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A spatial framework for representing nearshore ecosystems

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ABSTRACT

The shallow, coastal regions of the world's oceans are highly productive ecosystems providing important habitat for commercial, forage, endangered, and iconic species. Given the diversity of ecosystem services produced or supported by this ecosystem, a better understanding of its structure and function is central to developing an ecosystem-based approach to management. However this region – termed the 'white strip' by marine geologists because of the general lack of high-resolution bathymetric data – is dynamic, highly variable, and difficult to access making data collection challenging and expensive. Since substrate is a key indicator of habitat in this important ecosystem, our objective was to create a continuous substrate map from the best available bottom type data. Such data are critical to assessments of species distributions and anthropogenic risk. Using the Strait of Georgia in coastal British Columbia, Canada, as a case study, we demonstrate how such a map can be created from a diversity of sources. Our approach is simple, quantitative, and transparent making it amenable to iterative improvement as data quality and availability improve. We evaluated the ecological performance of our bottom patches using observed shellfish distributions. We found that observations of geoduck clam, an infaunal species, and red urchins, a species preferentially associated with hard bottom, were strongly and significantly associated with our soft and hard patches respectively. Our description of bottom patches also corresponded well with a more traditional, morphological classification of a portion of the study area. To provide subsequent analyses (such as habitat models) with some confidence in the defined bottom type values, we developed a corresponding confidence surface based on the agreement of, and distance between observations. Our continuous map of nearshore bottom patches thus provides a spatial framework to which other types of data, both abiotic (e.g., energy) and biotic, can be attached. As more data are associated with the bottom patches, we anticipate they will become increasingly useful for representing and developing species-habitat relationships, ultimately leading to a comprehensive representation of the nearshore ecosystem.

1. Introduction

The nearshore subtidal region (0–50 m depth) is a highly productive ecosystem providing both permanent and transitory habitat for commercial (e.g., rockfish, salmon), forage (e.g., sandlance, herring), endangered (e.g., abalone) and iconic (e.g., kelp, sea otters) species. Given the number of ecosystem services that are produced or supported by this ecosystem, a better understanding of its structure and function would clearly benefit any ecosystem-based approach to management (EBM). As the transition zone between the terrestrial and marine environments, it is also the region most directly affected by urbanisation and up-land influences. The nearshore is therefore also key to understanding the land-sea interface, and for managing anthropogenic risk and cumulative impacts.

The value of spatially continuous, accurate maps of this ecosystem is widely recognised by managers and conservationists (Cogan et al., 2009; DFO, 2010; Shumchenia and King, 2010). However, the nearshore – termed the "white strip" (Fig. 1) by marine geologists because of the lack of high-resolution bathymetric data – is a dynamic, highly variable, and poorly accessible ecosystem, making data collection difficult and expensive. Characterisation of this region is thus hindered by a general lack of continuous datasets (DFO, 2010).

Acoustic multi-beam methods provide high resolution bathymetry and can be used to derive bottom type (Anderson et al., 2008; Kvitek et al., 1999; MESH, 2010). However, their application in shallow waters is time-consuming. In British Columbia (BC), the time required to map the entire nearshore using multi-beam acoustics is measured in decades to centuries (Heap and Harris, 2011). Furthermore, only depth is obtained reliably, since the collected backscatter data must be post-processed into a model of bottom type.

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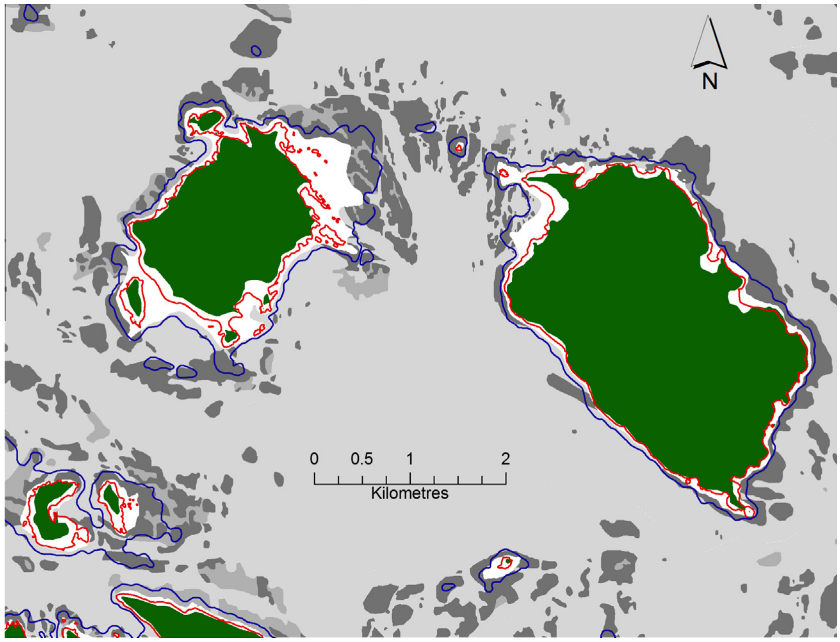

Fig. 1. Illustration of the extents of the 'white strip' around islands in the Strait of Georgia. Contour lines (red = low water line; blue = 10 m) are shown over top of bottom type classes (grey scale, hard is dark, soft is light) derived from morphological analysis that included acoustic multibeam backscatter data (Greene and Barrie, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In addition to depth and bottom type, a complete characterisation of the nearshore ecosystem will also require other physical factors such as energy, light, and nutrients. Then there is the representation of biota to consider, most of which can only sampled by direct observation (Kvitek et al., 1999) – an impossibility for the entire 35,000 km coast of BC. Maps of species distributions will therefore need to be based on species-habitat relationships derived from surveyed areas, and extrapolated to unsampled areas (Kvitek et al., 1999). Such extrapolations will depend on continuous maps of the physical predictor variables such as the surface developed here.

Given the ever-increasing pressures on marine systems, EBM would benefit from having such maps available as soon as possible, made from the best data currently available. Further, since data collection is on-going, any method used to make such maps would be of greater value if it was easily updatable, and supported the maintenance of the databases needed for EBM. In other words, describing and mapping marine ecosystems is likely to be an on-going effort, and this should be reflected in the tools applied.

To support the creation of such nearshore ecosystem maps, we present a spatial framework suitable for representing both abiotic and biotic ecosystem components. Based on the assumption that the ecological role of the ocean bottom in the nearshore is strongly related to substrate and depth, we describe how a map of bottom patches (BoPs – areas with similar depth and substrate) can be defined based on depth and a variety of bottom type data. The resulting patches describe the ocean bottom in a way that reflects the best available data in a region, making them suitable as a spatial framework to which other physical (e.g., energy) and biological (e.g., species abundance) characteristics can be attached. Through these associations, the BoPs will provide a framework suitable for the derivation and extrapolation of species-habitat relationships, leading ultimately to ecologically complete habitat patches suitable for advancing research and EBM in this important but often overlooked ecosystem.

2. Methods and results

The utility of a continuous physical characterisation of the nearshore to EBM is broadly recognised by the relevant management agencies in BC. We therefore convened a workshop in April 2006 to discuss the availability of physical data, and to develop a method for creating a physical representation of the nearshore using the best available data. We established the Nearshore Habitat Working Group (NHWG) to outline the objectives and direct the collection and integration of available data, and the development of the methods. The NHWG included a diverse group of scientists from a range of disciplines (e.g., ecology, geology, biology, hydrology, and cartography), highlighting the breadth of interest in the nearshore ecosystem. The disciplinary perspectives within the group led to some interesting discussions and provided some challenges to the design. Focusing on what would be necessary and sufficient from an ecological (i.e., habitat modelling) point of view resolved these differences and added considerable value to the final methods. Thus, the approach described herein is based in part on the outcomes from these meetings.

