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Detection of deep water benthic macroalgae using image-based classification techniques on multibeam backscatter at Cashes Ledge, Gulf of Maine, USA

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A B S T R A C T

Benthic macroalgae form an important part of temperate marine ecosystems, exhibiting a complex three-dimensional character which represents a vital foraging and spawning ground for many juvenile fish species. In this research, image-based techniques for classification of multibeam backscatter are explored for the detection of benthic macroalgae at Cashes Ledge in the Gulf of Maine, USA. Two classifications were performed using *QTC-Multiview*, differentiated by application of a threshold filter, and macroalgal signatures were independently extracted from the raw sonar datagrams in *Matlab*. All classifications were validated by comparison with video ground-truth data. The unfiltered classification shows a high degree of complexity in the shallowest areas within the study site; the filtered demonstrates markedly less variation by depth. The unfiltered classification shows a positive agreement with the video ground-truth data; 82.6% of observations recording *Laminaria* sp., 39.1% of *Agarum cribrosum* and 100.0% ($n = 3$) of mixed macroalgae occur within the same acoustically distinct group of classes. These are discrete from the 8.1% recorded agreement with absences and nulls (>40 m) of macrophytes ($n = 32$) from a total of 86 ground-truth locations. The results of the water column data extraction (*WCDE*) show similar success, accurately predicting 78.3% of *Laminaria* sp. and 30.4% of *A. cribrosum* observations.

The unfiltered classes which showed agreement with the ground-truth data were then compared to the *WCDE* results. Comparison of surface areas reveals the overall percentage agreement is relatively constant with depth (67.0–70.0%), with *Kappa* coefficient increasing from $k = 0.17–0.35$ as depth (and surface area) increases. The results have demonstrated that both methods were more effective at detecting the presence of *Laminaria* sp. (82.6–77.3%) than *Agarum cribrosum*, (66.6–30.4%), and that the efficiency of prediction decreased with depth. Canopy volume derived from the *WCDE* analysis was between 1.21×10^6 m^3 at <24 m water depth, 1.82×10^6 m^3 at <30 m and 2.45×10^6 m^3 at <40 m. These results suggest that the presence of benthic macrophytes has a significant capacity to affect image-based classification of acoustic data, and highlights the fact that multibeam backscatter and image-based classification have significant potential for benthic macroalgal research. This is beneficial to help refine segmentations of substrates, adding valuable contextual information about biological characteristics of infaunal and epifaunal benthic communities.

1. Introduction

Benthic macroalgae represent an important component of marine ecosystems, both in their own right and from the perspective of those organisms which utilise them for habitat at various stages in their life cycles. The complex three-dimensional structure of kelp canopies means that they provide a variety of niches which accommodate a wide range of species in temperate marine ecosystems (Dayton, 1985; Tegner and Dayton, 2000). Annual primary production for major marine macroalgae is higher than most comparable terrestrial biomass (Ross et al., 2008). Macroalgae have been shown to exhibit remarkable potential for CO_2 bioremediation (Gao and McKinley, 1994), in addition to presenting a potential alternative to fossil fuels (Yantovski, 2008). Commercial activities focus on the exploitation of macroalgae either directly

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(by extraction), or indirectly (by the extraction of resident species). Many species of commercial interest utilise macroalgae at various stages in their development; for example juvenile fish (Cote et al., 2003). The quality and availability of this habitat can have significant consequences for commercially significant species (e.g. *Gadus morhua*), although the relationship between individual species and use of habitat is not yet well understood. However, the lack of habitat availability will undoubtedly have profound implications for the sustainable exploitation of commercial stocks (e.g. Tegner and Dayton, 2000; Steneck et al., 2002).

