Estuarine, Coastal and Shelf Science xxx (2011) 1–14

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2)

H. van Rein [a,*], C.J. Brown [a,b], R. Quinn [a], J. Breen [c], D. Schoeman [a]

[a] Centre for Coastal and Marine Research, School of Environmental Science, University of Ulster, Coleraine, Northern Ireland, BT52 1SA, United Kingdom
[b] Fisheries and Oceans Canada, Bedford Institute of Oceanography, PO Box 1006, Dartmouth, Nova Scotia, Canada, B2Y 4A2
[c] Conservation Science, Northern Ireland Environment Agency, Belfast, Northern Ireland, BT7 2JA, United Kingdom

A R T I C L E   I N F O

Article history:
Received 7 October 2010
Accepted 25 April 2011
Available online xxx

Keywords:
sonar
seabed
mapping
monitoring
biotopes
seagrass
kelp
scale

A B S T R A C T

Acoustic seabed classification is a useful tool for monitoring marine benthic habitats over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2). Its utility in this context was evaluated using two approaches: by describing natural changes in the temporal distribution of marine biotopes across the broad-scale (4 km^2), and by attempting to detect specific experimentally-induced changes to kelp-dominated biotopes across the meso-scale (100 m^2). For the first approach, acoustic backscatter mosaics were constructed using sidescan sonar and multibeam echosounder data collected from Church Bay (Rathlin Island, Northern Ireland) in 1999, 2008 and 2009. The mosaics were manually segmented into acoustic facies, which were ground-truthed using a drop-video camera. Biotopes were classified from the video by multivariate exploratory analysis and cross-tabulated with the acoustic facies, showing a positive correlation. These results were integrated with bathymetric data to map the distribution of seven unique biotopes in Church Bay. Kappa analysis showed the biotope distribution was highly similar between the biotope maps, possibly due to the stability of bedforms shaped by the tidal regime around Rathlin Island. The greatest biotope change in this approach was represented by seasonal and annual changes in the growth of the seagrass, *Zostera marina*. In the second approach, sidescan sonar data were collected before and after the removal of 100 m^2 of kelp from three sites. Comparison of the data revealed no differences between the high-resolution backscatter imagery. It is concluded that acoustic seabed classification can be used to monitor change over broad- and meso-scales but not necessarily for all biotopes; its success depends on the type of acoustic system employed and the biological characteristics of the target biotope.

1. Introduction

Traditionally, *in situ* sampling methods, such as sediment grabs, quadrats and scuba divers, have been used to monitor marine habitats and communities from unconsolidated and consolidated substrata (Van Rein et al., 2009). However, across broad- (>1 km^2) and meso-scales (10 m^2–1 km^2), these methods typically lack the necessary data density and spatial coverage to accurately determine habitat heterogeneity. In addition, community variability measured using *in situ* monitoring techniques does not always reflect the variability of broad-scale processes (Hewitt et al., 1998). To effectively monitor marine benthic habitats across meso- and broad-scales, standard methods that address the issues of spatial coverage and data density need to be developed. Such methods should be generally applicable, and therefore, benefit the wider global community.

Acoustic mapping equipment, such as multibeam echosounders (MBES) and sidescan sonars (SSS), can ensonify areas of seabed >100 km^2 with 100% spatial coverage at a resolution finer than 1 m^2 (Anderson et al., 2007, 2008). Acoustic backscatter data generated by these systems can be used to derive roughness characteristics, material properties and morphological maps, greatly facilitating the mapping of seabed sediments, bedforms and rocky outcrops over broad-scales (Lurton, 2002). These features are usually verified by the collection of "ground-truth" samples, from which additional biological data can be linked to the seabed features. Commonly referred to as acoustic seabed classification (ASC) (Anderson et al., 2007, 2008), this approach holds great potential for use in the broad-scale monitoring of marine benthic habitats (Pickrill and Todd, 2003).

However, despite widespread application there has been little or no standardisation of ASC methods for the purposes of monitoring

* Corresponding author.
E-mail address: van_rein-h@email.ulster.ac.uk (H. van Rein).

0272-7714/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2011.04.011

marine benthic habitats (Davies et al., 2001; Coggan et al., 2007). Many studies have focused on the mapping of such habitats, including scallop grounds (Kostylev et al., 2003); *Lophelia* spp. reefs (Roberts et al., 2005); *Modiolus* spp. reefs (Wildish et al., 1998; Lindenbaum et al., 2008); *Lanice conchilega* reefs (Degraer et al., 2008); squid spawning grounds (Foote et al., 2006); kelp forests (Méléder et al., 2010; McGonigle et al., 2011); macroalgal habitats (Quintino et al., 2010); and numerous unconsolidated sediment habitats (Sager et al., 2003; Brown et al., 2004a,b; Ehrhold et al., 2006; Lathrop et al., 2006). Only a few studies have conducted repeat surveys over the same habitat for the purposes of assessing benthic habitat change, e.g., kelp forest (Grove et al., 2002), seagrass meadow (Ardizzone et al., 2006), and coral reef (Collier and Humber, 2007). Within Europe, the legislative requirements of the Habitats Directive (EEC, 1992), the Water Framework Directive (EC, 2000) and the Marine Strategy Framework Directive (EC, 2008) underpin the need to develop marine monitoring methods across all spatial-scales. Because of the current lack of habitat monitoring with ASC, despite its potential utility, the overall aim of this study is to assess the extent to which ASC can be employed for monitoring marine benthic habitats over meso- and broad-scales.

Before testing any ASC-based monitoring method, several issues must first be addressed. Problems can arise when time-lapse acoustic data are acquired by different sonar systems, under different data acquisition settings, meteorological conditions, or at different vessel speeds. This can introduce additional variability in backscatter responses irrespective of real environmental variability (McGonigle et al., 2010). Any monitoring method using acoustic mapping techniques therefore needs to take these factors into careful consideration, and potentially devise ways to counteract resulting variability (Diesing et al., 2006; Kubicki and Diesing, 2006). The defining biological features of targeted habitats must also be detectable by either the acoustic mapping technique or by ground-truth methods employed. For example, certain species of kelp macroalgae have been detected using MBES (McGonigle et al., 2011) and single-beam echosounders (SBES) (Méléder et al., 2010), however, there is little evidence to support that SSS can do the same without supporting ground-truth data (Mulhearn, 2001; Grove et al., 2002).

Where appropriate measures have been taken to standardise approaches, specific geological features have been monitored over seasonal (McDowell et al., 2007), annual (Du Four and Van Lancker, 2008) and decadal timescales (Diesing et al., 2006). If similar measures are taken to ensure that the spatial accuracy of maps is maintained over time, those biological features are detectable and that the habitat classification scheme remains consistent, then ASC could also be used to monitor the biological features of marine benthic habitats. In this study, the potential of ASC for habitat monitoring is assessed at broad- and meso-scales in the following two objectives:

(1) Firstly, we assess and describe broad-scale changes to marine biotopes over a period of a decade (1999–2009) using three independent biotope maps of the same area (hereafter called the biotope survey). The maps are constructed using the ASC guidelines detailed by Diesing et al. (2006), where georectification of the time-lapse acoustic data is achieved using common ground-control points and the identification of acoustic facies by expert interpretation of acoustic backscatter. Remotely-collected video data are used to classify the acoustic facies into the marine biotopes, as outlined by the Joint Nature Conservation Committee (JNCC) marine habitat classification scheme (Connor et al., 2004).
(2) Secondly, we assess short-term, meso-scale changes to kelp-dominated substrata (hereafter called the kelp survey). SSS backscatter data are visually compared, using expert judgement, to determine whether the experimental removal of 100 m^2 areas of kelp macroalgae is detectable solely from the analysis of backscatter imagery collected from the testing area.

2. Study area

This study was conducted in Church Bay off Rathlin Island, located to the west of the narrowest point of the North Channel between Northern Ireland and Scotland (Fig. 1). The Island has highly variable bathymetry around its perimeter, with sea cliffs of basalt and limestone that descend to depths of over 270 m off the northern approaches (Atkins, 1997). In Church Bay, the seafloor consists of a relatively flat plain of mixed sediments to 20 m depth, after which the seabed drops off more sharply to around 80 m depth (Breen et al., 2006). Although the tidal range is narrow (1.0 m at mean spring tides), tidal currents flow at speeds up to 2 m s^{-1} over the variable bathymetry to produce strong and complex current eddies around the island's perimeter (UK Hydrographic Office, 1995; Atkins, 1997). In Church Bay, the dominant tidal flow originates in the west, flows into the north-east corner of the embayment and then out towards the south (Fig. 1). This flow slackens only at low tide, and reverses for 2 h of the flood tide (UK Hydrographic Office, 1995). In calm weather, the seas around Rathlin Island typically have clear water with low-turbidity, capable of supporting communities of macroalgae to depths of 25 m (Breen et al., 2006). However, local disturbance can be high due to significant wave action fuelled by Atlantic storm waves and swells, 75% of which originate in the west (Atkins, 1997). A high-energy wave regime persists through much of the year, with mean significant wave heights (Hs) of 1.4 m (standard deviation ± 0.4 m), and with wave periods of 8.7 s (SD ± 1.1 s) (Backstrom et al., 2009). As a result, the depth of closure is estimated to be 6.7 m in Church Bay (Hallermeier, 1981; Backstrom et al., 2009).

Despite the frequent wave disturbance and strong tidal streams, the waters around the Island support 530 known marine species which makes it one of the most biodiverse marine areas in the UK and Ireland (Breen et al., 2006). In recognition of this diversity and range of marine habitats, the seabed around the island has been designated as a European Special Area of Conservation (SAC) that requires protection, involving a comprehensive monitoring and management regime. Due to this status, geographical location and range of biotopes (Breen et al., 2006), Church Bay provided an ideal area for investigating marine habitats across broad-scales. In addition, surveys conducted within the embayment in 1999 and 2008 provide the data necessary to evaluate temporal changes to the marine habitats.

3. Materials and methods

3.1. Biotope survey

3.1.1. Acoustic data

Acoustic surveys were conducted over the same 4 km^2 area in Church Bay over June 1999, February 2008 and June 2009 (Fig. 2a). 100 kHz analogue sidescan sonar data were acquired by the University of Ulster in 1999 using an EdgeTech Model 272-TD towfish and an EdgeTech Model 260-TH processor, with a range of 200 m per channel and 50% track overlap. Positional data were provided by a Trimble GeoExplorer II Global Positioning System (GPS) receiver (±50 m accuracy), with 2-m layback correction. The second survey was conducted in 2008 as part of the larger Joint Irish Bathymetric Survey (Quinn et al., 2009). This survey was

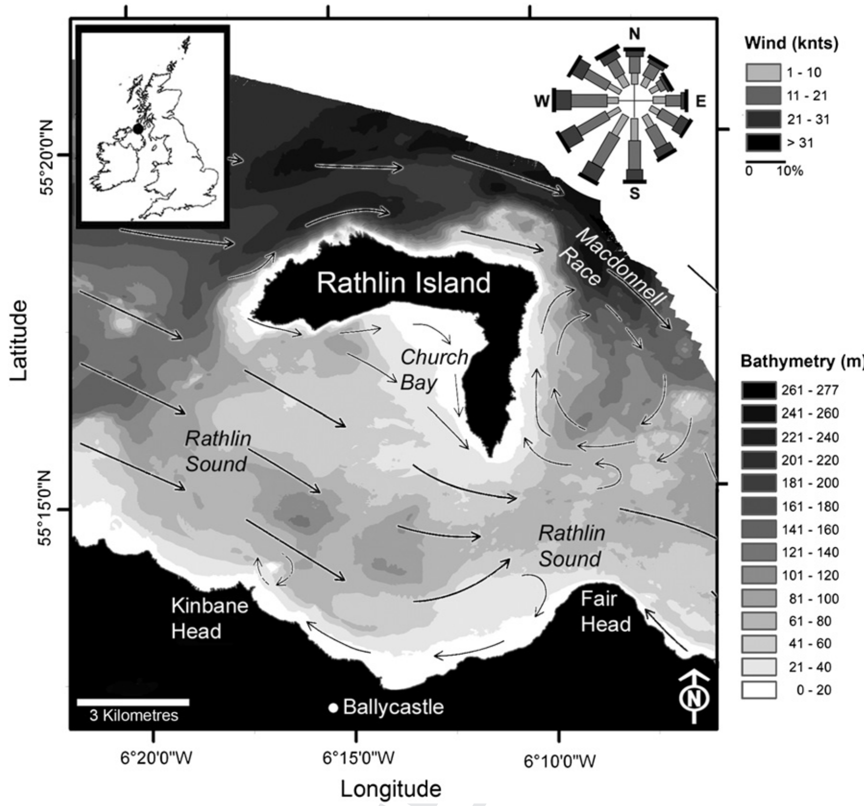


Fig. 1. Tidal streams, wind rose and local bathymetry of Rathlin Island and the study area for this investigation, Church Bay (as indicated). The map inset shows the location of Rathlin Island within the wider United Kingdom. The arrows indicate the tidal stream flows 5 h before high-water Dover (modified from UK Hydrographic Office, 1995). Hourly wind speeds and direction are for Malin Head, 1956–1996. Modified from Knight, 2002.

conducted to International Hydrographic Organisation (IHO) order 1 standard, with positional inaccuracies up to 2 m (International Hydrographic Bureau, 1998). Bathymetry and backscatter data were acquired simultaneously using a Kongsberg EM 3002D MBES, operating at a central frequency of 293 kHz. Positional and motion referencing data were provided by a Fugro Starfix Differential Global Positioning System (DGPS) and a Coda Octopus F180 motion sensor, respectively. The final acoustic survey was conducted in 2009 using the same sonar equipment and parameters as the 1999 survey. Positional data for this survey were provided by a Litton Marine LMX400 DGPS (±5 m accuracy).