To help contextualise the more detailed methods that follow, we briefly describe the steps involved in the creation of the BoPs (Fig. 2). Identification and collection of the available data was the obvious first step. However, since different data sets tend to use different bottom type nomenclature, we needed an approach to assign a common classification across the data sets. We then used Thiessen polygons to spatially extrapolate the sampling points. Thiessen polygons are created by placing a polygon around each point such that the polygon encloses all the space that is closer to the focal point than any other in the set (Rhynsburger, 1973). The boundaries between polygons are thus equidistant to the two nearest points. Recognising that with sparse data, such polygons will lead to unrealistic extrapolations, we created a simple background substrate layer to fill in areas where

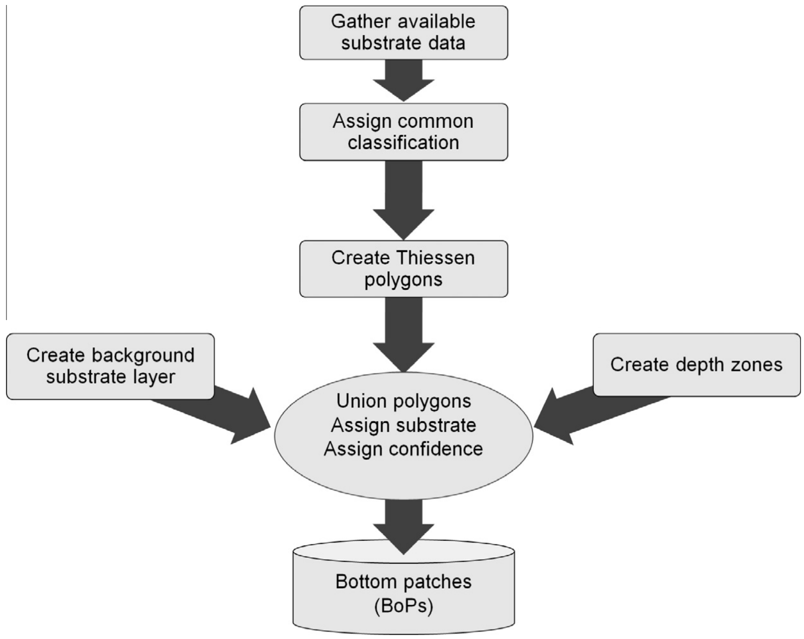

Fig. 2. Schematic of data processing from available data (top) to the final bottom patch (BoP) database at bottom. Each data source was first assigned a common classification of bottom type (BType). We then created Thiessen polygons from each source and combined these polygons with the depth zones and the default substrate layer. We assigned the resulting BoP fragments a bottom type (BType) and a confidence (BConf) value based on the relationship between the fragments and the different data sources. See Section 2.

sample data were unavailable, or extrapolation was considered unreasonable. Questions about what constituted sufficient bathymetric resolution for ecological studies led us to conclude that depth zones were an appropriate way to characterise the role of depth in nearshore ecosystems. We therefore stratified the study area by depth, using primarily ecological criteria. Finally, to create the BoPs, we intersected the Thiessen polygons (one layer for each source of substrate data) with the depth zones and the background substrate. We used decision rules to assign a final bottom type values to each resulting polygon, and to estimate a measure of confidence in this assignment based in part on the BoP size, and its proximity to a sampling point.

We illustrate our methodology using the Strait of Georgia (Fig. 3), BC, Canada as a case study. We used ArcGIS 9.3 (ESRI, 2008) for all spatial operations conducted in the BC Albers equal area projection. Many of the processing steps used to standardise and integrate the different data sets were coded in Python (Python, 2012) scripts to facilitate re-processing.

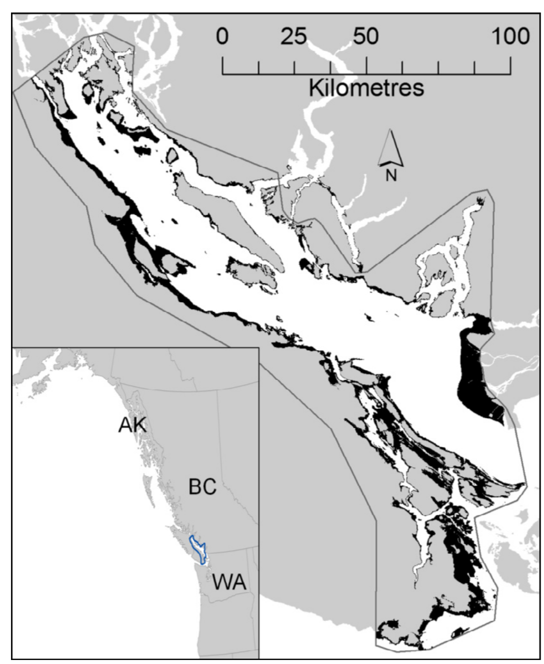

Fig. 3. The Strait of Georgia study area (black line) and the nearshore region (black), extending from land (light grey) to 50 m depth. Inset shows the location of the study area within the province British Columbia (BC), Canada.

2.1. Available data

Two types of bathymetric maps were available for our study area (Table 1). These included a 75 m raster produced by Natural Resources Canada (NRCan) from Canadian Hydrographic Service (CHS) sounding data, and depth polygons extracted from CHS electronic nautical charts previously compiled into a seamless polygon coverage (Ian Murfitt, Stock Assessment, Fisheries and Oceans Canada, personal communication). For the creation of the BoPs, we selected the polygon representation as it was much better resolved in the nearshore.

Through the NHWG, we identified six different sources of bottom type data. These included a variety of point and line features all with different attribute resolutions (Table 1).

ShoreZone is one of the most extensive continuous, spatial data sets in the world. The data, line features nominally associated with the high water line, describe the biophysical characteristics of the shoreline, and are based on an intertidal mapping process using oblique video imagery conceived by the BC government in the late 1980s. A biotic component was added in the early 1990s, followed by an estuarine component in the late 1990s (Howes, 2001). As such, the BC data represent the pilot or prototype version of the ShoreZone data now been collected throughout the Pacific Northwest (see Harney et al., 2008).

In addition to ShoreZone, we identified three observational and two grab sampling data sets containing substrate data for our

Table 1
Description of data sets used in this study, organised by their role in the study, with the six bottom type data sets classified as either observational or grab data. See text for details.

Data set	Feature type	*N*	Attribute resolution	Source[1]	Role
Bathymetry	Polygon	na	Depth range	Murffitt	Depth zones
ShoreZone	Polyline	6532	35 Classes	BC	Observation
Shellfish dive surveys	Points	2648	11 Classes, compound	DFO	Observation
Herring dive surveys	Lines	2099	7 Classes, compound	DFO	Observation
Parks Canada survey	Points	243	Narrative	PCA	Observation
Hydrographic surveys	Points	18721	38 Classes	CHS	Grab
Groundtruthing surveys	Points	914	16 Classes	CHS	Grab
Bathymetry	Raster (75 m)	na	Metre	NRCan	Background
Tidal energy	Point	na	Continuous	Foreman	Background

[1] Source abbreviations are: Murffit (Ian Murffit, personal communication); BC (Province of British Columbia); CHS (Canadian Hydrographic Service); DFO (Fisheries and Oceans Canada, Stock Assessment Group); PCA (Parks Canada Agency); NRCan (Natural Resources Canada, Geological Survey of Canada); Foreman (Mike Foreman, personal communication).

study area (Table 1). The observational data included shellfish and herring spawn dive samples collected by Fisheries and Oceans (DFO) stock assessment groups, and a regional survey conducted for Parks Canada (W.C. Austin, unpublished data). The grab samples obtained were collected by CHS as part of regular hydrographic surveys and during more recent multibeam groundtruthing surveys.

Each of the observational data sets required pre-processing to generate a set of bottom type points suitable for our analysis. For example, observations from stock assessments were related to a transect perpendicular to shore, with a single GPS reference point. We integrated these data into our study by creating a single point within each depth zone (defined below) crossed by the transect. Pre-processing of the herring data required tidal heights corrections as depths were referenced to dive gauge pressure. The Parks Canada regional survey contained narrative site descriptions which required pre-processing into the common bottom type codes defined. The inclusion of this data set demonstrates how qualitative field observations can be integrated into the methodology. Further pre-processing details would distract from the main points of this article, and be of limited interest since such pre-processing will be specific to each data set.

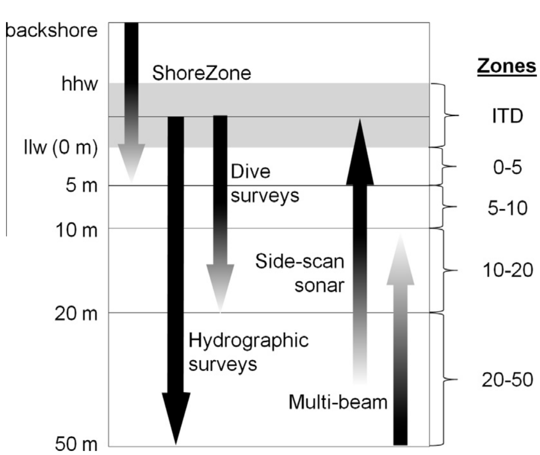

Fig. 4. Approximate depth distribution of various bottom type sampling methods in relation to the depth zones defined for the bottom patches. ShoreZone data captures the shoreline and intertidal (ITD) zone (defined as the area between high high water (hhw) and low low water (llw)), while dive surveys typically collect bottom type data as part of stock assessment surveys. Hydrographic surveys are conducted using a variety of methods to measure depth and sample bottom type. These include acoustic methods (side-scan and multi-beam sonar) that record depth and reflectance – a proxy for bottom type. Shaded arrows imply level of effort (lighter = less effort) in relation to depth.

