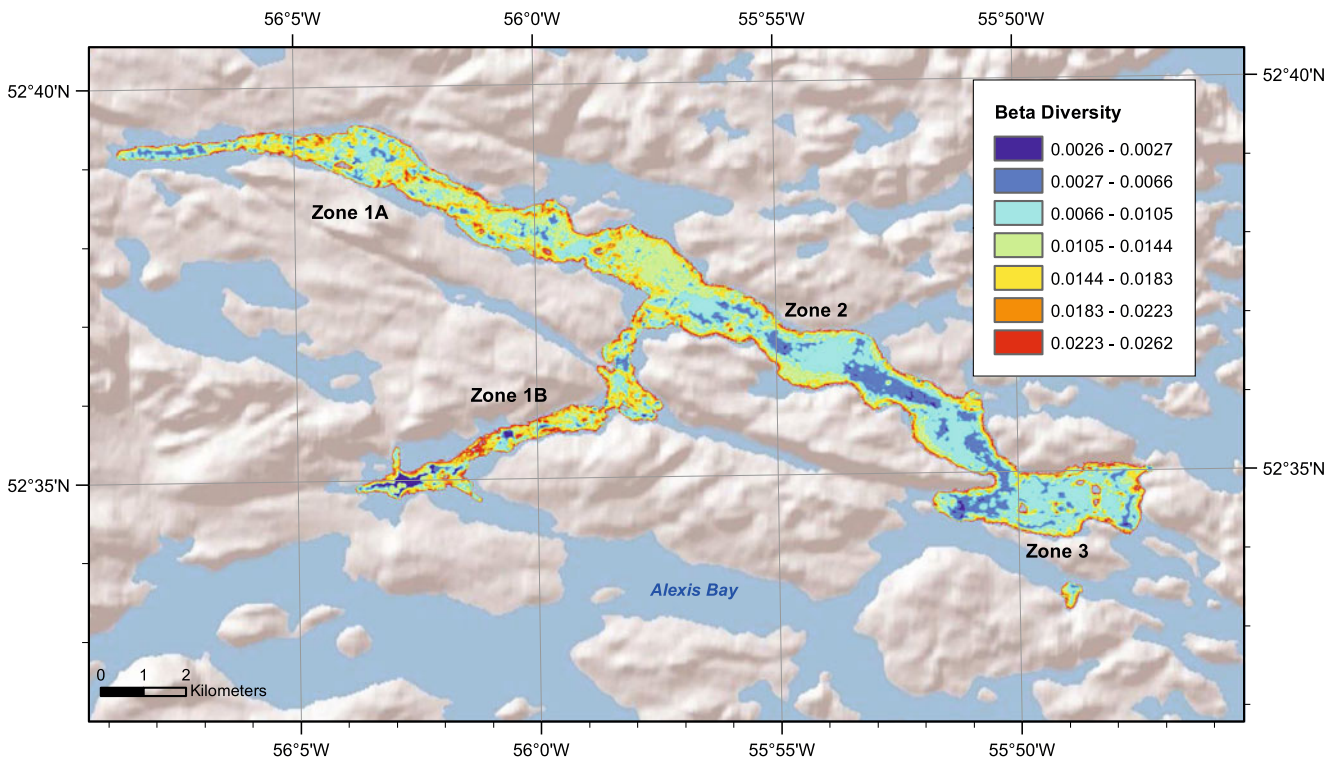


Fig. 8 Beta-diversity map for Gilbert Bay

strongly dependent on sampling method, and some benthic marine sampling methods are substrate-restricted. In most habitats of Gilbert Bay, alpha-diversity was higher in grab samples than in video, because the type and size of biota visible in video was different and much larger than the size of biota in the grab samples. Video transects could recognize only macrophytes and large epifauna, while grab sampling collected macrophytes, large and small epifauna, and infauna (Copeland et al. 2011). Some of the hard-substrate habitats, however, were impossible to sample by grab sample. The differences in composition of the fauna sampled by grabs and video transects illustrates the need for complementary sampling methods to fully characterize benthic biodiversity (cf. Brown et al. 2011).

Other biogeographic and habitat mapping approaches to marine protected area network planning have focused on definition and mapping of unique habitat types (e.g. Salá et al. 2002), marine ecoregions (e.g. Fernandes et al. 2005), particular species of concern related to the Key Biodiversity Areas (KBA) approach (Edgar et al. 2008), or to coral reef habitat maps and beta-diversity estimates as measures of fish diversity (e.g. Mumby et al. 2008). Measurements of beta-diversity for terrestrial conservation are common (e.g. McKnight et al. 2007), although methods of beta-diversity quantification vary, and are often based on analysis of large taxonomic datasets (e.g. Bacaro et al. 2007). Use of taxon-based beta-diversity measures for conservation planning requires extensive well-distributed biogeographic databases,

which are commonly available for marine fishes, but rarely so for marine invertebrates.