1.1. Temperate kelp forest habitats

Kelp forests dominate the rocky subtidal habitats of the vast majority of temperate marine ecosystems, with global their distribution controlled by the function of a suite of environmental factors including; light, substrata, sedimentation, nutrient availability, water motion, salinity and temperature (Dayton, 1985). Steneck et al. (2002) describe three distinct morphological forms, differentiated by the canopy height of their fronds. The groups are described as being either ‘canopy’, ‘stipate’ or ‘prostrate’. These differing adult morphologies can coexist, and this serves to increase the structural diversity of the system. This typically involves the presence of the three morphologies with an understory of corticated macrophyte turf with encrusting coralline algae (Dayton, 1985). It is with the third morphological group, the ‘prostrate’ kelps which cover the benthos with their fronds (Steneck et al., 2002), and the concept of canopy structure that this research is primarily concerned. This morphological group includes several common species of *Laminaria* which co-occur in depth banded zonations, common in the Gulf of Maine region in the North Atlantic coast of the USA.

1.2. Remote sensing of benthic habitats

Benthic habitat mapping is a rapidly expanding multidisciplinary science; its origins in surficial geology have broadened to include subsurface geology, hydrodynamics, biological and ecological elements of the seafloor environment (Brown et al., 2002; Beaman et al., 2005; Anderson et al., 2008; Brown and Blondel, 2009). This discipline is evolving largely in tandem with advances in acquisition hardware and software, with each generation of sensors increasing in sensitivity and resolvability (Mayer, 2006a). The sensor technology and processing units have developed rapidly in a relatively short period of time leading to a wide variety of instruments including; single and multibeam echosounders, side-scan sonar and synthetic aperture sonar. The relative merits are discussed at length in several seminal texts (Medwin and Clay, 1998; Lurton, 2002). Increasingly, multibeam echosounders (MBES) are becoming the tool of choice for seabed habitat mapping efforts (Hughes Clarke et al., 1996; Kostylev et al., 2001; Lathrop et al., 2006; McGonigle et al., 2009; Brown et al., in press), and the question arises as to which is the most effective way to process and interpret these data to maximum effect.

Techniques for the classification of remotely sensed data have developed in concert with the technology (Anderson et al., 2008). One of the main commercial packages in the marine sector is *QTC-Multiview*, which is designed to perform objective segmentations of MBES backscatter data (Preston et al., 2001; QTC, 2005). This software has previously been demonstrated to have performed effective, ecologically meaningful segmentations of backscatter data (e.g. Robidoux et al., 2008; Preston, 2009; McGonigle et al., 2009, 2010a, 2010b; Brown et al., in press). The overwhelming majority of previous examples of classification procedures for MBES data have been based around substrate classification (e.g. Collins and Preston, 2002; Fonseca and Mayer, 2007), or the detection of habitats which exhibit a strong geophysical signature e.g. biogenic reefs (Roberts et al., 2005) or scallop beds (Kostylev et al., 2001, 2003). However, the effectiveness of *QTC-Multiview* has not yet been fully examined, particularly with the anticipated presence of biogenic material in the water column. It has yet to be established whether this methodology can provide an acceptable technique for the differentiation of more subtle variations, such as that between gradational substrates or the presence/absence of benthic macrophytes.

1.3. Remote sensing of algal habitats

Remote sensing of benthic macroalgae is broadly divisible into either electromagnetic (EM) or acoustic approaches to detection. The theory and application of optical techniques for the remote sensing of aquatic vegetation are well summarised by Silva et al. (2008). However, irrespective of the mode of acquisition, the use of optical techniques for remote sensing in coastal and marine waters is fundamentally limited to shallow, clear coastal waters due to the attenuation of EM radiation by the water column (Lehmann and Lachavanne, 1997) and the inability to directly measure the depths at which algae occur.

The use of acoustic techniques resolves these issues, facilitating the detection of the vertical height of the macrophyte canopy relative to the seabed. The transmission and reception of sound of an appropriately high frequency with sufficient vertical resolution would theoretically allow for the differentiation of the vertical structure of a macrophyte canopy from the seabed interface. Acoustics have been used extensively in the detection of underwater vegetation, although the vast majority have done so using single beam echosounder technology (Anderson et al., 2002; Sabol et al., 2002; Quintino et al., 2010) and side-scan sonar (Kruss et al., 2006; Tegowski et al., 2007). Multibeam technology is gaining widespread adoption within the scientific community for a wide range of applications, although this potential has yet to be fully exploited. Potential reasons for this may include the relative infancy of the hardware and processing and the relatively costs associated with data acquisition.