The 1999 analogue SSS data were slant-range corrected, and output to six time/position-stamped heat-signature paper rolls. These sonograms were digitised, imported to *ArcMAP v9.2* as 8-bit rasters with 1-m spatial resolution and geo-rectified using time/position stamps as ground-control points, following the methodology outlined in Diesing et al. (2006). The 2008 MBES bathymetry data were cleaned by the UK Hydrographic Office and the Marine Institute of Ireland and released to the University of Ulster. These data were subsequently gridded and mosaiced in Interactive Visualization Systems (IVS) *Fledermaus Habitat* software. Backscatter data were imported into IVS *Fledermaus Geocoder* software as beam time-series data, and mosaiced at 1-m spatial resolution. The gridded bathymetric and backscatter mosaics were then exported into *ArcMAP v9.2* as 8-bit ArcGIS ascii rasters with 1-m spatial resolutions. The 2009 digital SSS backscatter data were slant-range corrected and mosaiced on the GeoAcoustics *GeoPro v4* system. They were then exported into *ArcMAP v9.2* as 8-bit rasters with 1-m spatial resolution, and geo-rectified using the grid position stamps.

Each backscatter mosaic was reduced from a variable grey-scale (0–255 units) to a reduced number of acoustic facies, the boundaries of which were subsequently digitised. Using a widely accepted segmentation approach, the facies were determined using the expert judgement of a single observer and achieved by grouping areas of similar backscatter characteristics, shade and pattern (Kostylev et al., 2001; Brown et al., 2002, 2005; Roberts et al., 2005; Ehrhold et al., 2006; Collier and Humber, 2007; Schimel et al., 2010). Despite operational differences between the MBES and SSS systems (i.e. frequency), backscatter segmentations from these systems are considered viable alternatives to one another due to high levels of similarity between the acquired imagery (Schimel et al., 2010). As such, the facies generated by the different acoustic systems were considered fit for comparison. Before this, however, the acoustic data were validated by ground-truthing areas targeted within each acoustic facie (Fig. 2b).

3.1.2. Ground-truth data

A single video camera survey was conducted in Church Bay over June 2009. A Rovtech Systems Ltd Hi8 microdigital colour camera, protected by a stainless steel drop-down frame, was used to collect coarse community (biotic hereafter) and geo-morphological (abiotic hereafter) data from stations within each pre-determined acoustic facie (Fig. 2b). This stratified approach to ground-truthing has been adopted by other ASC studies (Brown et al., 2002; Kendall et al., 2005; Ehrhold et al., 2006; Schimel et al., 2010). The location and number of stations in each acoustic facie are displayed in Fig. 2b. Although the ground-truth survey was conducted once over the decade 1999–2009, the position of each station remained within the same acoustic facie consistently over

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

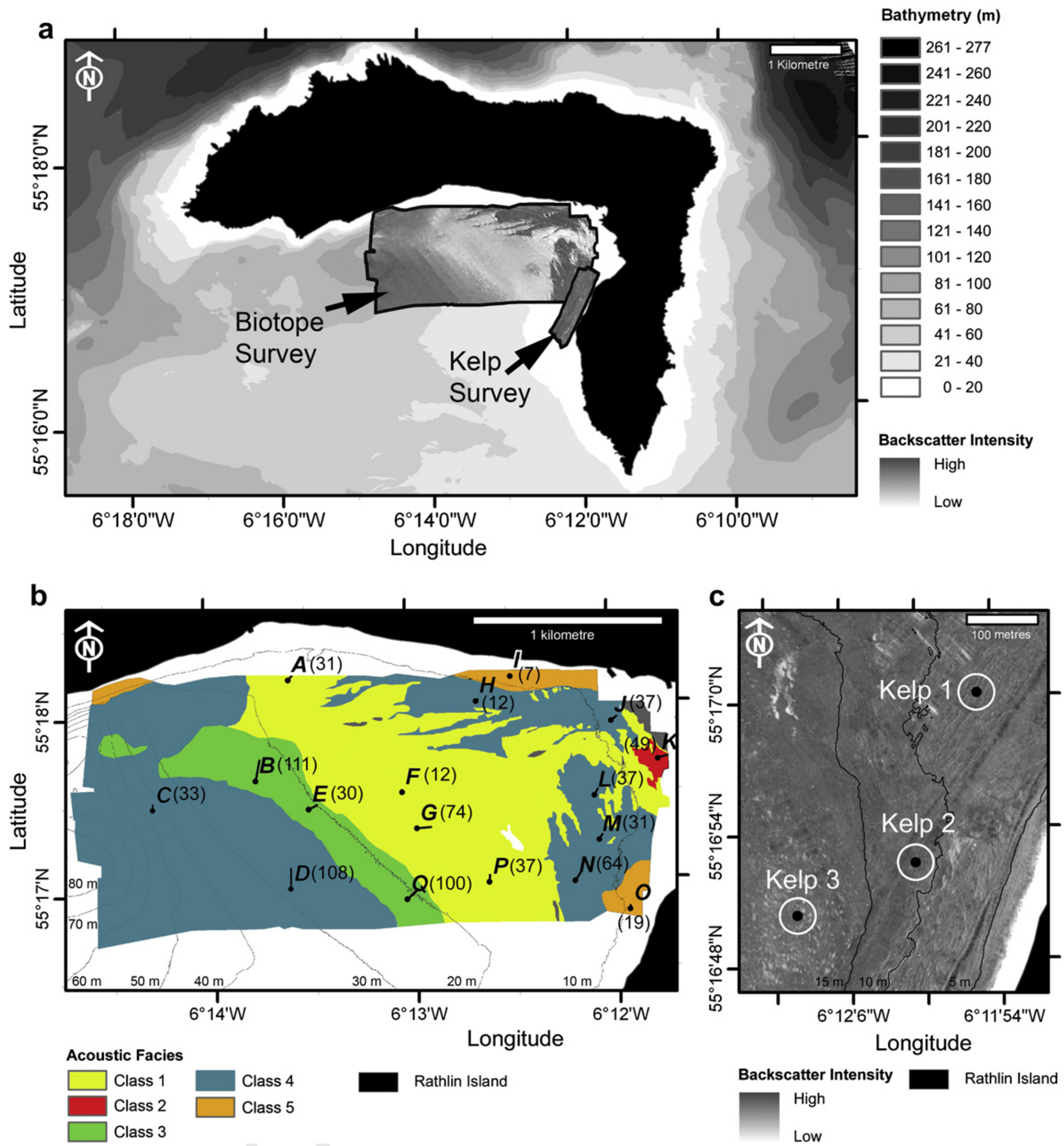


Fig. 2. (a) Bathymetric map of the seabed around Rathlin Island with backscatter inserts showing the location of the biotope and kelp surveys. (b) Acoustic facies map of biotope survey study area from 2009, showing the location of the drop-camera ground-truth stations within each of the five acoustic facies. Distances covered by each drop are indicated in metres next to each station. (c) Backscatter map of kelp survey study area showing the location of the three experimental impact sites. Depth contours are indicated in metres below chart datum.

the duration of the three acoustic surveys. The single camera drops per station typically lasted for 3 min, allowing adequate characterisation of the seabed features at each site. The bearing and speed of each drift was recorded to establish the distance of seabed surveyed in each drop, displayed in Fig. 2b.

Hi8 tapes were converted to *.avi files for analysis in Microsoft *Windows Media Player v11*. A simplified adaptation of other species-time methods, such as the Rapid Visual Count and Fast Visual Count (Michalopoulos et al., 1993; Service and Golding, 2007; Mitchell and Coggan, 2007), was developed to extract data from the video for biotope determination as objectively and efficiently as possible. The approximate 3 min of footage per station were divided into 20-s segments for data extraction. The presence or absence of nine abiotic (substratum type) and 20 biotic (broad taxonomic group) categories were recorded from each 20 s segment. The nine abiotic categories were boulders (>256 mm), cobbles (64–256 mm), pebbles (16–64 mm), gravels (4–16 mm), shell, and compacted, wave-dominated, rippled and bioturbated sands (<4 mm). The 20 biotic categories were encrusting biofilm, brown, red, green and crustose coralline algae, *Laminaria hyperborea*, *Laminaria saccharina*, seagrass, sponges, hydroids, corals, bryozoans, polychaete casts, gastropods, crabs, brittle stars, starfish, fin-fish, ascidians and burrows/holes/tubes. To summarise the data from each station, the presence/absence data of individual categories from each 20-s segment were added together and converted to a frequency of occurrence measure for that station. For example, if a category occurred in each 20-s segment from that station, it scored 100% occurrence. The scores of all individual abiotic and biotic categories were tabulated and standardised to represent the relative percentage contribution of each category to the overall characteristics of each ground-truth station. This method suited the quality of the video data and was deemed quicker than more traditional "SACFOR"-based data extraction methods (Holt and Sanderson, 2001; Diesing et al., 2009).

3.1.3. Data analysis

Biotopes were classified by exploratory analysis of the combined abiotic and biotic characteristics from each ground-truth station. The hierarchical clustering routine (CLUSTER) from *PRIMER v6* was used to reveal the similarities between the stations, based on their abiotic and biotic characteristics. The similarity profile permutation test (SIMPROF) then determined which similarities were statistically significant, irrespective of which acoustic facie the station came from. The significant clusters were visualised using non-parametric multi-dimensional scaling (nMDS). CLUSTER, SIMPROF and nMDS were carried out using a Bray–Curtis similarity matrix of root-transformed ground-truth data. Retaining the clusters, the similarity of percentages routine (SIMPER) was used to determine the similarity of stations within each cluster of stations and those abiotic and biotic categories which contributed $\geq$90% to that similarity. Biotopes were then classified from the SIMPER outputs using the JNCC marine habitat classification scheme (Connor et al., 2004). An advantage of this UK-based classification system is that the biotope units are interchangeable with the internationally recognised European Nature Information System (EUNIS) classification system and therefore retain their meaning outside of the UK (Davies et al., 2004). Using the cross-tabulation routine in *SPSS v15*, the percentage agreement of ground-truth data between the classified biotopes and the acoustic facies allowed the spatial integration of ground-truth and acoustic data. The shipwreck sites of the *HMS Drake* and *Ella Hewitt* were also included in the final biotope maps, although these features had no supporting ground-truth data.