Terrestrial bedrock geology and geomorphology have profound influence on vegetation types and on terrestrial biodiversity, and beta-diversity of bedrock types, is a very strong predictor of terrestrial biodiversity (Anderson and Ferree 2010). Our maps of substrate beta-diversity are analogous to measurements of geological type beta-diversity, but our method of calculation was somewhat different. While our method of beta-diversity quantification produced continuous, readily interpretable maps of habitat heterogeneity, it does not lend itself to parametric statistical analysis because the overlapping 1 ha circles are not independent samples. Refinements to our basic approach to substrate mapping and beta-diversity calculation could include object-based classification (as opposed to pixel-based), changes in the radius of pixels measured from each point, or measurement of beta-diversity within pre-defined spatial units, such as the management Zones or geographic subdivisions of the bay. Nonetheless, areas of highest conservation value could be identified based on substrate maps, showing the location of rare habitats (and locally rare taxa), and our quantified beta-diversity. In Gilbert Bay, beta diversity was high around glaciogenic geomorphic features, such as eskers, subglacial fans and moraine-derived sills, especially where these features formed small islands. This effect is partly dependent on bathymetric variation, analogous to the importance of elevation gradients in terrestrial

beta-diversity, but is also related to the close juxtaposition of hard- and soft-bottom substrates associated with some glacial features. While the apparent importance of islands may be partly an edge effect surrounding the edge of multibeam coverage, the importance of the other features is not an edge effect.

Highest average beta-diversity was found in management Zone 1B, followed by Zone 2 and then Zone 3. This order follows the levels of protection given to the MPA where Zone 1 has the most protection while Zone 3 has the least. While Fig. 8 suggests an overall higher beta-diversity for the Zone 1A compared to the Zones 2 and 3, Zone 1A had the lowest average beta-diversity. This surprising result could stem from shallower bathymetric gradients on the edge of the Zone 1A compared to the other Zones, particularly at the head of the bay, where the multibeam coverage was restricted to the central axis of the bay. Average beta-diversity calculations must be interpreted cautiously as they strongly rely on the original acoustic backscatter data which often present a number of data acquisition artefacts. These artefacts were most important in the basins of the bay, where nadir-related stripes of apparent high backscatter caused artefactual alternating stripes of pixels classified as mud or gravelly mud in the basins, or as gravelly mud or muddy gravel on the sills and basin margins. When beta-diversity was calculated for each management unit, Zones 2 and 3 had artificially high beta-diversity, particularly in the basin centres. Less of this striping was recorded in Zone 1a, than in Zones 2 and 3.

Uniqueness and vulnerability to human impacts

The types of substrates and habitats identified in Gilbert Bay are similar to those identified in fjords from other parts of Labrador and Newfoundland (e.g. Copeland et al. 2007a), and the range of habitats was greater than that in high-arctic fjords, which generally have higher rates of sedimentation associated with active glaciers or unvegetated watersheds (Dale et al. 1989). An unusual feature of Gilbert Bay was the rarity of large kelp (Laminariales). Kelp were only observed in a shallow current-swept region of the bay, outside the area of multibeam coverage, where they were encountered in an experimental scallop dredge of an area not usually fished, and rockweeds (*Fucus* spp.) were only observed at the mouth of the Shinneys River (Copeland et al. 2011).

Two rare and sensitive habitats were identified, both located in management Zone 1B, which has the strictest level of protection from human activities (Fig. 4). The current-swept gravel habitat mapped in Mogashu Tickle is unique within the bay, and is significant as it hosts high invertebrate species diversity, a large number of individuals and also a high density of scallops. An extensive rhodolith

bed was identified in River Out (Fig. 4). The rhodolith bed differed from other coralline-algae encrusted gravel habitat in that there was no gravel core to the rhodoliths, and no coralline algae-free gravel was observed in videos. The Shinneys have been identified as important spawning and nursery areas for Gilbert Bay cod. The combination of shallow water mud, which may provide important feeding habitat for young cod, adjacent to coralline-algae encrusted gravel, which could be used for shelter, may make high quality habitat for juvenile cod (Copeland et al. 2011).

By zoning the Gilbert Bay MPA to afford the highest amount of protection to known cod spawning, feeding and nursery habitats in Zone 1, the MPA managers also successfully protected many areas of substrates with high alpha-diversity, the areas with the highest beta-diversity in the bay, and several locally unique and bio-diverse habitats.

Due to the fragility of branching coralline-algae, the coralline-algae encrusted gravel is the most likely habitat to suffer negative effects from human disturbance, in particular from dragging to harvest scallops. Large tracts of coralline-algae encrusted gravel habitat are protected in Zones 1A and 1B of the MPA and are therefore not subject to scallop dragging. The coralline-algae encrusted gravel habitat in Zones 2 and 3 are, however, vulnerable to disturbance from dragging. Scallop fishing is usually concentrated at depths between 8 and 20 m (Morris et al. 2002), which correspond with the depths to which we mapped rhodolith and coralline-algae encrusted gravel habitat (4 to 15 m). Scallop dragging has well-documented impacts on coralline algae-based habitats in other locations (Hall-Spencer and Moore 2000).