Increasingly, attention is being drawn to using water column to better understanding the processes which control the distribution of benthic organisms and the communities to which they belong. Focusing on objects in the water column and directly above the benthos using MBES is a relatively recent phenomenon in seabed science, and is most commonly implemented for the detection of fish (e.g. Mayer et al., 2002; Cutter and Demer, 2007; Gurshin et al., 2009; Weber et al., 2009). Similar approaches have also been applied to the detection of benthic macrophytes using MBES bathymetric soundings (Komatsu et al., 2003; Mayer, 2006b; Kruss et al., 2008).

1.4. Study area

Cashes Ledge, a shallow offshore bank in the central Gulf of Maine off the US Coast of New England (Fig. 1) was the selected as the study area. The geology of the region has been described previously (Uchupi, 1968; Ballard and Uchupi, 1975; Uchupi and Bolmer, 2008), comprising a series of basins intermittently capped by irregularly crested ridges and banks. The Ammen Rock Pinnacle (Figs. 1 and 4a) is the shallowest part of the 8.88 km^2 study area (>10 m water depth) and is the focus of this investigation. The Pinnacle was the subject of previous scientific investigations into the distribution of deep water algae in the late 1980s (Vadas and Steneck, 1988).

Cashes Ledge has been historically noted for its productivity as a fishing ground (Collins and Rathbun, 1887; Rich, 1929). The area is

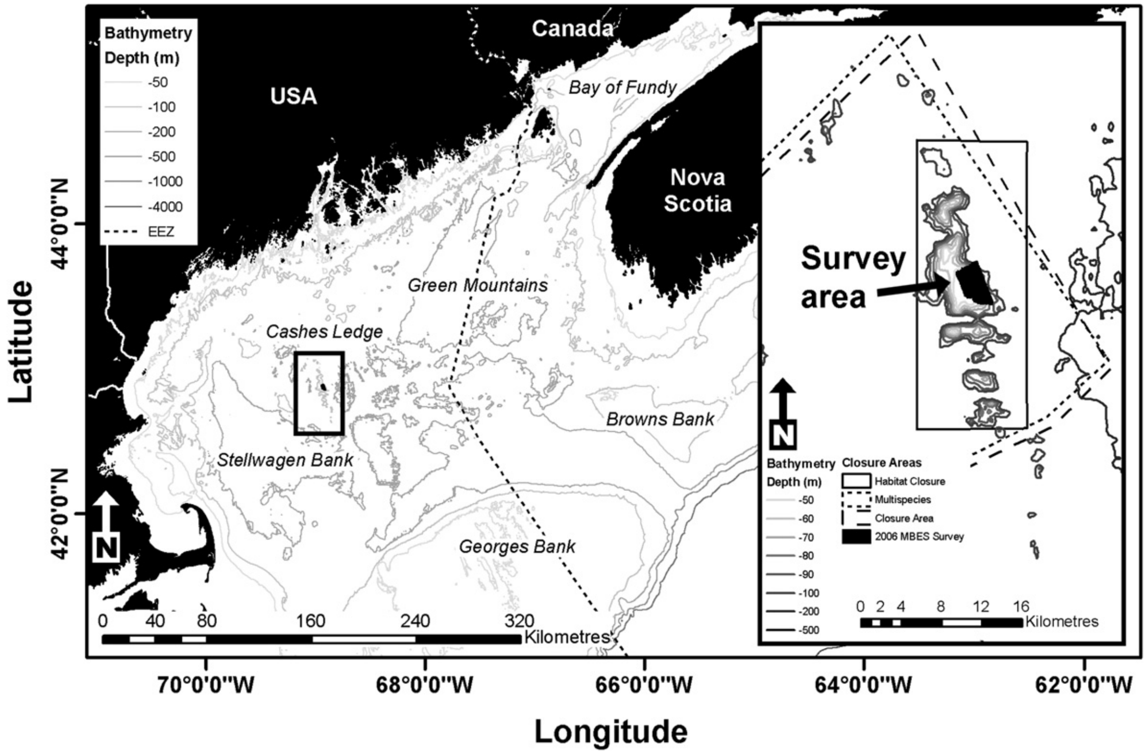

Fig. 1. Location map of Cashes Ledge in the regional context of the Gulf of Maine. Three of the seven US MPAs which Cashes Ledge is contained within are indicated on this figure: Cashes Ledge Habitat Closure; Closure area (Multispecies), Closure Area.