There were two steps used to evaluate broad-scale change in Church Bay. Firstly, the 1999, 2008 and 2009 biotope maps were compared using the *Map Comparison Kit v3.2* software, developed by the Research Institute for Knowledge Systems (RIKS). The software utilised the kappa statistic to compare raster maps based on similarity of quantity (KHisto) and similarity of location (KLocat) of raster pixels (Hagen, 2002; Visser and de Nijs, 2006). Values of 1 indicate complete similarity between maps (100%), values of 0 indicate complete dissimilarity (0%) and values 0.7 generally indicate high similarity (Visser, 2004). In addition, a simple relative change (RC) measure was calculated for each temporal biotope comparison. The RC measure was calculated by multiplying the absolute spatial change of each biotope, in hectares, by the relative change in spatial area, as a percentage. This measure served as an indicator of gross changes in the size of biotopes relative to their areas. For example; if the area of a large biotope, measuring 100 ha area, changed by 2 ha between the maps, the biotope area changed by 2% and would have a subsequent RC of 4. However, if a smaller biotope, measuring just 2 ha, changed by the same 2 ha area, then the area changed by 100% and would have an RC of 200. The RC measure, therefore, highlights spatial changes relative to the original area of a biotope.

The second step to evaluate broad-scale change was to estimate the spatial accuracy of each biotope map, to discriminate between actual change in biotope distribution and putative change, which might in fact be introduced through positioning errors. Using five control points from the shipwreck sites of the *HMS Drake* and *Ella Hewitt*, positional inaccuracy of each map was estimated in relation to the most accurate mosaic: the 2008 MBES map (maximum positional inaccuracy $\pm$ 2.0 m). As such, the mean maximum positional inaccuracy of the 1999 and 2009 SSS maps were estimated to be $\pm$22.2 m (SD 19.1 m) and $\pm$14.5 m (SD 6.2 m), respectively.

3.2. Kelp survey

Acoustic surveys were conducted in a narrow area ($\sim$0.3 km^2) of hard-substratum at the eastern edge of Church Bay, known to be dominated by the kelps *L. hyperborea* and *L. saccharina*, in early June 2009 using the same SSS survey equipment as that used for the 2009 survey outlined in 3.1.1 (Fig. 2a). Digital backscatter data were collected at an operational frequency of 500 kHz with range of 100 m per channel. Scuba divers were used to ground-truth the backscatter data, and from observation to determine the main biotope characteristics of three experimental stations selected from different depth bands: 5–10 m, 10–15 m and 15–20 m (Fig. 2c). In addition, mean kelp density per m^2 seabed was estimated for each station using the holdfast counts from five 1 m^2 quadrats, placed at random within 20 m of the centre position of each station. Once kelp density was estimated, a 100 m^2 area (10 $\times$ 10 m) of seabed was cleared of all kelp macroalgae (>10 cm height above the substratum) at each station. After this experimental impact, a repeat acoustic survey was conducted in late June 2009, using the same parameters as the first.

Backscatter images of each station from before and after the experimental impact were carefully compared by eye, to see if any evidence of the 100 m^2 cleared area was visible in the imagery. The search for the cleared area at each station was limited to an area within 25 m of each stations position ($\sim$2000 m^2), deemed to be the maximum area in which the impact would be observed.

4. Results

4.1. Biotope survey

From analysis of the acoustic backscatter and ground-truth data collected in Church Bay, seven classes of biotope were identified to the fourth level of the JNCC marine habitat classification scheme, the biotope complex (Connor et al., 2004). Four of the seven biotopes were identified from the SIMPER outputs of four unique clusters of stations, and determined by CLUSTER analysis with the SIMPROF routine (Fig. 3). These were: the infralittoral coarse sediments (M.SS.SCS.ICS); circalittoral coarse sediments (M.SS.SMX.CMx); kelp and seaweed on sublittoral sediments (M.SS.SMP.KSwSS) and kelp and red seaweeds on infralittoral rock (M.IR.MIR.KR). The fifth cluster identified by the analysis, containing the stations A, F, G, P and K, was split due to the presence of seagrass (*Zostera marina)* at station K, which resulted in the identification of two of the seven biotopes: infralittoral fine sands (M.SS.SSA.IFiSa) and sublittoral seagrass bed (M.SS.SMP.SSgr). Finally, the seventh biotope, the infralittoral fouling community (M.IR.FIR.IFou), occupied the site of a known navigation hazard in Church Bay: the combined shipwreck sites of *HMS Drake* and *Ella Hewitt*. The broad characteristics of all seven biotopes are presented in Table 1. The sublittoral seagrass bed (SSgr hereafter) and infralittoral fouling community (IFou hereafter) described here have not been previously identified in Church Bay (Breen et al., 2006).

The spatial extent and position of all seven biotopes in Church Bay from 1999, 2008 and 2009 were mapped using the results from the cross-tabulation of ground-truth stations with the acoustic facies from the backscatter segmentation (Table 2; Fig. 4). A positive correlation exists between the classified biotopes and the acoustic facies (Spearman's $\rho = 0.77$, $p \leq 0.001$, $n = 17$). However, the class 4 acoustic facie encompasses two biotopes: the kelp and seaweed on sublittoral sediments (KSwSS hereafter) and the circalittoral coarse

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

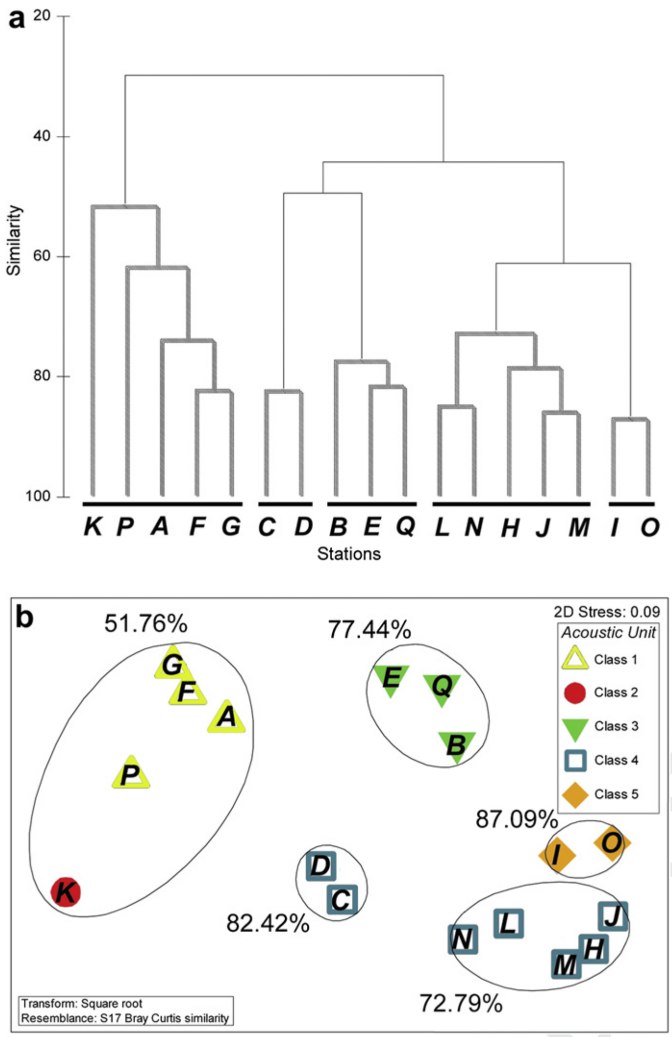


Fig. 3. Multivariate classifications of substratum category data. (a) CLUSTER Dendrogram and (b) nMDS plot of root-transformed substratum category data showing the clustering of drop-camera ground-truth stations based on statistical similarities determined using SIMPROF. Clusters are indicated by thick horizontal lines below the dendrogram (a) and by circles in the nMDS plot (b), where the percentage similarity of that cluster in also displayed.

sediments (CMx hereafter). Although these biotopes exist over areas of similar backscatter characteristics, bathymetry data shows the former to occur in <25 m depth and the latter to exist mostly deeper than this (Fig. 4). Therefore, the class 4 acoustic facie was split into two biotopes: biotope KSwSS which was characterised by the presence of macroalgae and was located in the shallower waters to the east of the study area, and biotope CMx which was present in the west of the survey area in deeper water where no macroalgae was recorded (Figs. 2 and 4).

The results of kappa analysis of the biotope maps show that a high overall similarity exists between maps compared over 15 months, 9-year and decadal periods (Table 3). The greatest similarity occurs between the maps derived from data collected with only 15 months of one another (91% between 2008 and 2009), and the greatest dissimilarity occurs between those collected a decade apart (82% between 1999 and 2009). The most similar maps (2008 and 2009) are also those with the smallest positional inaccuracies (±2.0 m and ±14.5 m respectively), and the least similar maps (1999 and 2009) are also those with the largest positional inaccuracy (±22.2 m and ±14.5 m respectively). Overall, the biotope maps differ more by spatial location (KLocat) than by spatial area (KHisto) of biotopes between the years. Spatial similarities and dissimilarities between the biotope maps are clearly visible from the insets in Fig. 5.

In each biotope map, the deepest portion of the survey area is made up of CMx, which ranges from about 80 to 25 m depth (Fig. 4). The CMx are represented by 28.6% of the ground-truth stations within the class 4 acoustic facie: stations C and D (Table 2). The areas of CMx have the highest expression of epifaunal diversity of all biotopes in this study and show a wide range of sediment grain sizes, including boulders, cobbles, pebbles, gravels and compacted sand (Table 1). This biotope has the highest kappa values of the individual biotopes, many of the lowest RC values and, therefore, is the most stable of all biotopes in this study (Table 3). In shallower water is an area of complex sediment ribbons and dunes, the infralittoral coarse sediments (ICS hereafter) (Fig. 4). In comparison with the CMx, the ICS features are more mobile and there is more geographical variation of this biotope between the maps (Table 3). This biotope occupies the edge of the gradual drop-off at 20 m depth, in an area where the orientation of the bedforms and position of sediment ribbons reflect the dominant tidal currents in Church Bay (Fig. 4), on display in Fig. 1. The ICS are represented by 3 ground-truth stations (B, E and Q) and the class 3 acoustic facie (Table 1).

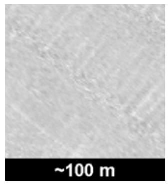
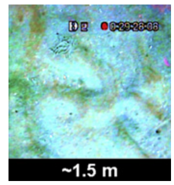
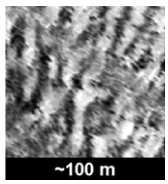
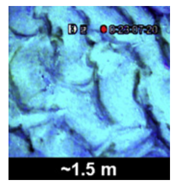
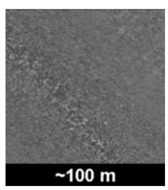
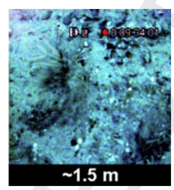
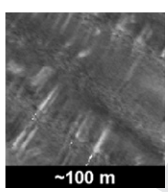
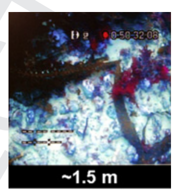
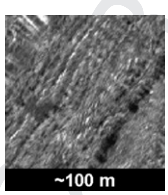
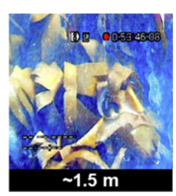
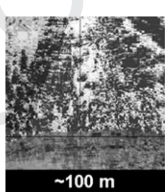
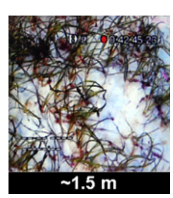
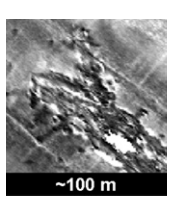
Landward of the drop-off is a large, relatively flat expanse of infralittoral fine sands (IFiSa hereafter) (Fig. 4). The IFiSa are represented by 4 ground-truth stations (A, F, G and P), which coincide with acoustic facie 5 (Table 1). The biotope is characterised by clean sands with little or no macroalgae present. There are small, regular sand waves present at all stations. In a few areas there is evidence of polychaete burrows, likely made by *Arenicola marina*. The IFiSa biotope is fringed along its north-east and south-east edges by KSwSS (Fig. 4). The KSwSS is represented by 71.4% of the ground-truth stations within the class 4 acoustic facie: stations H, J, L, M and N (Table 2). This biotope is characterised by areas of mixed sands, gravels and cobbles with frequent *L. saccharina* and red algae (Table 1). The boundaries between these two biotopes form complex ribbon-like features, measuring up to 500 m long and 100 m wide that remain stable between the biotope surveys (Fig. 5). The distribution of the IFiSa ribbons is indicative of the flow of the dominant tidal streams in Church Bay, presented in Fig. 1. Kelp and red seaweeds on infralittoral rock (KR hereafter) are recorded in the north-east and south-east areas of Church Bay (Fig. 4). This biotope is characterised by stable boulder slopes dominated by the kelp *L. hyperborea*, under which grows a variety of red algae (Table 1). This biotope is represented by two ground-truth stations (I and O) which coincided with acoustic facie 5 (Table 2).