The grab samples collected as part of hydrographic surveys represented the largest and most broadly distributed bottom type data set available to our study. These data have variable (though often high) resolution spatial coverage throughout the study area. The data range from old lead-line samples to those collected with more contemporary mechanical grabs. CHS also provided sampling data from more recent grab surveys collected to support multibeam classification of the Strait of Georgia. Unlike the hydrographic samples, these data were recorded with a consistent set of bottom type attributes.

2.2. Depth zones

We divided the nearshore into five zones according to our understanding of nearshore ecology. We found that the variety of methods used to sample bottom type within the white strip corresponded well with these ecologically defined depth ranges (Fig. 4).

The intertidal zone (ITD), bounded by the high high water (hhw) and low low water (llw) lines, is the most dynamic of the nearshore zones being subject to both the highest wave action and regular tidal exchange. Aerial surveys (e.g., ShoreZone) provide the most comprehensive description of bottom type in this zone. The 0–5 m zone can be considered ecologically distinct because of high illumination and significant wave action. It contains the densest concentration of sampling from dive surveys. The 5–10 m zone receives less frequent wave disturbance and intermediate light levels. The ecological significance of the 10 m contour is evidenced by both changes in community composition (O'Clair and Lindstrom, 2000) and in substrate type (DFO Shellfish stock assessment divers, personal communication). This zone is subjected to a mix of sampling procedures (Fig. 4), with dive, grab, and acoustic sampling being applied. It is the area of greatest overlap between the various sampling methods. The 10–20 m zone represents the limit of the photic zone and, in the Strait of Georgia, although severe storm waves may reach 35 m deep, typical waves (i.e., wave height ~1 m, period ~5 s) are only likely to suspend sand-sized sediment to approximately 10–15 m depths (Komar, 1998), making 20 m the practical limit of wave-disturbed sediments. Sampling of this zone is sparser as both dive and hydrographic sample resolution decreases with depth. We included the 20–50 m zone in our area of interest primarily as a boundary region with deeper waters. It is the zone where acoustic sampling dominates, and may thus provide a reasonable interface through which our BoPs could eventually be linked to emerging acoustic-based classifications of deeper waters. Deeper waters in BC have a more consistent and generally softer bottom type due to the region's geological history (Cannings and Cannings, 1996) and the reduced energy at depth. This reduction in spatial variability likely leads to a corresponding reduction in ecological variability, suggesting lower resolution classifications may be more appropriate in these deeper zones.

2.3. Standardising bottom type

Descriptions of bottom type depend on the sampling method used, with each providing a different perspective on the nature of the sea floor. For example, the comprehensive coverage from video and acoustics supports descriptions of geomorphology (i.e., form), but must make significant assumptions about the composition of the sediment. In contrast, point sampling (e.g., grab samples and dive surveys) can provide a more accurate description of sediment type, but a high density of points is required to provide an indication of form. The diverse sampling methods lead to different nomenclatures and attribute resolution for bottom type (i.e., Table 1). We therefore developed a common set of bottom type attributes to allow the different data sources to be combined.

We considered adopting an existing classification system (e.g., the Folk classification – Folk, 1968), but the attribute resolution of many source data sets do not support this level of detail, nor is grain size or sediment composition always necessary for ecological studies. Instead, we focused on deriving classes that could accommodate the available source data, while remaining ecologically significant (defined as being sufficiently resolved to identify the biologically important features).

We adopted a Bottom Patch Type (BType) description based on substrate rather than form because the three deepest zones (5–10 m, 10–20 m, and 20–50 m) are sampled almost exclusively with point data. We also recognised the need to integrate detailed data with more general information. As with the depth zones, we were guided by ecological relevance which in this case relates to the role of bottom type in providing habitat for either infaunal or epifaunal organisms. We settled on a hierarchical classification system where the primary classification captures the general nature of the bottom (hard, soft, mixed) and, if supported by the data, a secondary classification to describe the relative complexity within each primary class, essentially capturing the form (Table 2).

The Primary classification (Hard – ***1***, Mixed – ***2***, Soft – ***3***) recognises that immobile substrates (Hard) will typically support sessile communities of plants and animals. Hard substrates include bedrock as well as boulders and cobbles; boulder-cobble veneers are quite common in the BC nearshore, and are more likely to occur over glacial till (a composite of mud, sand, pebble, cobble, and boulder) than over bedrock (J. Harper, personal observation). We included a Mixed substrate class to capture the patchy nature of nearshore substrate such as sand-mud drapes over bedrock, and discontinuous veneers of boulder-cobble over a sand bottom. Such patchy substrates are likely to support a mix of fixed sessile and infaunal communities. Soft substrates such as muds and sands usually do not support stable, sessile plant communities (eelgrass beds and sea pens being important exceptions). The biomass in soft substrates is therefore typically dominated by infaunal animal communities. Pebble-sand, sand, and mud were the most common types of soft-sediment seabed substrates.

For each of these three primary classes, we added a secondary code (***a*** or ***b***) if information was available to describe the dominant structure of the BoP. For example, Hard bottoms can be comprised of either bedrock or large boulders and cobble; mixed areas can be either hard over soft (e.g., boulders on sand) or soft over hard (e.g., mud over bedrock); and soft bottoms can be comprised of sand or mud. We therefore used an 80:20 rule to subdivide the primary classes by form (Table 2). While somewhat arbitrary, this threshold assumed that ecosystem function of a particular patch will be largely determined by the dominant class (i.e., if there is more than 80% veneer of boulder-cobble over sand, then the dominant ecosystem function will be related to the hard substrate). The resulting organisation of the six BType codes, from ***1a*** to ***3b***, represents a relative ordering of particle size and can thus be considered a modified Folk system. The scheme allows both coarse and fine resolution attributes to be included, thereby accommodating the diverse classifications used in the source data.

We had to associate the bottom type classes from each source data set to the BType codes individually. We combined ShoreZone's 35 coastal classes with an exposure covariable to derive a mapping to BTypes (Table 3). Bottom Quality (BQ) values extracted from digitised hydrographic field sheets contained 25 feature codes reflecting the dominant and secondary bottom type (e.g., BS represented primarily boulders with some sand, while SB represented primarily sand with some boulders). This schema mapped well to our BType hierarchy (Table 4). The more current set of CHS grab samples used the modified Folk system which also mapped well to our BType classes (Table 4).

Although scientific dive surveys typically focus on the habitat needs of particular species, the DFO Shellfish group uses the same codes across species, allowing a common mapping to be developed (Table 5). However, the data record a dominant, secondary and sometimes tertiary substrate class, occasionally making the assignment of a secondary code unambiguous. The herring data contained only a dominant substrate type, requiring us to assume that when boulders, cobble or pebbles were recorded, they were dominant over soft substrate. The narrative descriptors contained in the Parks Canada data easily translated to a primary code, but

Table 2
Bottom type (BType) classification system adopted for the Bottom Patches (BoPs) in the Strait of Georgia.

Primary and secondary bottom type categories	Code	Bottom type description
Hard	1	Immobile substrates that support well-developed epibenthic communities, with a low likelihood of infaunal organisms
Bedrock dominant	1a	Largely (>80%) bedrock, with little relief in terms of boulders or corals. May contain some patches of sand/mud/other
Boulder dominant	1b	Largely (>80%) dominated by boulders and cobbles; crevices amongst boulders provide habitat complexity; some soft sediment may exist below the boulder-cobble armour layer and support some infauna
Mixed	2	Mix of hard and soft substrate with a likelihood of both infaunal and epibenthic communities represented
Soft surface, patchy distribution of larger particles	2a	Mix of soft sediments with patchy distribution of larger particles (cobble, boulder) with overall cover <80%. Diverse biota expected with both infaunal and epilitho communities
Soft surface, overlaying hard substrate	2b	Mix of soft sediments distributed over bedrock with patches not to exceed 80% cover. Epibenthic-dominated community expected with potential for some infaunal organisms
Soft	3	Unconsolidated bottom type with negligible hard components. Very low likelihood of epibenthic organisms
Sand/shell	3a	Sand or shell dominant (>80%) potentially mixed with larger particles to granules
Mud	3b	Mud dominant (>80%) potentially mixed with larger particles to granules

Table 3
Assignment of Bottom Types based on ShoreZone wave energy (VE – very exposed; E – exposed; SE – semi-exposed; SP – semi-protected; P – protected; VP – very protected) and coastal classes (1 through 35). No value indicates the combination does not occur. See Harney et al. (2008) for ShoreZone technical details.