affected by several restrictions on activities (Fig. 1), most significantly to commercial fishing by the New England Fisheries Management Council. Recent studies have recorded the highest population of cod densities in the literature (Whitman and Sebens, 1992; Steneck, 1997; Steneck and Carlton, 2001).

Investigations of the deep water benthic algal communities of the Ledge (Vadas and Steneck, 1988) have helped to inform the significance of the macroalgae species at Cashes Ledge for various stages in cod development. The findings of this research describe a tripartite zonation; with leathery macrophytes dominating to 40 m water depth, foliose red algae to 50 m and crustose red algaes to depths of 63 m. In this work, the focus is on the ability to resolve the material in the upper 40 m of the water column. Vadas and Steneck (1988) describe the dominance of a large species of *Laminaria* sp. which closely resembles *Laminaria digitata*, with fronds up to 2 m in length spaced 0.2–0.5 m apart (Taylor, 1937; Fig. 2a). These algae were observed to form an open park like canopy, mostly between 25 and 30 m water depth (Vadas and Steneck, 1988). Smaller, non-digitate plants resembling the genus *Laminaria* were observed in deeper water (35–40 m). The occurrence of *Laminaria longicruris* was recorded extremely rarely, interspersed with the *Laminaria* sp. in the shallower water (>30 m). *L. longicruris* is a large macroalgae, commonly 3–5 m but occasionally up to 12 m, with the holdfast being typically 1.5–2.0 m (Taylor, 1937; Fig. 2b and d). The holdfast is solid at the base, becoming hollow at diameters above 2–3 cm. In deeper waters around the coast of New England, the inflated stipes are commonly visible drifting on surface waters (Taylor, 1937). The dominant macroalgae in the deeper water was *Agarum cribrosum*, which was observed to occur in water depth of up to 40 m (Vadas and Steneck, 1988). This species is of moderate size, with a stalk of 2–5 (up to 30) cm in length, the characteristically perforated blade being 20–30 (up to 60) cm wide, and 5–150 cm in length (Taylor, 1937; Fig. 2c).

1.5. Rationale

The focus of this research is based on the application of MBES technology for the detection of benthic macrophytes. Although the detection and quantification of aquatic vegetation in this manner is not without precedent (e.g. Komatsu et al., 2003; Kruss et al., 2008), this study differs in that it effectively compares two independent methods and examines the significance of their relatedness using accepted methodology for comparison of categorical data (Hagen, 2002).

The first method utilises image-based classification software *QTC-Multiview*, while the second approach is based on the quantitative extraction of water column data. The results of each of the classifications and independently classified ground-truth data are evaluated in the context of existing work at the site (Vadas and Steneck, 1988).

1.6. Aims and objectives

The principal hypothesis being tested is that image-based classification of multibeam backscatter has potential validity for detecting and quantifying the presence and extent of benthic macrophytes. This research has four specific objectives:

(1) To determine the phycological significance of a *QTC-Multiview* classification, with and without the application of a threshold filter;
(2) To examine the similarity between predictive approaches to presence/absence macrophyte detection using *QTC-Multiview* and independent analysis in *Matlab*;
(3) To derive provisional estimates of volume for the kelp canopy at the study area on Cashes Ledge; and
(4) To investigate the significance of water column scattering objects in affecting the results of image-based classification procedures.