Although no ground-truth data were collected from the IFou biotope, it was classified using the position of the combined shipwrecks of *HMS Drake* and *Ella Hewitt*. IFou biotopes are typified by dense coverings of filamentous and foliose algae on vertical as well as the upper faces of artificial substrata (Connor et al., 2004). The position of these shipwrecks from the 1999, 2008 and 2009 maps indicates high positional similarity between the maps (Fig. 5d). In contrast, however, the kappa values of 0.34, 0.47 and 0.65 from decadal, 9-year and 15-month comparisons respectively, show that the IFou biotope has the lowest similarity of spatial area and spatial location of any biotope in this study. This biotope is also the smallest of all those mapped in Church Bay (Table 1; Fig. 4), and has the highest RC values of this study (Table 3).

The most substantial change between the biotope maps occurs in 2009, when the seagrass biotope, SSgr, appears in the north-west corner of Church Bay (Fig. 4). This biotope is characterised by the presence of the seagrass *Z. marina* in the ground-truth data from station K collected in 2009, and matches the class 2 acoustic

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

Table 1
Final biotope classification of biotope survey study area in Church Bay. The characteristics of each biotope are outlined, with only the substratum categories responsible for 90% of the biotopes characteristics displayed (determined by SIMPER routine). Biotopes with no SIMPER analysis, ground-truth data or initial backscatter class are indicated. Backscatter images are from MBES data, gridded to 1 m^2 resolution, except for sublittoral seagrass bed which is from SSS data. All video images are from drop-video camera. All scales for images are indicated. Av. Sim. = Average similarity. % Contrib. = percentage contribution. Q4

Biotope complex (general features)	Backscatter image	Video grab image	Substratum categories	Av.Sim.	% Contrib.
Infralittoral fine sand JNCC class: M.SS.SSA.IFiSa EUNIS class: A5.23 Mean area: 141.5 ha (SD = 1.5) Stations: A, F, G and P Initial backscatter class: Class 1			Average similarity within group Shell Bact/Turf crust Sand–bioturb Burrows/holes/tubes Sand–waves Red algae Polychaete casts	69.4% 14.4 13.7 11.6 8.0 7.1 6.2 6.0	 20.8 19.8 16.7 11.5 10.2 9.0 8.7
Infralittoral coarse sediments JNCC class: M.SS.SCS.ICS EUNIS class: A5.12 Mean area: 38.8 ha (SD = 2.0) Stations: B, E and Q Initial backscatter class: Class 3			Average similarity within group Shell Bact/Turf crust Sand–ripples Brown algae Red algae Kelp – *L. saccharina* Cobbles Pebbles	78.9% 12.6 12.6 12.0 10.3 9.8 5.9 4.4 4.3	 16.0 16.0 15.3 13.1 12.4 7.5 5.5 5.5
Circalittoral mixed sediments JNCC class: M.SS.SMX.CMx EUNIS class: A5.44 Mean Area: 132.1 ha (SD = 1.5) Stations: C and D Initial backscatter class: Class 4			Average similarity within group Bact/Turf crust Shell Sand – compacted Pebbles Bryozoans Gravel Hydroids Red algae Boulders Cobbles Starfish	82.4% 9.0 8.8 8.5 8.1 7.3 7.2 6.0 5.8 5.1 4.4 4.2	 10.9 10.7 10.3 9.8 8.9 8.7 7.3 7.1 6.2 5.4 5.1
Kelp & seaweed on sublittoral sediments JNCC class: M.SS.SMP.KSwSS EUNIS class: A5.52 Mean area: 61.8 ha (SD = 1.0) Stations: H, J, L, M and N Initial backscatter class: Class 4			Average similarity within group Kelp – *L. hyperborea* Red algae Gravel Pebbles Brown algae Kelp – *L. saccharina* Cobbles	76.5% 11.8 11.7 11.6 11.3 10.3 8.2 6.9	 15.4 15.3 15.1 14.8 13.4 10.8 9.0
Kelp & red seaweeds on infralittoral rock JNCC class: M.IR.MIR.KR EUNIS class: A3.21 Mean area: 15.0 ha (SD = 1.9) Stations: I and 0 Initial backscatter class: Class 5			Average similarity within group Kelp – *L. hyperborea* Red algae Boulders Pebbles Gravel Cobbles Bact/Turf crust	87.1% 16.4 15.0 14.6 10.6 10.6 10.3 9.8	 18.8 17.2 16.7 12.1 12.1 11.8 11.2
Sublittoral seagrass bed JNCC class: M.SS.SMP.SSgr EUNIS class: A5.53 Area: 2.2 ha Station: K Initial backscatter class: Class 2			** No simper analysis ** Sand – compacted Sand – bioturb Bact/Turf crust Seagrass Ascidians Polychaete casts		 28.1 21.9 13.2 10.3 10.3 7.4
Infralittoral fouling community JNCC class: M.IR.FIR.Ifou EUNIS class: A3.72 Mean area: 0.5 ha (SD = 0.2) No stations No initial backscatter class			** No simper analysis ** HMS Drake (shipwreck) *Ella Hewitt* (shipwreck)		

facie, only present in 2009 backscatter segmentation map (Fig. 4). Closer inspection of the backscatter from the local area shows that the "patchy" areas of high backscatter in the 2009 acoustic survey, attributed in this case to the presence of seagrass, was not present in the acoustic data from the other surveys (Fig. 6). Further analysis of these areas, using the raw backscatter data (no time-varied gain corrections or image enhancement), shows the same patchy areas of "seagrass" present in only the 2009 data.

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

Table 2
Cross-tabulation of drop-video stations against acoustic facies determined from backscatter segmentation of biotope surveys (frequency [% contribution]). JNCC biotope complex codes indicate the following: IFiSa = infralittoral fine sand; ICS = infralittoral coarse sediment; CMx = circalittoral coarse sediment; KSwSS = kelp and seaweed on sublittoral sediment; KR = kelp and red seaweeds on infralittoral rock; SSgr = sublittoral seagrass bed. The acoustic facie, class 2*, was present only in the 2009 data set. In the 1999 and 2008 data sets, all data from class 2 were present in the class 1 acoustic facie.

Biotope	Acoustic facie (class no.)					Total
	1	2*	3	4	5	
IFiSa	4 (100)	–	–	–	–	4 (100)
ICS	–	–	3 (100)	–	–	3 (100)
CMx	–	–	–	2 (28.6)	–	2 (28.6)
KSwSS	–	–	–	5 (71.4)	–	5 (71.4)
KR	–	–	–	–	2 (100)	2 (100)
SSgr	–	1 (100)	–	–	–	1 (100)
Total	4 (100)	1 (100)	3 (100)	7 (100)	2 (100)	17 (100)

Therefore, the appearance of this new biotope is not considered an error of data acquisition, processing or backscatter segmentation. However, as no corresponding areas of patchy backscatter are present in either the 1999 or 2008 backscatter mosaics, in those years the area is classified as IFiSa, rather than SSgr. As a result, the SSgr biotope area shows up as an area of high dissimilarity between the 2008 and 2009, and 1999 and 2009 biotope map comparisons (Fig. 5).

4.2. Kelp impact detection

Two biotope complexes were classified from observations of the three experimental stations: Kelp survey stations 1 and 2 were classified as biotope KR, dominated by *L. hyperborea,* boulders and bedrock while Kelp survey station 3 was classified as biotope KSwSS, with more *L. saccharina* than *L. hyperborea,* on gravels and cobbles. Kelp macroalgal densities per m^2 decrease with depth among the stations, with the lowest density of kelp at the deepest station, Kelp 3, and the highest densities at the shallowest station, Kelp 1 (Fig. 7). Backscatter imagery collected from before (pre-impact) and after (post-impact) the removal of 100 m^2 of kelp from the experimental stations, was compared by eye. Visual analysis reveals no discernable differences in the backscatter imagery within 25 m of each experimental station between any of the three pre- and post-impact surveys (Fig. 7). Unfortunately, the area under investigation at each station is closer to the SSS nadir in the post-impact survey tracks and therefore suffers more nadir-related effects, such as image saturation. Although, evidence of the kelp removal may be present in the post-impact backscatter imagery, it is likely obscured by the more prevalent nadir-related effects.

5. Discussion

This study demonstrates that ASC can be used as a tool to detect spatial changes to marine habitats across broad-scales. Within the biotope survey area in Church Bay, there were biotopes that showed little or no spatial change over the decade 1999–2009, and there were those that changed substantially in extent and position. However, experimentally-induced changes to kelp biotopes across meso-scales were not convincingly detected from acoustics alone. Issues raised in the results have highlighted a few methodological concerns that warrant further discussion.

5.1. Biotope survey

The overall spatial stability of the biotopes within the study area suggests a consistent and stable hydrodynamic regime exists in Church Bay. Indeed, it is remarkable that despite the strength of the tidal currents and reputed force of the storms around Rathlin Island (Atkins, 1997), the distribution of biotopes within the survey area remains so stable over the decade, 1999–2009. Similar inter-annual stability of bedforms has been reported from other areas off the north coast of Northern Ireland, where the distribution of bedforms remained annually consistent (McDowell et al., 2007). However, seasonal changes in the distribution of bedforms have also been described, and have been attributed to a shift in the dominant hydrodynamics between summer and winter, from a tidal- to wave-dominated regime, respectively (McDowell et al., 2007; Backstrom et al., 2009). At another high-energy, geologically-confined embayment along the north coast of Northern Ireland, Backstrom et al. (2009) showed that wave energy mostly affected the substratum shallower than 5 m, and only up to a maximum depth of 15 m over severe storm events (Hs = 3.8 m, $T = 11.6$ s, with onshore wind speeds of up to 16 m s^{-1}). Wave and wind energy are likely to contribute to the distribution of bedforms and biotopes in Church Bay in a similar way, due to an estimated depth of closure of 6.7 m (Hallermeier, 1981; Backstrom et al., 2009). However, a lack of substantial seabed changes beyond the depth of closure, especially between the seasons, suggests that the biotope distribution in Church Bay is not wholly dependent on wave energy. Tidal stream energy, which remains relatively constant over the seasons, is more likely to be responsible for the overall stability of biotopes in Church Bay over the decade 1999–2009. Relative to the known flow of tidal streams around Rathlin Island, the distribution of the ICS, along the edge of the 20 m “drop-off” in Church Bay, and the ribbon-like structures at the interface between the IFiSa and KSwSS biotopes further support this notion. Subtle spatial changes in the distributions of these biotopes are, therefore, probably a result of natural tidal forces.

The spatial distribution of only the IFou and SSgr biotopes changes substantially over the decade, 1999–2009. Thus far, all changes discussed were attributable to natural phenomena in Church Bay, such as tidal streams. However, because the IFou biotope represents the combined shipwreck sites of *HMS Drake* and the *Ella Hewitt*, the large spatial changes over a decade are unexpected and likely to be erroneous. With the highest RC values of this study, the observed changes in this biotope are likely to be a product of its small size (~0.5 ha). Theoretically, spatial changes among small biotopes are more likely to be detected by kappa analysis, as the comparison matrix utilised is based on the ratio of similar to non-similar raster pixels (Hagen, 2002; Visser and de Nijs, 2006). Therefore, smaller biotopes with fewer pixels have a greater potential for change than larger biotopes with many more pixels. This issue also relates to the method of backscatter segmentation used. Although it was beyond the scope of investigation, a more objective automated backscatter segmentation routine may have increased the accuracy of the comparisons of smaller biotopes, such as the IFou (Cochrane and Lafferty, 2002; Brown and Collier, 2008).