ShoreZone coastal class	ShoreZone wave exposure class					
	High		Moderate		Low	
	VE	E	SE	SP	P	VP
1. Rock Ramp, wide	1a	1a	1a	2b	2b	2b
2. Rock Platform, wide	1a	1a	1a	2b	2b	2b
3. Rock Cliff	1a	1a	1a	2b	2b	2b
4. Rock Ramp, narrow	1a	1a	1a	2b	2b	2b
5. Rock Platform, narrow	1a	1a	1a	2b	2b	2b
6. Ramp with gravel beach, wide	1a	1a	2a	2a	2a	2b
7. Platform with gravel beach, wide	1a	1a	2a	2a	2a	2b
8. Cliff with gravel beach	1a	1a	2a	2a	2a	2b
9. Ramp with gravel beach	1a	1a	2a	2a	2a	2b
10. Platform with gravel beach	1a	1a	2a	2a	2a	2b
11. Ramp w gravel and sand beach, wide	2b	2b	2b	2b	2b	2b
12. Platform w gravel and sand beach, wide	2b	2b	2b	2b	2b	2b
13. Cliff with gravel/sand beach	2b	2b	2b	2b	2b	2b
14. Ramp with gravel/sand beach	2b	2b	2b	2b	2b	2b
15. Platform with gravel/sand beach	2b	2b	2b	2b	2b	2b
16. Ramp with sand beach, wide	2b	2b	2b	3a	3a	3b
17. Platform with sand beach, wide	2b	2b	2b	3a	3a	3b
18. Cliff with sand beach	2b	2b	2b	3a	3a	3b
19. Ramp with sand beach, narrow	2b	2b	2b	3a	3a	3b
20. Platform with sand beach, narrow	2b	2b	2b	3a	3a	3b
21. Gravel flat, wide	1b	1b	2a	2a	2a	3b
22. Gravel beach, narrow	1b	1b	2a	2a	2a	3b
23. Gravel flat or fan	1b	1b	2a	2a	2a	3b
24. Sand and gravel flat or fan, wide	2a	2a	2a	2a	3a	3b
25. Sand and gravel beach, narrow	2a	2a	2a	2a	3a	3b
26. Sand and gravel flat or fan, narrow	2a	2a	2a	2a	3a	3b
27. Sand beach, wide	3a	3a	3a	3a	3a	3b
28. Sand flat	3a	3a	3a	3a	3a	3b
29. Mudflat	–	–	3b	3b	3b	3b
30. Sand beach, narrow	3a	3a	3a	3a	3a	3b
31. Estuaries, marshes	–	–	3a	3b	3b	3b
32. Man-made, permeable	1b	1b	2a	2a	3a	3b
33. Man-made, impermeable	1a	1a	2b	2b	3a	3b
34. Channel	2a	2a	2a	2a	2a	2a
35. Glacier	–	–	2a	2a	2a	3b

a secondary code was only assigned when the description was unambiguous.

2.4. Creating the background substrate layer

Our approach includes a background bottom type to avoid the unrealistic extrapolation of point data across larger distances. While a substrate layer exists for BC waters (Zacharias et al., 1998), it is poorly resolved, particularly in the nearshore, and has limited (i.e., hard, sand, mud) attribute resolution. We therefore created a simple background bottom type based on an estimate of bottom roughness and tidal energy.

We derived bottom roughness from the NRCan bathymetric model (75×75 m^2). We assigned each pixel one of three roughness classes based on the natural breaks in the standard deviation of depth among its immediate neighbours (focal statistics; ESRI, 2008). This measure captures steep areas and areas with highly variable bottom depth, both of which have a higher likelihood of exposed hard substrate. We obtained maximum bottom tidal energy from Foreman et al. (2008) and created a 50×50 m^2 raster which we classified into low (<15 cm/s), medium and high ($\geqslant$60 cm/s) erosion velocities based on Hjulström curves for sediment transport. The low threshold was the limit for sand transport, while the high value was the velocity at which coarse material begins to erode (Hjulström, 1935).

We created the background substrate using a simple combination of these roughness and energy classes. We classified any pixel with low velocity as soft, while a hard classification required at least medium roughness and energy. Intermediate values were assigned a mixed substrate (Table 6).

The relatively coarse resolution of these background data meant that some nearshore areas were incorrectly represented as land pixels. However, we found this had no effect on our results as these (shallower) areas were comprehensively covered by the ShoreZone data.

2.5. Creating bottom patches

After standardising the bottom types across our six source data sets, we merged them into observational and grab data sets so that we could use different integration rules for the two types of data. This also simplified the BoP processing by reducing the data sets processed. We converted the grab and observational data sets into Thiessen polygons, producing a polygon layer for each data type.

To process the ShoreZone data, we extracted the line vertices, created Thiessen polygons for each vertex, and dissolved the resulting polygons according to the line segment code. This essentially turned the ShoreZone line into a polygon extending both landward and seaward. We preferred this approach to using only the midpoint of each line segment because we found it improved the alignment of polygon boundaries with the ends of the ShoreZone line segments.

These three polygon layers (Grab, Observation, and ShoreZone) represent the initial extrapolation of original six source data sets. Within each layer, the size of the polygons depend on the local sample density, and is not necessarily a reflection of either the true

Table 4
Classification of CHS Grab sample and Bottom Quality codes into Bottom Type (BType) codes assigned to Bottom Patches.

Primary and secondary Bottom Type category	BType Code	CHS Bottom Quality Codes	Grab sample codes *(Modified Folk)*
Hard	1	BQHD – hard BQRC – rock DLRA – rock awash DLRK – rock below datum DLRKREP – reported DLSF – intertidal rock	
Bedrock dominant	1a	–	R – bedrock
Primarily boulders	1b	BQBO – boulder DLBE – boulder BQBS – boulders and sand BQBG – boulder gravel BQSN – shingles	B – boulders
Mixed (unconsolidated)	2		
Primarily soft substrate with patchy cobble/gravel	2a	BQCA – coarse BQCO – cobble	
Sand to pebbles	2b	BQPB – pebble BQGR – gravel	G – Gravel sG – sandy Gravel mG – muddy Gravel msG – muddy sandy Gravel shG – shell hash with Gravel
Soft	3		
Sand/shell	3a	BQGS – gravel sand BQSO – sand BQSD – sand BQSG – sand gravel BQSH – shell BQSS – sand shell BQSM – sand mud BQWS – weed sand	S – Sand mS – muddy Sand gS – gravelly Sand gmS – gravelly muddy Sand shS – shell hash with Sand
Mud	3b	BQCY – clay BQFN – fine BQFS – fines and sand BQMD – mud BQMG – mud gravel BQMS – mud sand BQOZ – ooze	M – Mud sM – sandy Mud gM – gravelly Mud gsM – gravelly sandy Mud

bottom type, or its extents. Thus, to limit unreasonable extrapolation in areas of sparse data, we applied two filters. First, we intersected each set of polygons with the depth zones (using the ArcGIS Union function) and discarded the polygons that did not contain points. In this way, we limited the extrapolation of each point to its depth zone. Second, we restricted the ShoreZone polygons to the shallowest two depth zones (ITD and 0–5 m), since we found that its extrapolation beyond 5 m depth did not agree with the other data sources.

We joined these filtered polygons layers together with the background substrate using the Union operation to make the final set of BoPs. As with the operation described above, this produced fragments that did not contain points. However, because in this case the fragments were created from the filtered source polygon layers, they represent areas of shared influence rather than unrealistic extrapolation – many BoPs were the product of one or more parent polygons. We used each BoP's lineage along with the distance from each BoP to the nearest point in each source layer, to assign BType when multiple data sources overlapped, or when a BoP did not contain a source point.

BoPs containing a point were simply assigning the BType of that point. For BoPs not containing points, we assigned BType based on depth zone, the source polygons, and if necessary, the nearest sampling point. In the ITD zone, we preferentially assigned BType according to the ShoreZone data. In the subtidal zones we prioritised observational or grab BTypes if their Thiessen polygons influenced the fragment. If both observational and grab samples influenced the fragment, and both source points occurred within 500 m, then the value from the closest sample point was assigned. If no source point was within 500 m of the fragment, the ShoreZone value was assigned in the 0–5 m zone, while the background value was assigned in the deeper zones.

We simultaneously assigned a simple Confidence score (BConf) to each BoP based on the characteristics of its source data: We assigned BoPs containing a sample point BConf = 4, while those in the ITD or with source data points within 100 m were assigned BConf = 3. We assigned BConf = 2 when the source was between 100 and 500 m distant, and 0 if there was no point within 500 m (i.e., when background values were used). For fragments influenced by multiple points, we used BConf to indicate the level of agreement between the sources. We assigned Conf = 33 when all three sources (i.e., ShoreZone, grabs, and observational) influencing the fragment agreed; and Conf = 22 when 2 of 2 sources agreed. In contrast, we assigned Conf = 12 when two sources disagreed, and 13 when three sources influenced the fragment, but all disagreed. This simple confidence scheme is an example of how the BType assignments can be ranked based on their source data. Such a scheme can be considerably more complex if desired.