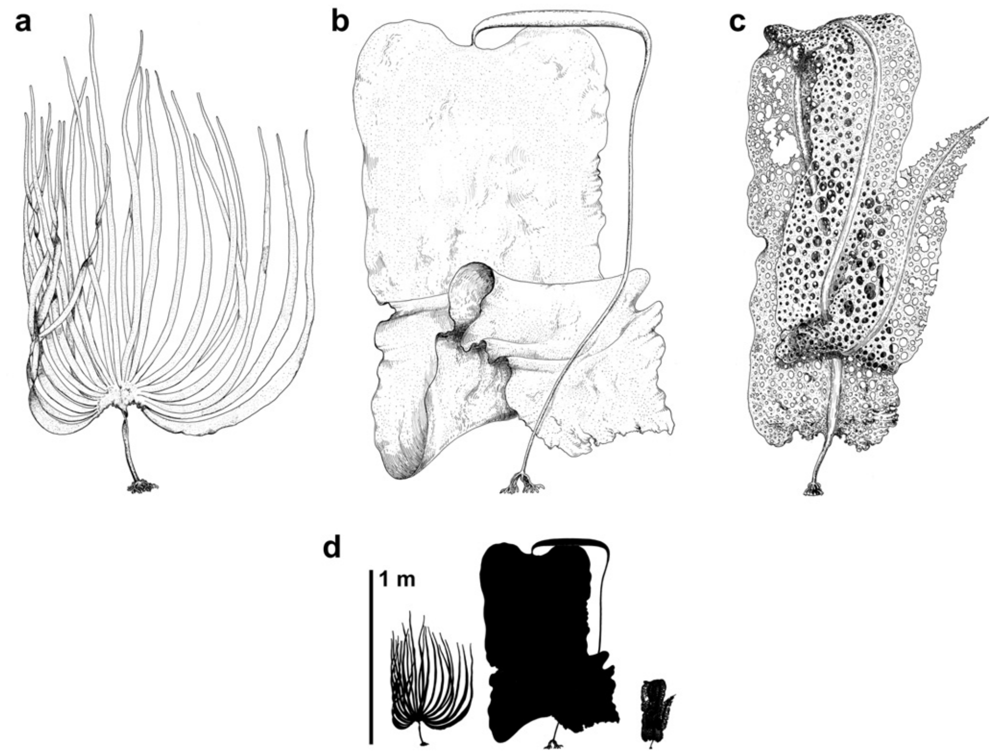

Fig. 2. Description of the principal macroalgal species of relevance in this study recorded as present at the Ammen Rock Pinnacle, Cashes Ledge Gulf of Maine. Modified from Taylor (1937). (a) *Laminaria digitata* ×0.23 magnification; (b) *Laminaria longicruris* ×0.14 magnification; (c) *Agarum cribrosum* ×0.45 magnification; (d) All models (a, b and c) shown to common scale relative to 1 m height.

2. Methodology

2.1. Geophysical data acquisition

MBES data from Cashes Ledge were acquired between 21st and 23rd of June 2006 aboard *FV Ballbreaker* using a *Reson Seabat 7125* operating at 400 kHz.

The transducer was operated in 256 beam equiangular configuration with an across-track beamwidth of >145° in the transmit and 0.54° ± 0.03° (centre) in the receive orientation. The along-track beamwidth was >1° in transmit and 31° ± 3.5° in the receive configuration (RESON, 2005). The angular sector of the sonar was 128° and vessel speed was maintained at 3.6 ms^{-1}. The lane spacing was 50 m in water depths exceeding 30 m, and 25 m for lines shallower than 30 m around the summit of the Ammen Rock Pinnacle (Figs. 1 and 4a). A total of 52 northwest to southeast orientated survey lines were collected, covering a total distance of approximately 200 km and an area of 9 km^2. All of the water column data were logged, with a pulse length of 70 µs, and a sample interval of 1 Hz. Positioning and attitude data were managed by a Coda Octopus F180 inertial navigation system, which had a positional accuracy of 0.5–4.0 m (dGPS), a pitch and roll accuracy of 0.025° and a heave accuracy of 5% of amplitude or 0.05 m.