Another possible source of error could be the different spatial accuracies of the three acoustic data sets in this study. If the positional inaccuracies of comparative maps are large, it is consequently more difficult to distinguish between changes due to the timing and positional inaccuracy of the survey. Such positional errors are common among “older” data sets, such as those collected before May 2000, when potential positional inaccuracies of ±50 m were caused by the selective availability of the GPS (Grewal et al., 2007). Such inaccuracy in the 1999 data could invalidate all observations and conclusions made with respect to this data set. However, after acquiring, processing, digitising and geo-rectifying these data, actual maximum positional inaccuracy was estimated to be ±22.2 m. Comparison of IFou biotope polygons shows that the

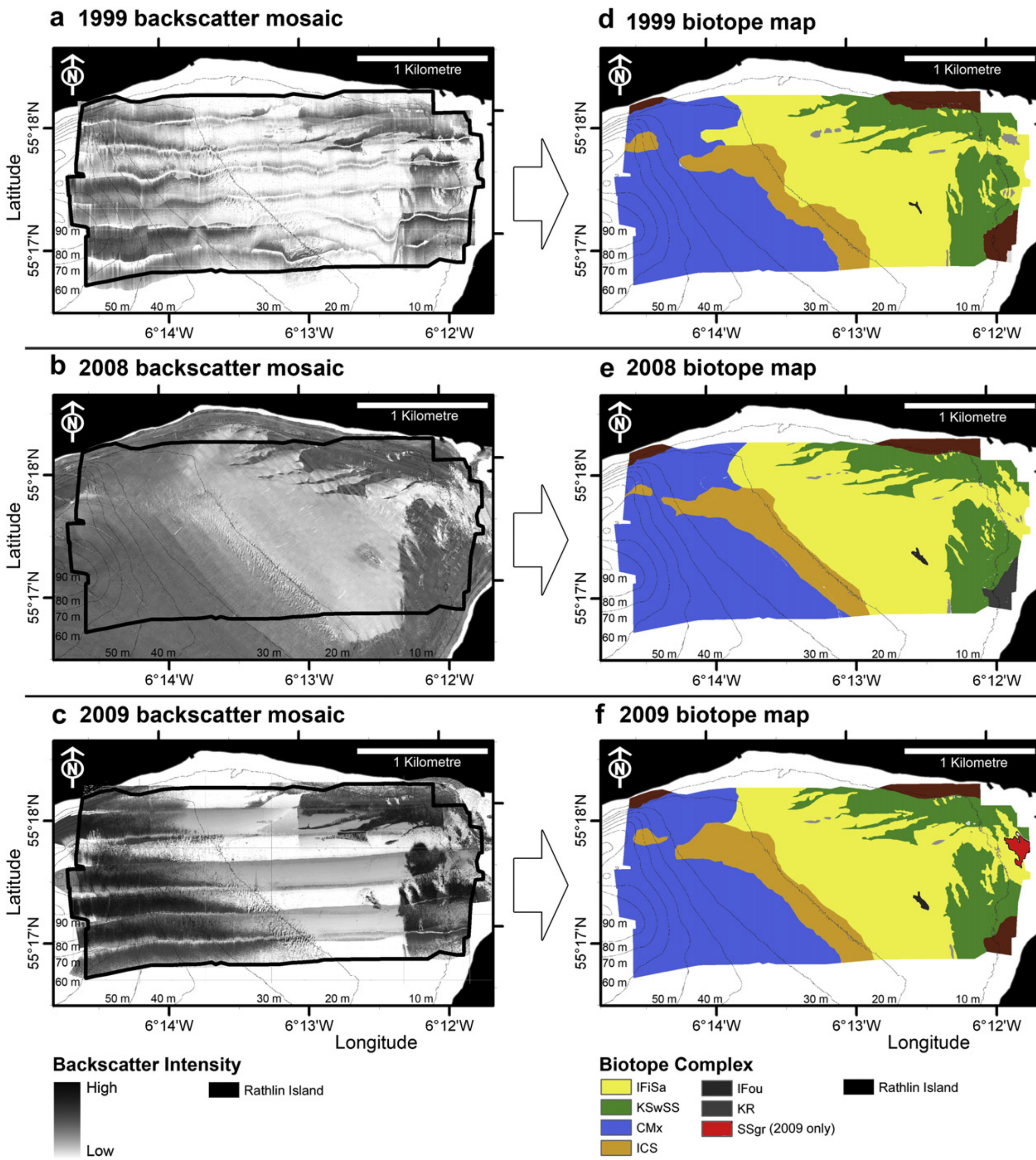


Fig. 4. Backscatter mosaics of Church Bay from (a) a sidescan sonar survey in 1999, (b) a mulitbeam echosounder survey 2008 and (c) a sidescan sonar survey in 2009. The black box indicates the biotope survey area common to all three data sets. Within this survey area, biotope maps were constructed from analysis of the backscatter and ground-truth data, for (d) 1999, (e) 2008 and (f) 2009. JNCC biotope complex codes indicate the following: IFiSa = infralittoral fine sand; KSwSS = kelp and seaweed on sublittoral sediment; CMx = circalittoral coarse sediment; ICS = infralittoral coarse sediment; IFou = infralittoral fouling community; KR = kelp and red seaweeds on infralittoral rock; SSgr = sublittoral seagrass bed. Depth contours are indicated in metres below chart datum.

common area shared by each polygon is sufficient in size to minimise such bias. Further comparison of other biotope polygons, with respect to potential positional inaccuracies, showed that biotope changes described in the results were real and not just artefacts of positional inaccuracy. This demonstrates the importance of having common geo-referencing points in each survey area for this type of study (Diesing et al., 2006; Kubicki and Diesing, 2006).

Closer inspection of the SSS survey track lines from the 1999 survey shows that a deviation in track orientation around the IFou biotope is responsible for the difference in the spatial extent of the 1999 IFou biotope relative to those from 2008 to 2009. The action successfully avoided snagging the SSS towfish and survey vessel propellers on the surface marker buoys of lobster pots located in the pre-planned SSS track line. In the process, it is very probable that the starboard transceiver of the SSS towfish rose higher into the water column, away from the seabed. The limited echo return from the combined shipwrecks of *HMS Drake* and *Ella Hewitt* resulted in inaccurate backscatter acquisition and, therefore, segmentation of the 1999 IFou biotope from the backscatter imagery.

Table 3
Similarity between and relative change (RC) of biotope maps from different years (as indicated). Map similarities were calculated using the Map Comparison Kit, where the Kappa statistic (Kappa) is a product of the quantity comparison (KHisto) and the spatial comparison (Klocat). Numbers in italics highlight potential dissimilarities. As the sublittoral seagrass bed was present only in the 2009 biotope map, it was excluded from the Map Comparison Kit analysis. RC was calculated by multiplying the absolute spatial change in a biotope (ha) with the percentage change of its spatial area (%), between two time frames. Larger numbers indicate large changes in area relative to the original size of the biotope. Biotope classes: CMx = circalittoral mixed sediments; KR = kelp and red seaweeds on infralittoral rock; IFiSa = infralittoral fine sands; KSwSS = Kelp and seaweeds on sublittoral sediments; ICS = infralittoral coarse sediments; IFou = infralittoral fouling community and SSgr = sublittoral seagrass bed.

	Map similarity			RC
	Kappa	KHisto	Klocat	
A. 1999–2008				
Overall	0.83	0.98	0.85	–
CMx	0.92	0.99	0.93	1.36
KR	0.85	0.93	0.91	3.75
IFiSa	0.82	0.98	0.83	6.42
KSwSS	0.78	0.99	0.79	2.93
ICS	0.74	1.00	0.74	0.04
IFou	*0.47*	*0.62*	0.76	249.72
B. 1999–2009				
Overall	0.82	0.97	0.85	–
CMx	0.94	0.98	0.95	2.57
KR	0.80	0.87	0.92	8.74
IFiSa	0.80	0.99	0.81	3.30
ICS	0.74	0.95	0.78	32.01
KSwSS	0.73	0.99	0.74	5.55
IFou	*0.34*	*0.56*	*0.60*	581.68
SSgr	–	–	–	221.02
C. 2008–2009				
Overall	0.91	0.98	0.93	–
CMx	0.95	1.00	0.95	0.52
KR	0.91	0.93	0.98	0.99
IFiSa	0.91	1.00	0.91	0.50
KSwSS	0.88	0.98	0.90	1.09
ICS	0.86	0.95	0.90	29.78
IFou	*0.65*	0.93	*0.70*	26.19
SSgr	–	–	–	221.02

A range of different explanations is explored to determine why the backscatter imagery associated with the SSgr biotope is present in only the 2009 biotope map. The first relates to the different methods of data acquisition and processing employed by the different acoustic tools: SSS and MBES. The 1999 and 2009 data were collected by a towed SSS towfish using a frequency of 100 kHz to ensonify the seabed with a very low grazing angles (1–40°), while 2008 data were collected by a hull-mounted MBES transceiver using a central frequency of 293 kHz with a low to mid-grazing angles (25–90°). Although it may seem inappropriate to compare data from two different approaches, other seagrass backscatter detection studies have shown little dependence of backscatter response on different frequencies and grazing angles of sonar systems (McCarthy, 1997; Lyons and Pouliquen, 1998). The different position-fixing accuracies of the two systems were also ignored in the comparisons, as the estimated positional inaccuracies of the SSS surveys could not account for the differences in the backscatter imagery. Differences in the backscatter imagery are not due to processing differences either; examination of the raw backscatter, before any contrast enhancement and time-varied gain corrections were applied, shows the same patterns as those observed in the processed data.

Further exploration relates to natural phenomena, such as changes to the density of seagrass between the surveys. In other studies, seagrass beds have not been easily detectable from visual analysis of backscatter imagery when individual plants were present at low densities (Davidson and Hughes, 1998; Mulhearn, 2001). Indeed, populations of *Z. marina* have been shown to take over five years to become stable, after which the spread and growth of the bed is more rapid (Olesen and Sand-Jensen, 1994; Davidson and Hughes, 1998). It is generally accepted that perennial *Z. marina* spreads predominantly by vegetative growth in high salinities (Giesen et al., 1990), such as the salinities encountered (34.25 PSU) around Rathlin Island (Atkins, 1997). The growth and spread of *Z. marina* is also highly dependent on available light for photosynthesis (Dennison and Alberte, 1985; Nelson and Waaland, 1997; Moore and Wetzel, 2000). Leaf growth is dramatically less under low-light conditions, which if prolonged (3 weeks) can result in the complete disappearance of the seagrass bed (Moore et al., 1997; Cabello-pasini et al., 2002). As such, sublittoral seagrass beds often exhibit seasonality in their distribution, directly related to the availability of light. They are present in high densities, with high biomass and associated-epifaunal biomass in summer months (more available light), and in comparatively lower densities in the winter, with significantly lower biomass and associated-epifaunal biomass (Nelson and Waaland, 1997; Cabello-pasini et al., 2002). Laboratory study has shown that gas-filled chambers (lacunae) in the leaves of healthy plants return the strongest echo from acoustic ensonification (McCarthy, 1997). Therefore, it is plausible that the seagrass bed is detected only in the 2009 backscatter mosaic, and not 1999 backscatter mosaic, as the bed had matured, reaching a threshold density necessary for detection using acoustics. It is also likely the bed was not detected from the analysis of the 2008 backscatter data due to the seasonal variability of seagrasses, as these data were collected in winter (February), when the seagrass communities were likely to be in a reduced state (Cabello-pasini et al., 2002) and not as readily detectable with acoustics (Davidson and Hughes, 1998; Mulhearn, 2001). Although no obvious seasonality is observed in the distribution of physical bedforms in this study, direct comparison of backscatter collected from the winter of 2008 and summer of 2009 demonstrates that ASC detects the seasonality of biological features in Church Bay, beds of the seagrass *Z. marina* in this case.