The analysis created 103,824 polygons ranging in size from less than 1 m^2 (n = 1039) to over 10^6 m^2 (1 km^2; n = 99). Many of these polygons, particularly the smallest ones, were similar to their neighbours in terms of BType, BConf, or both. We therefore set a threshold of 4 m^2 as the minimum BoP size, and merged the smaller fragments with their largest adjacent neighbour with the same BType. The final layer contained 101,770 BoPs for the study area (e.g., Fig. 5).

A total of 29% of the BoPs were in the ITD zone, and therefore determined by the ShoreZone data. In the subtidal about 17% of the BoPs contained sample points, while only 5% were more than

Table 5
Bottom type (BType) classification of shellfish and herring survey data.

1° BType Code	Primary and secondary BType descriptions	2° BType Code	Shellfish codes recorded for each unit (1-10 m^2) sampled		Herring substrate
			Substrate 1	Substrate 2	
1	Hard				
	Bedrock dominant	a	1	All values	Rock
			2	1, 5 to 11, 0, null	
	Bedrock dominant	b	2	3, 4	Boulders Cobbles
			3	All values	
			0	3	
			4	1, 2, 3, 5, 6, 11, null	
			5, 6, 7, 8, 10, 11	1, 2, 3, 4	
2	Mixed (unconsolidated)				
	Primarily soft substrate with patchy cobble/gravel	a	4	7, 8, 9, 10, 11, 0	
			5	6, 7, 8, 9, 10, 11, 0, null	
			6	5, 7, 8, 9, 10, 11, 0, null	
			11	4, 5, 6	
	Sand to pebbles	b	0	4, 5, 6, 11	Pebbles
			7, 8, 10	5, 6	
			11	7, 8, 9, 10, 0, null	
3	Soft				
	Sand/shell	a	0	7, 8, 10	Sand, shell
			7	8, 9, 10, 0, null	
			8, 10	7, 9, 10, 0, null	
	Mud	b	0	9, null	Mud
			9	All values	

Shellfish codes: 1. bedrock smooth, 2. bedrock crevices, 3. boulders, 4. cobble, 5. gravel, 6. pea gravel, 7. sand, 8. shell (old code), 9. mud, 10. crushed shell, 11. whole shell, 0. wood debris.

Table 6
Background substrate based on bottom roughness and modelled bottom tidal velocity.

	Roughness		
Tidal energy	Low	Medium	High
Low	Soft	Soft	Soft
Medium	Mixed	Mixed	Hard
High	Mixed	Hard	Hard

500 m from any sampling point. Not surprisingly, the largest polygons were classified as Soft and generally occurred in the 20–50 m depth zone. In terms of proportions, bottom types were fairly evenly distributed across the primary categories, and Hard samples were less often assigned to a sub-category than Mixed or Soft samples (Fig. 6). Despite the largest polygons being classified as Soft, Hard classification was dominant in the 20–50 zone, while being almost absent in the ITD (Fig. 7). This rather unintuitive result is likely due to inherent biases in the dominant sampling methods in these two zones (see Discussion).

2.6. Model evaluation

We evaluated our BoPs in two ways: First, we compared the BType assigned to our BoPs to the bottom type derived from a morphological analysis of a portion of the study. We then considered the ecological performance of our BoPs by comparing them to two independent data sets describing the spatial distribution of commercial shellfish.

Greene and Barrie (2011) recently completed a morphological classification of the southern Strait of Georgia using a manual, interpretive analysis of bathymetry, rugosity, and multibeam backscatter information. We compared the general bottom type characteristics (hard, mixed, soft) assigned to the resulting geomorphological units (Fig. 8a) to the primary substrate assigned to our BoPs in the same region (Fig. 8b) by intersecting the two maps, effectively assigning the NRCan classification to the BoPs they overlay. Applying Kendall's Tau correlation test to the resulting paired bottom type measures (Fig. 8c) showed significant correlation ($z = 34.8$, p-value < 2.2e−16, tau = 0.2).

We evaluated how well our BoPs performed in ecological terms by comparing them to shellfish data not included in the creation of the patches. We overlaid red sea urchin fishing data and geoduck beds used for stock assessment onto the BoPs and assessed how well observations of these species were distributed across our primary substrate classes.

The geoduck clam (*Panopea generosa*) occurs in the eastern North Pacific from Alaska to the Gulf of California, from the intertidal zone to at least 110 m depth, occupying deep, soft substrates (DFO, 2011). This substrate requirement aggregates geoducks into beds. In Pacific Canada, these beds were originally delineated based harvest information and have been refined in recent years by dive and acoustic surveys because the geoduck fishery is managed on a by-bed basis. Approximately 2300 beds have been identified along the BC coast with 324 in the Strait of Georgia. We used the latest spatial delineation of the geoduck beds to assess how well they were captured by our BoPs.

Red sea urchins (*Strongylocentrotus franciscanus*) occur throughout the North Pacific Rim from Baja California to Hokkaido Island, Japan. The largest of five sea urchin species occurring in BC, the red sea urchin is usually found on rocky substrates in shallow waters with moderate to strong currents, typically from the intertidal to 50 m depth. DFO collects digitised harvest locations (as polygons) from harvesters as a condition of license. We used harvest locations from the years 2000 to 2009 to evaluate how well hard, urchin-bearing areas were represented by the BoPs.

We intersected the evaluation data sets with the BoPs and looked at the proportion of spatial overlap by substrate category. We hypothesised that the majority of the red urchin fishing areas would fall over hard substrate while the majority of geoduck beds would occur in areas predicted to have soft substrate. We compared the equality of bottom type proportions within and outside of the fishing areas using Pearson chi-square test. We used integer measures of total proportion of the overlap area as the test requires

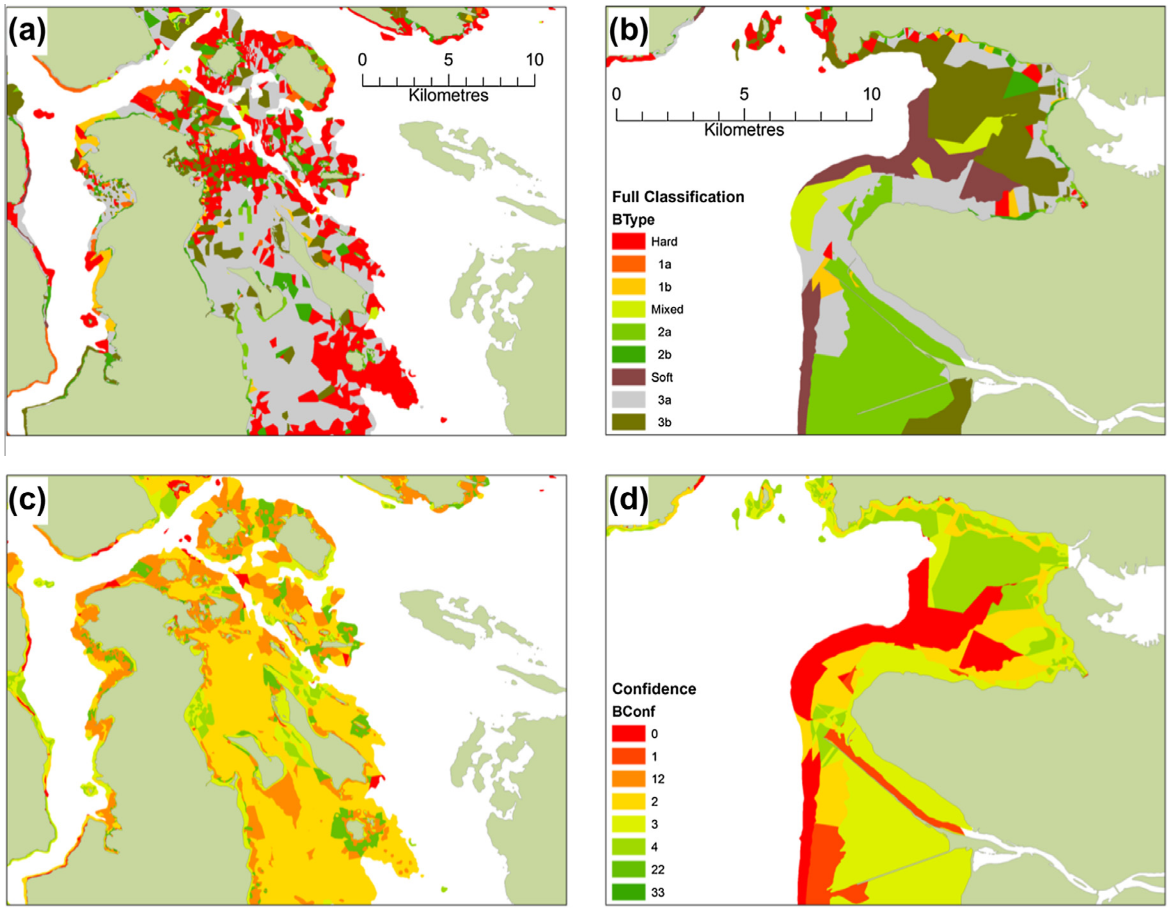

Fig. 5. Example of Bottom Patch Classification (BType –a, b) and confidence (BConf –c, d; low = red; high = green) for two representative areas with high (a, c) and low (b, d) expected heterogeneity.

frequencies, and because it is the proportion in the total overlapping area that was the important factor, not the number of overlapping locations.