Scallop harvesters reported fishing for scallops primarily on coralline-algae, pebble, cobble and small boulder substrates (Morris et al. 2002). High scallop densities were observed in Mogashu Tickle and adjacent parts of the Outer Shinneys. Not surprisingly, video observations of coralline-algae in areas subjected to frequent commercial fishing activities often found broken structures. Intact colonies of coralline-algae were rare in video or grab samples, in striking contrast to the pristine coralline-algae habitats observed in River Out and other unfished areas. Scallop dragging in Zones 2 and 3 clearly impacts bottom habitat, particularly the coralline-algae encrusted gravel habitat. Size-frequency distributions in various parts of the bay suggest that scallop beds in many areas of Zones 2 and 3 are overfished (Wroblewski et al. 2009).

Limitations and broader applications of acoustically derived marine habitat maps for marine conservation

Acoustic mapping of coastal marine habitats *per se* has not been used as much as more general marine conservation

approaches, perhaps due to its novelty, its relatively laborious nature in shallow water, or the perceived need for continuous multibeam coverage (Cogan et al. 2009). Because the swath width of most multibeam echosounder (MBES) systems is approximately 5 times water depth, the efficiency of MBES-based habitat mapping increases dramatically with water depth. In very shallow water areas such as Gilbert Bay, MBES mapping is tedious and time-consuming, and can be hindered by a relatively large littoral gap between multibeam sonar coverage and the shoreline. Where the littoral gap in Gilbert Bay was sampled using video transects and single-beam depth soundings, the substrates and biota observed were mostly consistent with the habitat distributions in areas with multibeam sonar coverage. In some areas of The Shinneys, the littoral gap and edge of multibeam coverage included highly complex bathymetry and juxtaposed hard and soft substrates, which may contribute to juvenile cod habitat, for which shelter from predators (especially older juvenile cod) is particularly important (Copeland et al. 2011). The only substrate observed in the littoral gap that was not observed elsewhere was the nearshore gravel, which had very low species richness. In sub-arctic environments, such as Gilbert Bay, intertidal and very shallow subtidal diversity is often limited by ice scour – in this study, the lowest diversity habitat identified was the nearshore gravel. Similarly, intertidal exposures of bedrock in Gilbert Bay typically had very little biota, except in cracks and crevices where small mussels, barnacles, and seaweeds found protection from ice scour. Thus in the case of Gilbert Bay, the large littoral gap probably did not affect our results in most parts of the bay.

This littoral gap can be filled by bathymetric LiDAR (e.g. Parrott et al. 2008; Collin et al. 2011), which is optically based, and is typically limited to shallow water. Such intervening coverage would have been very helpful in a case like Gilbert Bay. Nonetheless, the results regarding differences in habitat heterogeneity among management Zones and geographic portions of the bay retain their validity.

The relatively continuous nature of most continental shelf and slope depth environments, compared to the high heterogeneity of the coastal Zone, makes interpolation of habitats between areas with multibeam coverage (e.g. based on bathymetry derived from compiled single-beam sonar surveys), more reliable than for coastal areas. Some deep-water exceptions to this trend would be seamounts (Pitcher 2007), hot vent fields (e.g. Marcus et al. 2009), and submarine canyons (e.g. Maier et al. 2011; Huvenne et al. 2011), all of which have high fine-scale habitat heterogeneity.

Finally, the spatial scale of the habitat maps produced in this study makes them appropriate for design and management

zoning of a single MPA, rather than placement of an MPA network. Because surficial geology can have a strong influence on the nature of benthic habitats, we feel that MBES-based habitat mapping has great potential for marine conservation planning at a variety of spatial scales, particularly in offshore settings where the efficiency of multibeam-sonar mapping is high (e.g. Cogan et al. 2009, Harris and Baker 2011).

Conclusions

Acoustic marine habitat mapping, ground-truthed by video transects and benthic grab sampling, identified 8 substrates and 5 biotically distinct habitats within Gilbert Bay, a shallow sub-arctic fjord on the coast of southern Labrador, Canada. Supervised classification was based on depth, acoustic backscatter, and derived slope values for each pixel.

Highest alpha-diversity was found in coralline-algae encrusted gravel and in other gravelly substrates. Continuous maps of beta-diversity found highest habitat heterogeneity associated with glaciogenic landforms, such as moraine-derived sills and eskers, around islands and along shorelines, and near hard substrate features swept by strong currents.

Although the Gilbert Bay marine protected area (MPA) was designed for protection of a unique population of a single species, its management plan coincidentally gave highest protection to the portions of the bay with highest alpha- and beta-diversity. This result is likely due to the fact that the management plan protects spawning and juvenile fish habitat for this species.

Acoustic marine habitat mapping can provide useful maps of alpha- and beta-diversity for design and management of marine protected areas and MPA networks in coastal areas, including bathymetrically complex regions, such as fjords.

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