5.2. Kelp impact detection

Visual analysis of the backscatter imagery shows neither the presence of any 10 × 10-m cleared areas, or any other feature that could resemble the kelp-cleared areas. As shown by Mulhearn (2001), the backscatter imagery reflects the presence of substratum features at the site, such as rocky ledges and patches of coarser sediments, but not the actual kelp itself. Beds of the giant kelp, *Macrocystis pyrifera*, have been previously detected using acoustic techniques by Grove et al. (2002). However, it was likely the gas-filled bladders of this species of kelp that led to its successful detection. The kelp species in this study, *L. hyperborea* and *L. saccharina*, are similar to *Ecklonia radiata* studied by Mulhearn (2001) in that they lack the gas-filled bladders of the giant kelp, *M. pyrifera* (Lalli and Parsons, 1997). Therefore, it seems that successful monitoring of kelp using SSS at meso-scales, might rely on the kelp species having gas-filled bladders (or some other reflective structure) within its morphology.

A survey error incurred during the acoustic sampling precluded any useful interpretation from the image-based histograms. The "nadir effect", observed in the backscatter samples of this study, is a problem common to all SSS-acquired backscatter imagery (White et al., 2007). Other approaches to acoustic backscatter analysis may have proven more effective, such as semi-automated backscatter segmentations (Brown and Collier, 2008; McGonigle et al., 2010), angular range analysis (Fonseca and Mayer, 2007; Fonseca et al., 2009) or inclusion of water column data in analysis (McGonigle

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

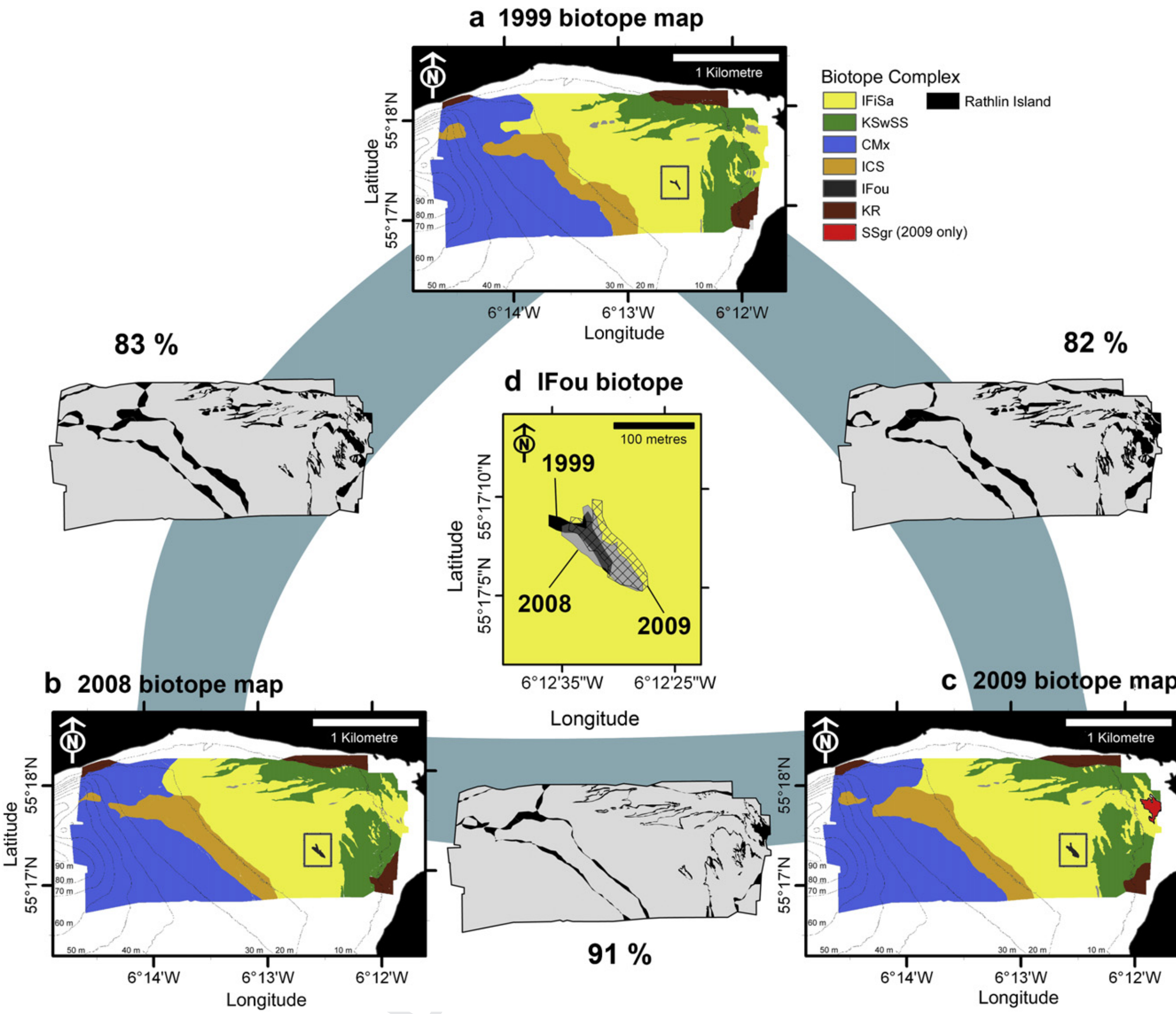


Fig. 5. Final biotope maps of biotope survey study area within Church Bay, from (a) 1999, (b) 2008 and (c) 2009. The thick grey lines, and associated figure insets, show which biotope maps were compared and where dissimilarities (areas of black) were detected from the Map Comparison Kit Kappa analysis. The percentages adjacent to the figure insets show the percentage agreement between the biotope maps compared. (d) The centre image shows the spatial overlap between the three year's surveys of the infralittoral fouling community, associated with the shipwrecks of *HMS Drake* and the *Ella Hewitt*. Biotope complexes: IFiSa = infralittoral fine sands, KSwSS = Kelp and seaweeds on sublittoral sediments, CMx = circalittoral mixed sediments, ICS = infralittoral coarse sediments, IFou = infralittoral fouling community, KR = kelp and red seaweeds on infralittoral rock and SSgr = sublittoral seagrass bed. Depth contours are indicated in metres below chart datum.

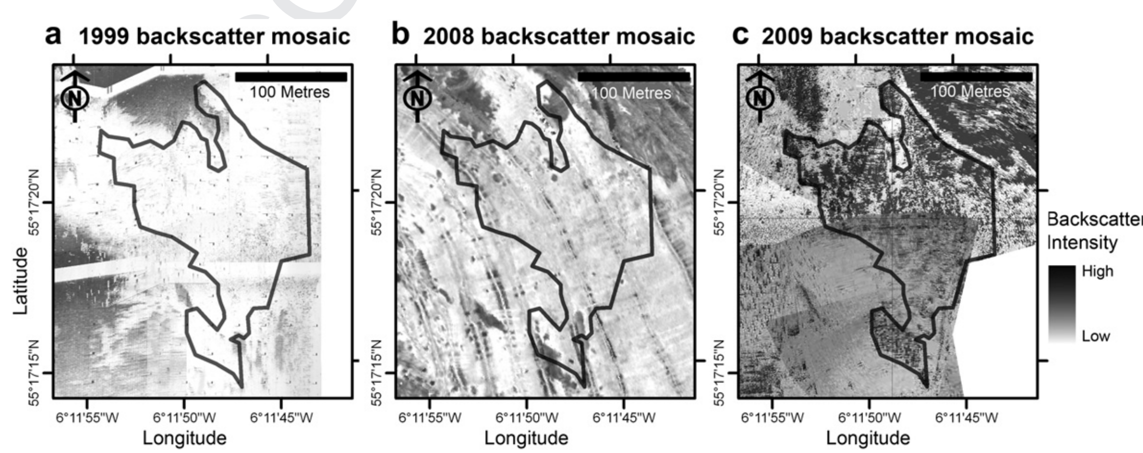


Fig. 6. Comparison of backscatter imagery from an area of seagrass beds in Church Bay between acoustic data sets from (a) a sidescan sonar survey in 1999, (b) a multibeam echosounder survey 2008 and (c) a repeat sidescan sonar survey 2009. Extent of seagrass bed in 2009 is indicated by the black outline. The seagrass, *Zostera marina*, can be seen in the 2009 backscatter as areas of patchy, high intensity backscatter within the black outline.

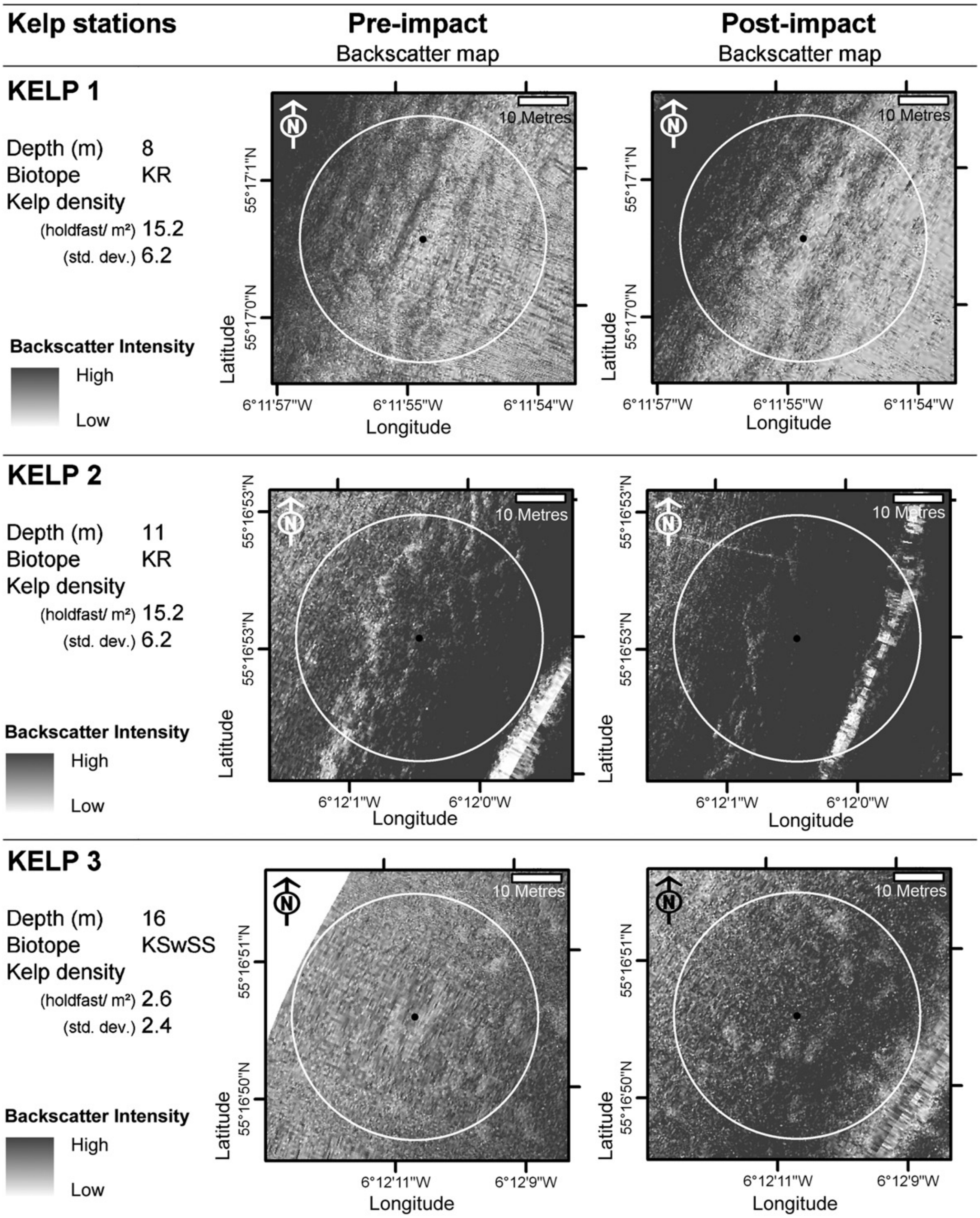


Fig. 7. Backscatter maps and histograms from kelp survey sites before and after the experimental impact. Kelp 1 and 2 biotope KR = kelp and red seaweeds on infralittoral rock; Kelp 3 biotope KSwSS = kelp and seaweeds on sublittoral sediments. Std. dev. = standard deviation.

et al., 2011). Using these MBES-based data analyses, the full acoustic signal rather than processed backscatter image itself is analysed for kelp-related acoustic signatures, thus removing the observer-based limitations of image-based analyses (McGonigle et al., 2011). In addition, MBES backscatter imagery typically does not suffer nadir-related effects to the same extent as with SSS imagery (White et al., 2007). Therefore, successful kelp monitoring will likely require a combination of technologies, most likely using MBES acoustic techniques, SCUBA divers and drop-video (Mulhearn, 2001; Grove et al., 2002).