We found that 75%, 5% and 17% of the red urchin fishing area overlaid BoPs with Hard, Mixed and Soft substrates, respectively. Conversely, 34%, 8% and 58% of the geoduck bed area corresponded with Hard, Mixed and Soft substrates. These proportions were significantly different to the proportions of the bottom types found outside of the fishing areas (red urchin: $X^2 = 408$, $df = 8$, $p \ll 0.001$; geoduck: $X^2 = 163$, $df = 8$, $p \ll 0.001$) indicating that BoP's substrate allocation in areas of overlap was significantly different from areas with no overlap. The BoPs thus performed well in capturing these ecological characteristics.

3. Discussion

3.1. Using bottom patches

We emphasise that our BoPs are not an ecological bottom classification as generally conceived (e.g., Roff et al., 2003). Rather, they represent a synthetic data layer necessary for any meaningful marine classification. The BoPs define spatial units, delineated by depth and the best available bottom type information, to which other known physical attributes can be attached. This makes them equivalent to other maps describing "potential benthic habitats", based on multibeam backscatter data (e.g., Greene et al., 2005). However, we believe maps delineating abiotic features are better referred to as bottom type or substrate maps, and prefer the term habitat to be reserved for maps that explicitly include a biological component.

Nevertheless, bottom type is a determining habitat characteristic for many nearshore species, and we expect our BoPs will support the development of species-specific habitat maps in the nearshore environment. Such maps are an important type of classification for stock assessment and biodiversity assessments, and are central to implementing marine EBM (Cogan et al., 2009). The BoPs will also support the delineation of important marine features (sensu Gregr et al., 2012) necessary for defining Ecologically and Biologically Sensitive Areas (EBSAs) in on-shelf regions. In combination with a coastal land use layer, the BoPs can also support analyses of land–sea interactions, including the identification of sensitive coastal areas and the potential adverse impacts of terrestrial stressors on the nearshore.

Several aspects of the BoP's design are intended to maximise their utility for this diversity of applications. First, the associated database retains all the necessary information on the source data. Second, the patch boundaries provide a primitive spatial unit of reference to which other data (e.g., exposure, currents, species abundance) can be assigned, thereby ensuring they are initially represented at the best available resolution. The attributed, primitive BoP polygons can then be aggregated into larger patches according to the needs of any subsequent analysis, providing maximum flexibility. This ability to derive need-specific data layers from the primitive BoPs is one of the greatest strengths of these data. Classifications with more singular goals (e.g., Marine Protected Areas) are less adaptable, and less suitable for data synthesis (Cogan et al., 2009). Additionally, many such classifications, while claiming to delineate habitats, actu-

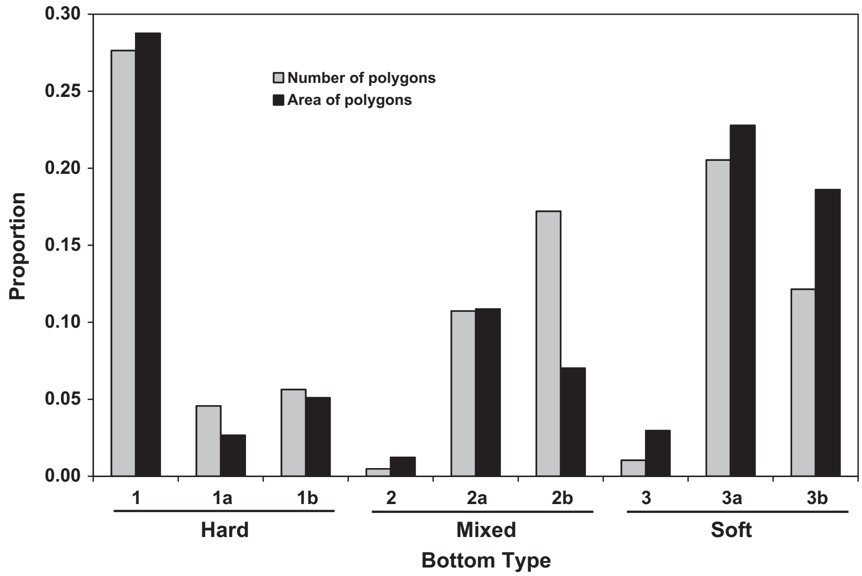

Fig. 6. Proportion of each bottom type (see Table 2 for descriptions) by number of polygons (grey bars) and by polygon area (black bars).

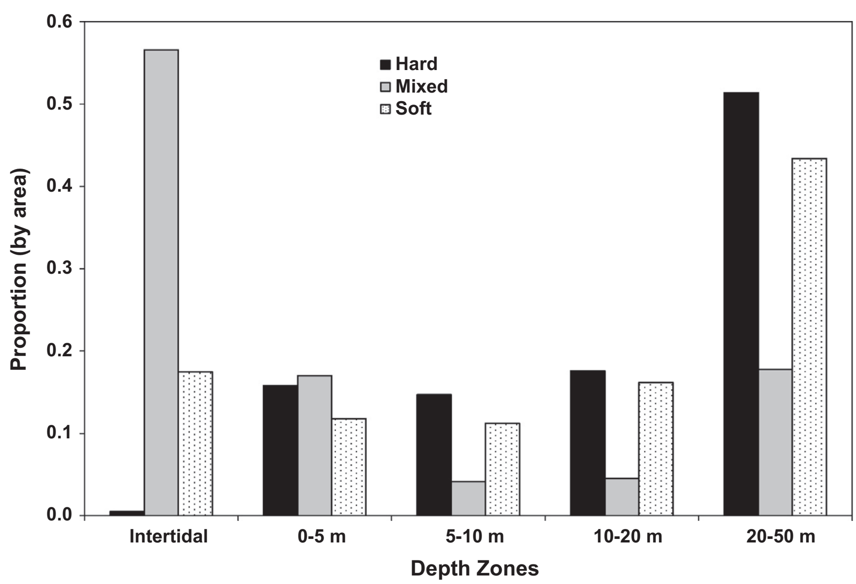

Fig. 7. Proportion (by area) of primary bottom type classes (Hard, Mixed, Soft) across the five depth zones in the study area.

ally make untested and usually implicit assumptions about biological significane (Gregr et al., 2012).

3.2. Design retrospective

A number of key design decisions were the focus of extensive discussion by the NHWG. These included how best to represent bathymetry, how to deal with the relative nature of benthic patchiness, and the dynamic nature of the nearshore. To assist others considering these or similar questions, we offer a brief overview of these issues and the rationale adopted by the NHWG to support this work.

Bathymetry forms the backbone of any benthic mapping effort. The data used, and their representation are therefore fundamental design decisions. While the attraction of using the highest resolution data (i.e., from multibeam surveys) was strong, multibeam data will remain relatively rare, particularly in the nearshore, for the foreseeable future. Depth polygons from digital marine charts were attractive because they accurately represented the coastline, completely captured the nearshore region, and were available throughout the area of interest. Their one shortcoming was that they reflect chart resolution, and thus vary in the ranges represented. This led us to consider what constituted a sufficient bathymetric resolution for ecological studies. We argue that in nearshore ecosystems, depth is actually a proxy for wave energy and light penetration, two factors correlated with depth that are more closely related to ecological function. Thus, the absolute depth at any point has less ecological relevance than the abiotic conditions encountered at the bottom. We concluded that these conditions would be better represented by stratifying the bottom according to ecological characteristics rather than using absolute measures of bathymetry.

The decision to use polygons rather than a raster (i.e., grid) to represent the depth zones thus stemmed in part from the source data used. However, polygons provide a number of advantages in this context. First and foremost is their computational efficiency.