5.3. Conclusions and recommendations

This study addresses the standardisation of low-cost, easily-repeatable monitoring methods using ASC. Over broad- to meso-scales (>100 m^2) the techniques outlined in this study are well suited to the detection of biotopes (Van Rein et al., 2009) and as such provide appropriate tools for the monitoring requirements of the Marine Strategy Framework Directive (EC, 2008) in Europe and similar legislation elsewhere. Changes in the distribution of marine biotopes in Church Bay between 1999, 2008 and 2009 are

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011

described from the biotope maps, meeting the first objective. For the second objective, the removal of 100 m^2 areas of kelp was not detected by visual analysis of backscatter imagery from kelp biotopes, suggesting that when used under the settings of this study, high-frequency SSS cannot detect the presence of certain kelp macroalgae. Alternatives to detecting kelp with ASC, however, are noted (McGonigle et al., 2011). Overall, this study achieves its aim and demonstrates that remote monitoring of seabed habitats using ASC is achievable and beneficial over broad- and meso-scales, but requires further trial. We make three recommendations to address issues highlighted by this study:

(1) The acquisition errors in both surveys and increased nadir-related effects highlight consistent issues of using SSS. MBES-acquired imagery does not suffer nadir-related effects to the same extent as SSS-acquired imagery (White et al., 2007). Furthermore, MBES can acquire simultaneous bathymetric and backscatter data from a single survey at higher positional accuracies than the SSS. The bathymetric data proved invaluable in visualising the depth profile of Church Bay, which related to the distribution of biotopes. In addition, the potential of conducting automated backscatter segmentations further promotes the suitability of MBES systems for the monitoring of biotopes over broad- and meso-scales.

(2) Physically-defined biotopes (e.g.: IFiSa, ICS) were easily distinguished by ASC. However, biologically-defined biotopes (e.g.: KSwSS, SSgr) were distinguished with less consistency. If not for the additional bathymetric mapping (using the MBES) and the seasonality of sampling, features critical to the identification of the KSwSS and SSgr biotopes, respectively, would not have been utilised. This highlights the importance of conducting pilot studies of an area, to establish local bathymetry and issues of seasonality, before the commencement of any annual monitoring.

(3) Ground-truth surveys should accompany every acoustic survey to adequately verify the acoustics and determine temporal shifts in biological characteristics. The use of drop-video cameras is highly recommended for biotope monitoring, due to a strong correlation between the biotopes from the video data and the acoustic facies from the backscatter segmentation. Furthermore, data extraction from the video is cheap and efficient, relative to other ground-truth methods.

Uncited references

Brown and Coggan, 2007; Diaz et al., 2004; Ellingsen et al., 2002; Gilkinson et al., 2003; James, 2007; McGonigle et al., 2009; Olenin and Ducrotoy, 2006; Valentine et al., 2005.

Acknowledgements

The authors would like to thank the Maritime and Coastguard Agency, the Marine Institute of Ireland and the crew of the *RV Gulfstream* for providing the Joint Irish Bathymetric Survey data for the 2008 biotope survey. We also thank Ruth Plets for processing the 2008 MBES collected data; the crew of the *RV Blackwater* for their valuable support during the SSS surveys of 2009; Martin Sayer, Simon Thurston, Hugh Brown and Elaine Azzopardi of the National Facility of Scientific Diving for their valuable diving support; and Nigel McCauley for his technical support in the construction of the drop-video frame. The work was funded by Natural Environment Research Council grant no. NFSD/08/01, and the Northern Ireland Environment Agency project entitled "Investigating monitoring methods for assessing change in seabed habitats" (University of Ulster grant: 1203-R-0187).

References Q2

Q3 Anderson, J.T., Holliday, V., Kloser, R., Reid, D., Simard, Y., 2007. Acoustic Seabed Classification of Marine Physical and Biological Landscapes. In: ICES Co-operative Research Report, vol. 286 Copenhagen, Denmark.

Anderson, J.T., Van Holliday, D., Kloser, R., Reid, D.G., Simard, Y., 2008. Acoustic seabed classification: current practice and future directions. ICES Journal of Marine Science 65, 1004–1011.

Ardizzone, G., Belluscio, A., Maiorano, L., 2006. Long-term change in the structure of a Posidonia oceanica landscape and its reference for a monitoring plan. Marine Ecology-An Evolutionary Perspective 27, 299–309.

Atkins, W.S., 1997. Geology and physical environment. In: Barnes, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P., Davidson, N.C., Buck, A.L. (Eds.), Coasts and Seas of the United Kingdom: Region 17, Northern Ireland. Joint Nature Conservation Committee, Peterborough, pp. 19–37.

Backstrom, J.T., Jackson, D.W.T., Cooper, J.A.G., 2009. Shoreface morphodynamics of a high-energy, steep and geologically constrained shoreline segment in Northern Ireland. Marine Geology 257, 94–106.

Breen, J., Hanna, J., Harrison, T., 2006. A Survey of the Marine Environment of Rathlin Island Environment and Heritage Service Report. Belfast: 82 p.

Brown, C.J., Cooper, K.M., Meadows, W.J., Limpenny, D.S., Rees, H.L., 2002. Small-scale mapping of sea-bed assemblages in the eastern English Channel using sidescan sonar and remote sampling techniques. Estuarine, Coastal and Shelf Science 54, 263–278.

Brown, C.J., Hewer, A., Meadows, W.J., Limpenny, D.S., Cooper, K.M., Rees, H.L., 2004a. Mapping seabed biotopes at Hastings Shingle Bank, eastern English Channel. Part 1. Assessment using sidescan sonar. Journal of the Marine Biological Association of the United Kingdom 84, 481–488.

Brown, C.J., Hewer, A.J., Limpenny, D.S., Cooper, K.M., Rees, H.L., Meadows, W.J., 2004b. Mapping seabed biotopes using sidescan sonar in regions of heterogeneous substrata: case study east of the Isle of Wight, English Channel. Underwater Technology 26, 27–36.

Brown, C.J., Mitchell, A., Limpenny, D.S., Robertson, M.R., Service, M., Golding, N., 2005. Mapping seabed habitats in the Firth of Lorn off the west coast of Scotland: evaluation and comparison of habitat maps produced using the acoustic ground discrimination system, RoxAnn, and sidescan sonar. ICES Journal of Marine Science 62, 790–802.

Brown, C.J., Coggan, R., 2007. Verification of acoustic classes. In: Anderson, J.T., Holliday, V., Kloser, R., Reid, D., Simard, Y. (Eds.), Acoustic Seabed Classification of Marine Physical and Biological Landscapes. ICES, Copenhagen, pp. 127–144.

Brown, C.J., Collier, J.S., 2008. Mapping benthic habitat in regions of gradational substrata: an automated approach utilising geophysical, geological, and biological relationships. Estuarine, Coastal and Shelf Science 78, 203–214.

Cabello-pasini, A., Lara-Turrent, C., Zimmerman, R., 2002. Effect of storms on photosynthesis, carbohydrate content and survival of eelgrass populations from a coastal lagoon and the adjacent open ocean. Aquatic Botany 74, 149–164.

Cochrane, G.R., Lafferty, K.D., 2002. Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California. Continental Shelf Research 22, 683–690.

Coggan, R., Populus, J., White, J., Sheehan, K., Fitzpatrick, F., Piel, S., 2007. Review of Standards and Protocols for Seabed Habitat Mapping. Mapping European Seabed Habitats (MESH), Peterborough, UK. 210 p.

Collier, J.S., Humber, S.R., 2007. Time-lapse side-scan sonar imaging of bleached coral reefs: a case study from the Seychelles. Remote Sensing of Environment 108, 339–356.

Connor, D.W., Allen, J.H., Golding, N., Howell, K.L., Lieberknecht, L.M., Northen, K.O., Reker, J.B., 2004. The Marine Habitat Classification for Britain and Ireland (Version 04.05). URL:. Joint Nature Conservation Committee, Peterborough http://www.jncc.gov.uk/page-1584 (accessed 27.01.11.).

Davidson, D.M., Hughes, D.J., 1998. Zostera Biotopes (Volume I). An Overview of Dynamics and Sensitivity Characteristics for Conservation Management of Marine SACs. UK Marine SACs Project, Scottish Association for Marine Science, Dunstaffnage. 95 p.

Davies, C.E., Moss, D., Hill, M.O., 2004. EUNIS Habitat Classification Revised 2004. Report to the European Topic Centre on Nature Protection and Biodiversity. European Environment Agency, Copenhagen. 307 p.

Davies, J., Baxter, J., Bradley, M., Connor, D., Khan, J., Murray, E., Sanderson, W., Turnbull, C., Vincent, M., 2001. Marine Monitoring Handbook. Joint Nature Conservation Committee, Peterborough. 405 p.

Degraer, S., Moerkerke, G., Rabaut, M., Van Hoey, G., Du Four, I., Vincx, M., Henriet, J., Van Lancker, V., 2008. Very-high resolution side-scan sonar mapping of biogenic reefs of the tube-worm Lanice conchilega. Remote Sensing of Environment 112, 3323–3328.

Dennison, W.C., Alberte, R.S., 1985. Role of daily light period in the depth distribution of Zostera marina (eelgrass). Marine Ecology Progress Series 25, 51–61.

Diaz, R.J., Solan, M., Valente, R.M., 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. Journal of Environmental Management 73, 165–181.

Diesing, M., Kubicki, A., Winter, C., Schwarzer, K., 2006. Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea. Continental Shelf Research 26, 902–916.

Diesing, M., Coggan, R., Vanstaen, K., 2009. Widespread rocky reef occurrence in the central English Channel and the implications for predictive habitat mapping. Estuarine, Coastal and Shelf Science 83, 647–658.

Du Four, I., Van Lancker, V., 2008. Changes of sedimentological patterns and morphological features due to the disposal of dredge spoil and the regeneration after cessation of the disposal activities. Marine Geology 255, 15–29.

E.C., 2000. Establishing a framework for community action in the field of water policy. Directive 2000/60/EC of the European Parliament and of the Council. Official Journal of the European Communities 327, 1–72.

E.C., 2008. Establishing a framework for community action in the field of marine environmental policy. Directive 2008/56/EC of the European Parliament and of the Council. Official Journal of the European Communities 164, 19–40.

E.C., 1992. On the conservation of natural habitats and of wild fauna and flora. Council Directive 92/43/EEC. Official Journal 206, 7–50.

Ehrhold, A., Hamon, D., Guillaumont, B., 2006. The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore macrobenthic habitats: application to the Bay of Concarneau (South Brittany, France). ICES Journal of Marine Science 63, 1604–1615.

Ellingsen, K.E., Gray, J.S., Bjørnbom, E., 2002. Acoustic classification of seabed habitats using the QTC VIEW system. ICES Journal of Marine Science 59, 825–835.

Fonseca, L., Mayer, L., 2007. Remote estimation of surficial seafloor properties through the application of Angular Range Analysis to multibeam sonar data. Marine Geophysical Researches 28, 119–126.

Fonseca, L., Brown, C., Calder, B., Mayer, L., Rzhanov, Y., 2009. Angular range analysis of acoustic themes from Stanton Banks Ireland: a link between visual interpretation and multibeam echosounder angular signatures. Applied Acoustics 70, 1298–1304.

Foote, K.G., Hanlon, R.T., Iampietro, P.J., Kvitek, R.G., 2006. Acoustic detection and quantification of benthic egg beds of the squid Loligo opalescens in Monterey Bay, California. Journal of the Acoustical Society of America 119, 844–856.

Giesen, W.B.J.T., van Katwijk, M.M., den Hartog, C., 1990. Eelgrass condition and turbidity in the Dutch Wadden Sea. Aquatic Botany 37, 71–85.

Gilkinson, K.D., Fader, G.B.J., Gordon, D.C., Charron, R., McKeown, D., Roddick, D., Kenchington, E.L.R., MacIsaac, K., Bourbonnais, C., Vass, P., Liu, Q., 2003. Immediate and longer-term impacts of hydraulic clam dredging on an offshore sandy seabed: effects on physical habitat and processes of recovery. Continental Shelf Research 23, 1315–1336.

Grewal, M.S., Weill, L.R., Andrews, A.P., 2007. Global Positioning Systems, Inertial Navigation, and Integration, second ed. John Wiley and Sons. 525 p.

Grove, R.S., Zabloudil, K., Norall, T., Deysher, L., 2002. Effects of El Nino events on natural kelp beds and artificial reefs in southern California. ICES Journal of Marine Science 59, 330–337.

Hagen, A., 2002. Multi-method assessment of map similarity. In: Ruiz, M., Gould, M., Ramon, J. (Eds.), Proceedings of the Fifth AGILE Conference on Geographic Information Science, Palma, Spain, pp. 171–182.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Journal of Coastal Engineering 4, 253–277.

Hewitt, J.E., Thrush, S.F., Cummings, V.J., Turner, S.J., 1998. The effect of changing sampling scales on our ability to detect effects of large-scale processes on communities. Journal of Experimental Marine Biology and Ecology 227, 251–264.

Holt, R., Sanderson, B., 2001. Procedural guideline no. 3–5: identifying biotopes using video recordings. In: Davies, J., Baxter, J., Bradley, M., Connor, D., Khan, J., Murray, E., Sanderson, W., Turnbull, C., Vincent, M. (Eds.), Marine Monitoring Handbook. Joint Nature Conservation Committee, Peterborough, UK, pp. 241–251.

International Hydrographic Bureau, 1998. IHO Standards for Hydrographic Surveys – Special Publication, fourth ed., vol. 44.

James, C., 2007. Sidescan sonar. In: Coggan, R., Populus, J., White, J., Sheehan, K., Fitzpatrick, F., Piel, S. (Eds.), Review of Standards and Protocols for Seabed Habitat Mapping. Mapping European Seabed Habitats (MESH), Peterborough, UK, pp. 45–52.

Kendall, M.S., Jensen, O.P., Alexander, C., Field, D., McFall, G., Bohne, R., Monaco, M.E., 2005. Benthic mapping using sonar, video transects, and an innovative approach to accuracy assessment: a characterization of bottom features in the Georgia Bight. Journal of Coastal Research 21, 1154–1165.

Kostylev, V.E., Todd, B.J., Fader, G.B.J., Courtney, R.C., Cameron, G.D.M., Pickrill, R.A., 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Marine Ecology Progress Series 219, 121–137.

Kostylev, V.E., Courtney, R.C., Robert, G., Todd, B.J., 2003. Stock evaluation of giant scallop (*Placopecten magellanicus*) using high-resolution acoustics for seabed mapping. Fisheries Research 60, 479–492.

Kubicki, A., Diesing, M., 2006. Can analogue sidescan sonar data still be useful? An example of sonograph mosaic geocoded in Decca Navigation System. Continental Shelf Research 26, 1858–1867.

Lalli, C.M., Parsons, T.R., 1997. Biological Oceanography: an Introduction, second ed. Butterworth-Heinemann. Elsevier Butterworth-Heinemann, Oxford. 314 p.

Lathrop, R.G., Cole, M., Senyk, N., Butman, B., 2006. Seafloor habitat mapping of the New York Bight incorporating sidescan sonar data. Estuarine, Coastal and Shelf Science 68, 221–230.

Lindenbaum, C., Bennell, J.D., Rees, E.L.S., Mcclean, D., Cook, W., Wheeler, A.J., Sanderson, W.G., 2008. Small-scale variation within a Modiolus modiolus (Mollusca: Bivalvia) reef in the Irish Sea: I. Seabed mapping and reef morphology. Journal of the Marine Biological Association of the United Kingdom 88, 133–141.

Lurton, X. (Ed.), 2002. An Introduction to Underwater Acoustics: Principles and Applications. Springer, Chichester, p. 347.

Lyons, A.P., Pouliquen, E., 1998. Measurements of high-frequency acoustic scattering from seabed vegetation. Journal of the Acoustical Society of America 103, 2934.

Méléder, V., Populus, J., Guillaumont, B., Perrot, T., Mouquet, P., 2010. Predictive modelling of seabed habitats: case study of subtidal kelp forests on the coast of Brittany, France. Marine Biology 157, 1525–1541.

McCarthy, E., 1997. Acoustic characterisation of submerged aquatic vegetation. In: Pace, N.G., Pouliquen, E., Bergem, O., Lyons, A.P. (Eds.), High Frequency Acoustics in Shallow Water. NATO SACLANT Undersea Research Centre, pp. 363–369.

McDowell, J.L., Knight, J., Quinn, R., 2007. Mesoscale changes in present-day nearshore surface sediments and bedform dynamics off the north coast of Ireland. In: Balson, P.S., Collins, M.B. (Eds.), Coastal Shelf and Transport. Geological Society of London, Special Publications, vol. 274, pp. 103–116.

McGonigle, C., Brown, C., Quinn, R., Grabowski, J., 2009. Evaluation of image-based multibeam sonar backscatter classification for benthic habitat discrimination and mapping at Stanton Banks, UK. Estuarine, Coastal and Shelf Science 81, 423–437.

McGonigle, C., Brown, C., Quinn, R., 2010. Operational parameters, data density and benthic ecology: considerations for image-based classification of multibeam backscatter. Marine Geodesy 33, 16–38.

McGonigle, C., Brown, C., Quinn, R., 2011. Detection of deep water benthic macroalgae using image-based classification techniques on multibeam backscatter at Cashes Ledge, Gulf of Maine, USA. Estuarine, Coastal and Shelf Science 91, 87–101.

Michalopoulos, C., Auster, P.J., Malatesta, R.J., 1993. A comparison of transect and species-time counts for assessing faunal abundance from video surveys. Marine Technology Society Journal 26, 27–31.

Mitchell, A., Coggan, R., 2007. Remote video techniques. In: Coggan, R., Populus, J., White, J., Sheehan, K., Fitzpatrick, F., Piel, S. (Eds.), Review of Standards and Protocols for Seabed Habitat Mapping. Mapping European Seabed Habitats (MESH), Peterborough, pp. 179–203.

Moore, K.A., Wetzel, R.L., 2000. Seasonal variations in eelgrass (Zostera marina L.) responses to nutrient enrichment and reduced light availability in experimental ecosystems. Journal of Experimental Marine Biology and Ecology 244, 1–28.

Moore, K.A., Wetzel, R.L., Orth, R.J., 1997. Seasonal pulses of turbidity and their relations to eelgrass (Zostera marina L.) survival in an estuary. Journal of Experimental Marine Biology and Ecology 215, 115–134.

Mulhearn, P.J.O., 2001. Mapping Seabed Vegetation with Sidescan Sonar. Defense Science and Technology Organisation, Australia, Aeronautical and Maritime Research Laboratory Report No. DSTO-TN-038128 pp.

Nelson, T.A., Waaland, J.R., 1997. Seasonality of eelgrass, epiphyte, and grazer biomass and productivity in subtidal eelgrass meadows subjected to moderate tidal amplitude. Aquatic Botany 56, 51–74.

Olenin, S., Ducrotoy, J.P., 2006. The concept of biotope in marine ecology and coastal management. Marine Pollution Bulletin 53, 20–29.

Olesen, B., Sand-Jensen, K., 1994. Patch dynamics of eelgrass, Zostera marina. Marine Ecology Progress Series 106, 147–156.

Pickrill, R.A., Todd, B.J., 2003. The multiple roles of acoustic mapping in integrated ocean management, Canadian Atlantic continental margin. Ocean & Coastal Management 46, 601–614.

Quinn, R., Forsythe, W., Plets, R., Westley, K., Bell, T., McGrath, F., Robinson, R., Benetti, S., Clements, A., McGonigle, C., 2009. Archaeological Applications of the Joint Irish Bathymetric Survey (JIBS) Data: Phase 2 Irish National Strategic Archaeological Research (INSTAR) Programme 2009, Report No. 16702. 110 p.

Quintino, V., Freitas, R., Mamede, R., Ricardo, F., Rodrigues, A.M., Mota, J., Pérez-Ruzafa, Á., Marcos, C., 2010. Remote sensing of underwater vegetation using single-beam acoustics. ICES Journal of Marine Science 67, 594–605.

Roberts, J.M., Brown, C.J., Long, D., Bates, C.R., 2005. Acoustic mapping using a multibeam echosounder reveals cold-water coral reefs and surrounding habitats. Coral Reefs 24, 654–669.

Sager, W.W., MacDonald, I.R., Hou, R.S., 2003. Geophysical signatures of mud mounds at hydrocarbon seeps on the Louisiana continental slope, northern Gulf of Mexico. Marine Geology 198, 97–132.

Schimel, A.C.G., Healy, T.R., Johnson, D., Immenga, D., 2010. Quantitative experimental comparison of single-beam, sidescan, and multibeam benthic habitat maps. ICES Journal of Marine Science 67, 1766–1779.

Service, M., Golding, N., 2007. Procedural guideline no. 3–14: in situ survey of sublittoral epibiota using towed sledge video and still photography. In: Davies, J., Baxter, J., Bradley, M., Connor, D., Khan, J., Murray, E., Sanderson, W., Turnbull, C., Vincent, M. (Eds.), Marine Monitoring Handbook. Joint Nature Conservation Committee, Peterborough, UK, pp. 331–338.

UK Hydrographic Office, 1995. Admiralty Tidal Stream Atlas: North Coast of Ireland and West Coast of Scotland, NP 218, fifth ed. Taunton, Somerset.

Valentine, P.C., Todd, B.J., Kostylev, V.E., 2005. Classification of marine sublittoral habitats, with application to the Northeastern North America Region. American Fisheries Society Symposium 41, 183–200.

Van Rein, H., Brown, C.J., Quinn, R., Breen, J., 2009. A review of sublittoral monitoring methods in temperate waters: a focus on scale. Underwater Technology 28, 1–15.

Visser, H., 2004. The Map Comparison Kit: Methods, Software, Applications Research Institute for Knowledge Systems Report 550002005/2004, 127 p.

Visser, H., de Nijs, T., 2006. The map comparison Kit. Environmental Modeling and Software 21, 346–358.

White, J., Jegat, V., Van Lancker, V., Deleu, S., Vanstaen, K., 2007. Multibeam echo Sounders. In: Coggan, R., Populus, J., White, J., Sheehan, K., Fitzpatrick, F., Piel, S. (Eds.), Review of Standards and Protocols for Seabed Habitat Mapping. Mapping European Seabed Habitats (MESH), Peterborough, UK, pp. 53–72.

Wildish, D.J., Fader, G.B.J., Lawton, P., MacDonald, A.J., 1998. The acoustic detection and characteristics of sublittoral bivalve reefs in the Bay of Fundy. Continental Shelf Research 18, 105–113.

Please cite this article in press as: van Rein, H., et al., An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2–1 km^2), Estuarine, Coastal and Shelf Science (2011), doi:10.1016/j.ecss.2011.04.011