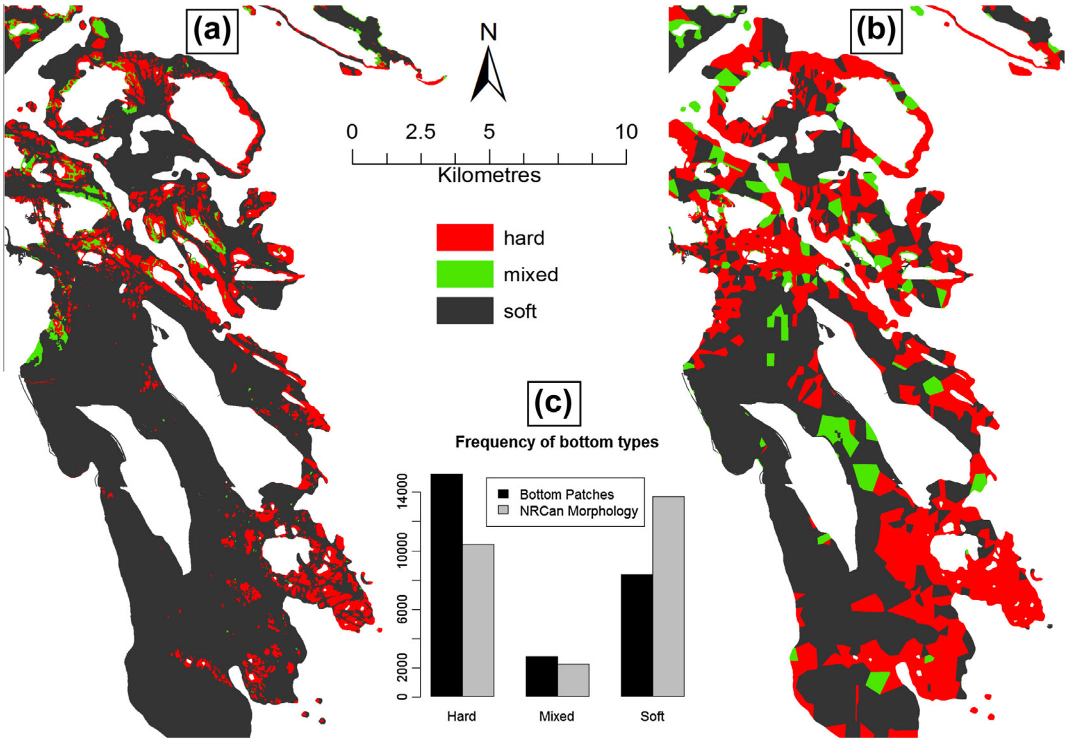

Fig. 8. Hard, mixed, and soft bottom types according to (a) a traditional morphological analysis based on bathymetry, rugosity, and multibeam backscatter information (from Greene and Barrie, 2011), and (b) the bottom patches derived herein for a portion of the study area. The frequency of the different bottom types (c) shows that the bottom patches tend to be biased towards hard assignment, possibly at the expense of soft bottom types.

Rasters require a performance trade-off between extents and resolution: high resolution analyses over large spatial extents are computationally expensive. Rasters must also use rectangular extents, often inculding large regions irrelevant to the analysis (i.e., land). Most importantly, rasters use a fixed, pre-defined resolution onto which results are interpolated. This obfuscates the resolution of the source data since it is unclear on a raster whether an area is homogeneous or under-sampled. In contrast, polygons allowed the BoPs to represent only the area of interest, using a variable resolution determined by the density of the source data. The result is not only better overall performance, but also a visual indication of source data density. The polygons can therefore be considered a more honest representation of the source data than an interpolated raster. The polygon representation also simplified the creation of the BoPs by allowing straightforward spatial operations to be applied to the data, and facilitated the pre-processing of bottom type data with poor bathymetric precision. Finally, because the depth zones integrated polygons from a range of depths, this mitigated the problem of variable resolution among the depth polygons used as the source of the depth zones.

Another question we struggled with was how to best represent the true nature of substrate, particularly in terms of patchiness, or how variable the bottom type truly was. The patchiness of substrate is relative, depending strongly on the scale and method of measurement. Patchiness therefore tends to manifest itself differently for different disciplines using different sensors. Again, our discussions were facilitated by emphasising ecological relevance, and the realisation that role of environmental heterogeneity is determined by ecology, not any particular observation method. This means it is species-specific, for example some benthic species will be concerned about sediment size and composition (e.g., sandlance, see Robinson et al. this volume), while others (e.g., kelps) will be more influenced by the extent and patchiness of larger particles. This ecological relativism further supports our assertion that marine classifications must clearly distinguish between geophysical classes and habitats. By explicitly reflecting patchiness in the secondary classes within the implicit particle size represented by the primary hardness classes, our BoPs facilitate this linkage between species and bottom type.

Finally, we discussed the accuracy of the BoP boundaries in the context of a dynamic nearshore environment where sediment input is an ongoing process and where some (particularly soft) bottom types are in constant motion. This question is inseparable from the broader question of uncertain boundaries due to patchy data and extrapolation methods, and several relevant observations were made by the NHWG. First, by including energy and landside inputs, areas with more dynamic bottom types can likely be identified and included. Second, from a habitat perspective, most organisms will perceive the bottom type boundaries as relatively invariant, thus making the longer-term geophysical processes less relevant to the primary purpose of the BoPs. Third, the NHWG rejected the use of fuzzy boundaries to represent this uncertainty as it would make it more difficult to track variability arising at the resolution of the primitive BoPs once they were aggregated. Finally, uncertainty about boundaries emphasises the point that mapping bottom type is best seen as an on-going process. This highlights the value of a transparent, repeatable process. through which any changes due to geophysical processes or improved sampling will eventually be captured.

3.3. Model performance

The significant correlation between the BoPs and the more traditional form-based classification demonstrates that the BoPs provide a reasonable approximation of primary bottom type. However, there is a clear bias in the BoPs towards hard substrate in the deeper depth zones, which is also reflected in the ecological evaluation which associated 34% of geoduck beds with hard substrate.

We believe this is due to two factors. First, the method yields larger patches when sampling is sparse. Thus, unless the true bottom type in the location is homogenous, the extrapolation of a single point sample will over-estimate the size of its particular patch. The second factor is the inherent bias in grab sampling.

Successful grabs samples allow accurate separation of the soft classes (i.e., between BTypes 3a, and 3b). However, when a grab sample is not obtained, bottom type is reported as hard, and unless the point sampling is sufficiently dense, there is no way to distinguish the heterogeneity of the sampled area. In this way, grabs reported as hard will bias the bottom type characterisation against mixed classes, leading to more patches described as hard. In contrast, observations of the bottom explicitly describe patchiness and thus do capture the harder mixed classes (e.g., boulders or gravel on soft) well. However, these methods are less able (compared to grab samples) to distinguish sediment composition. Thus, shallower depths sampled predominantly with observations (e.g., ShoreZone, dive surveys) will contain a higher proportion of mixed bottom types (e.g., the ITD zone – Fig. 7), while at depth, the abundance of grab samples leads to the dominance of Hard BoPs.

Fundamentally, the objective is to correctly identify whether an area is truly patchy (e.g., Fig. 5a), or whether it has a more homogeneous bottom type (e.g., Fig. 5b). The challenge is that while patchy areas emerge from relatively coarse sampling, it is difficult to distinguish homogeneous areas from those that are under-sampled. This leads to the question of how dense point sampling needs to be to accurately make this distinction. One indication of sufficient sampling is the level of agreement among adjacent samples, reflected in both the BType and confidence assignments. Areas with low agreement may be considered mixed or patchy, depending on the observer's assumptions about the distance to which the point samples can be extrapolated. This is inseparable from the question of correctly bounding the BoPs, because a patch defined as mixed may, with increased sampling resolution, decompose into smaller, homogeneous patches. The identification of mixed patches is therefore clearly influenced by sampling resolution. However, because sampling requires a trade-off between resolution and extent, an increase in sampling resolution often leads to more detail but about less area. This is a troublesome, but unavoidable dilemma when striving for a continuous coastwide coverage.

There is no easy answer to the question of what is the best, or correct resolution for a habitat patch. Rather, the question of model sufficiency is best answered by considering the purpose of the model (Rykiel Jr., 1996). Given our objective of creating a spatial framework for supporting EBM, the most reasonable performance metric for the BoPs is how well they contribute to our understanding of relevant ecosystem components, as demonstrated for urchins and geoducks. Further, since EBM needs to be applied over broad spatial extents, the utility of the BoPs to such efforts will likely depend less on perfect agreement with local representations of bottom type. We therefore argue that improvements to bottom type characterisation are best done from the perspective of ecological and management objectives rather than to slavishly attempt to create a 'perfect' representation of bottom type. Ecological performance should be the focus when evaluating the performance of any such maps.

3.4. Next steps

Extending the BoPs to deeper regions by integrating them with more traditional classifications is perhaps the highest priority task for future efforts. The 30–50 m zone was intended to provide an interface between the shallower BoPs, and deeper regions where acoustic backscatter classification can be efficiently applied. The integration of these data where they occur in the nearshore would also provide a valuable means of refining the BoP boundaries. Coupling the BoPs to a continuous description of bottom type in deeper waters would create a powerful data set extending from the high water line to the seafloor that truly encompassed all available data.

Developing methods for including other relevant data are also a priority. For example, ROV surveys are often conducted for stock assessment, although these surveys are generally conducted over small spatial extents and the data require considerable post-processing to extract bottom type. Nevertheless, the availability of this and similar observational data should be reviewed periodically as data collection and processing are on-going. Local knowledge is also likely to be quite valuable, particularly in remote areas with few sampling programs. Depending on the nature of the knowledge, such data could be used to augment either the database of bottom samples, or the background layer. Ideally, integrating such additional data will be possible without extensive processing, since biases are likely to increase with the number of assumptions required.

An update of the BC ShoreZone data would be extremely valuable to this and many other analyses on Canada's Pacific coast. The BC ShoreZone data are an early vintage (1990s), generated during the prototyping phase. ShoreZone has since evolved into a robust classification system that includes a well developed cross-shore component, characterising the shore from the supra-tidal to the subtidal (Harney et al., 2008). An updated version of these data would provide considerably more detail for the deeper zones.

The utility of the BoPs and similar data sets is enhanced by ensuring the appropriate attributes are available for subsequent analyses. To allow bottom type definitions to be reviewed, and the data to be updated and refined over time, links to the source data have been retained for each BoP. Design decisions will be required about how to summarise the data recorded for each BoP as they evolve into a full ecosystem representation. For example, how should multiple species associated with the BoPs be represented? The obvious choice of using a unique field for each species attribute (e.g., abundance, date of observation, etc.) would eventually lead to a very complex attribute database, potentially making the BoPs difficult to work with. An alternative is to list communities, but then indices like diversity and evenness could not be calculated. The challenge is to design a database that balances data completeness – which is necessary for ecosystem studies – while minimising complexity. Any resulting database will undoubtedly be a compromise between comprehensiveness and conciseness. The trick will be to maximise utility while striking this balance.

4. Conclusions

The BoPs presented herein represent the first, high-resolution characterisation of the nearshore (high water line to 50 m) in the Strait of Georgia ecosystem. Our method demonstrates how a collection of existing data sets, at various spatial scales, with variable attribute resolution, can be combined to create a 'best-available' representation of bottom type. The transparent, straightforward, quantitative nature of the approach means it can quickly be re-applied to integrate improvements in data quality and availability. We expect the BoPs to serve as the framework for the development of habitat suitability maps for a range of nearshore species including commercially important invertebrates (e.g., geoducks, urchins, clams), endangered species (e.g., abalone), and ecologically important species such as forage fish (e.g., sandlance – see Robinson et al. this issue).

By explicitly capturing the resolution of the underlying source data, the BoPs identify the most data deficient areas, as well as those that appear to have sufficient sampling. Combined with the associated confidence map showing the heterogeneity of the source data, these two pieces of information provide considerable insight into the spatial accuracy and bottom type assigned on the map. Also, by representing the best available resolution, the polygons can be treated as primitive spatial units, suitable for integration over larger areas if a coarser analysis is warranted. The question of whether the BoPs are sufficiently defined is best assessed using specific ecological or management objectives to evaluate their performance in each context. Focusing on how the BoPs contribute to such objectives will help maximise their utility.

Despite their imperfections, such bottom type maps are nevertheless needed to fill an important gap in nearshore ecology. By providing a generic description of the seafloor, we hope the product will be of broad utility across the different disciplines that contributed to its development. We will make the framework widely available so that researchers can continue to create, collate, and improve habitat maps at regional, national, and international levels. By serving as a platform to which physical and biological attributes can be assigned, the BoPs represent the first step in creating a spatial representation of the nearshore ecosystem.

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References

Anderson, J., Holliday, D., Kloser, R., Reid, D., Simard, Y., 2008. Acoustic seabed classification: current practice and future directions. ICES Journal of Marine Science 65, 1004–1011.
Cannings, R., Cannings, S., 1996. British Columbia: A Natural History. Greystone Books, Vancouver, BC.
Cogan, C., Todd, B., Lawton, P., Noji, T., 2009. The role of marine habitat mapping in ecosystem-based management. ICES Journal of Marine Science 66, 2033–2042.
DFO, 2010. 2010 Canadian Marine Ecosystem Status and Trends Report. Can. Sci. Advis. Sec. Sci. Advis. Rep., 2010/030 (Revised). Fisheries and Oceans Canada. Ottawa, ON.
DFO, 2011. Pacific Region Integrated Fisheries Management Plan – Geoduck and Horse Clam, January 1 to December 31, 2011. Fisheries and Oceans Canada. Nanaimo, BC. 34 p. + Appendices and maps.
ESRI, 2008. ArcGIS 9.3. Redlands. CA: Environmental Systems Research Institute.
Folk, R.L., 1968. Petrology of Sedimentary Rocks. Hemphills, Austin, TX.
Foreman, M.G.G., Crawford, W.R., Cherniawsky, J.Y., Galbraith, J., 2008. Dynamic ocean topography for the Northeast Pacific and its continental margins. Geophysical Research Letters 35, L22606.
Greene, H.G., Barrie, J.V., 2011. Shaded Seafloor Relief, Southern Gulf Islands and San Juan Archipelago, Canada and USA, Open File 6627. Geological Survey of Canada.
Greene, H.G., Bizzarro, J.J., Tilden, J.E., Lopez, H.L., Erdey, M.D., 2005. The benefits and pitfalls of geographic information systems in marine benthic habitat mapping. In: Wright, D.J., Scholz, A.J. (Eds.), Place Matters. Oregon State University Press, Portland, OR, pp. 34–36.
Gregr, E.J., Ahrens, A.L., Perry, R.I., 2012. Reconciling classifications of Ecologically and Biologically Significant Areas in the world's oceans. Marine Policy 36, 716–726.
Harney, J.N., Morris, M., Harper, J.R., 2008. ShoreZone coastal habitat mapping protocol for the Gulf of Alaska. In: Prepared for the Nature Conservancy, NOAA-NMFS, and Alaska State Department of Natural Resources, Juneau, AK. Coastal & Oceans Resources Inc. Sidney, BC, 137 p.
Heap, A.D., Harris, P.T., 2011. Geological and biological mapping and characterisation of benthic marine environments – introduction to the special issue. Continental Shelf Research 31, S1–S3.
Hjulström, F., 1935. Studies of the morphological activity of rivers as illustrated by the River Fyris. Bulletin of the Geological Institution of the University of Upsala 25, 221–527.
Howes, D.E., 2001. BC Biophysical Shore-Zone Mapping System – A Systematic Approach to Characterize Coastal Habitats in the Pacific Northwest. Puget Sound Research Conference, p. 11.
Komar, P.D., 1998. Beach Process and Sedimentation, second ed. Prentice-Hall, Englewood Cliffs, NJ, 544p.
Kvitek, R.G., Iampietro, P.J., Sandoval, E., Castleton, M., Bretz, C., Manouki, T., Green, A., 1999. Early Implementation of Nearshore Ecosystem Database Project, Final Report, San Jose State University Foundation Contract # FG 7335 MR. Prepared for the California Department of Fish and Game, 149 p.
MESH, http://www.searchmesh.net/default.aspx, 2010. Development of a framework for Mapping European Seabed Habitats (MESH). MESH Partnership (accessed 28.09.12).
O'Clair, R.M., Lindstrom, S.C., 2000. North Pacific Seaweeds. Plant Press, Auke Bay, AK, 159p.
Python, http://docs.python.org/index.html, 2012. Python v2.7.3 Documentation. Python Software Foundation (accessed 26.09.12).
Rhynsburger, D., 1973. Analytic delineation of Thiessen polygons. Geographical Analysis 5, 133–144.
Roff, J.C., Taylor, M.E., Laughren, J., 2003. Geophysical approaches to the classification, delineation and monitoring of marine habitats and their communities. Aquatic Conservation: Marine and Freshwater Ecosystems 13, 77–90.
Rykiel Jr., E.J., 1996. Testing ecological models: the meaning of validation. Ecological Modelling 90, 229–244.
Shumchenia, E.J., King, J.W., 2010. Comparison of methods for integrating biological and physical data for marine habitat mapping and classification. Continental Shelf Research 30, 1717–1729.
Zacharias, M.A., Howes, D.E., Harper, J.R., Wainwright, P., 1998. The British Columbia marine ecosystem classification: Rationale, development and verification. Coastal Management 26, 105–124.