2.2. Geophysical data processing

2.2.1. Bathymetry and backscatter

The bathymetric soundings were cleaned in *Caris HIPS v.5.2.*, gridded to a 5 m cell size and converted to a floating point raster in *ArcGIS v.9.2*. Beam time-series (snippets) MBES data was used to construct a geometrically compensated backscatter mosaic at 1 m resolution using the developer's version of *Geocoder* (Fonseca and Mayer, 2007) at the Center for Coastal and Ocean Mapping (CCOM), University of New Hampshire, USA.

2.2.2. QTC-Multiview classification

Image-based classification of the MBES backscatter was performed using *QTC-Multiview*. The use of *QTC-Multiview* for defining objective segmentations has been well supported in the recent literature (e.g. Preston, 2009; McGonigle et al., 2009, 2010a, 2010b; Brown et al., in press). These studies have explored in significant detail the biological and geological validity of the segmentations, and examined the effect of variations of acquisition settings and environmental conditions on the outcomes produced. The principal difference between these examples and this study is that in this case two classifications were performed independently and the results were compared; in one a threshold was applied to clean the depth values, and in the other it was not (hereafter referred to as filtered and unfiltered respectively). The diversification of this method was directed by field knowledge of the study site, as the area was known to have a dense coverage of benthic macrophytes based on the reports of Vadas and Steneck (1988). This consideration was unnecessary in any of the previous work using similar approaches as the minimum water depths were 60 m below chart datum (McGonigle et al., 2009, 2010a, 2010b).

The threshold is an internal operation within *QTC-Multiview* based on the observed depths, where it is described as a metric based on the difference between each pixel's depth, those of its neighbours and the standard deviation of pixels in the immediate neighbourhood (QTC, 2005). The value of the metric is relative to the range of values contained in the data; for example in the case of single line of data from this survey the minimum value [0] represents exclusion of all values, and the maximum value [39,728] represents the inclusion of all values. For the filtered dataset, the threshold value was fixed at 500, as this was iteratively determined to suppress spikes in the bathymetric values without compromising the coverage of the bathymetric surface.

The backscatter imagery was then segmented in cognisance of the filtered pixels into rectangular patches of dimensions 513 × 9 image pixels, leading to an average footprint of 11.1 m (across-track) × 32.4 m (along-track). The application of image-processing algorithms to the pixels contained within each rectangular patch (Preston et al., 2001; Preston, 2009) led to the generation of a single geospatial vector composed of 132 individual values for each patch of backscatter imagery. These values were then reduced by Principal Components Analysis (PCA) to three summarising the variance within the data and classified into an objectively defined number of groups by the software through the application of a simulated *k*-means clustering algorithm (Preston, 2009). The first three principal components have been demonstrated to typically capture 90–95% of the variance in the original 132 variables, because so many of the features are correlated (Preston, 2009). Subsequent to acceptance of the optimum defined class, each of these three principal components represents the axes in the 3-D ordination where the classification takes place. The relative proximity of individual clusters is reflected in the scaled similarity of their colour in the ordination, where each principal component is described by the level of colour saturation; the first component is described by red saturation, the second by green, and the third by blue.

These classified data were then processed to derive a categorically interpolated surface of the vector based classification; using *QTC-Clams*. The interpolation parameters were iteratively derived, with a view to minimising the effects of range dependent artifacts in the vector classification whilst maximising the integrity of the original classification. In both instances of the *QTC-Multiview* classification, the interpolation parameters were consistent, based on a 40 m search radius taking into account the class values of the five closest neighbouring points to the centre of each grid node. This search radius provided the best balance between loss of detail in the classification and the dilution of range artefacts. Grid node spacing was maintained at 5 m to preserve the integrity of the boundaries between classes.

2.2.3. Water column data extraction (WCDE)

Water column data from the MBES were processed to extract kelp descriptors (presence/absence and height above bottom) from the raw sensor outputs in *Matlab*. The high topographic relief in the study area made the MBES water column data susceptible to contamination from sidelobes, which confounded the extraction of the kelp descriptors. Contamination effects were reduced by retaining only the middle 100 beams (±25°), retaining data only at depths between 0.5 and 5 m above the bottom detection reported by the MBES for each beam, and performing a simple kelp classification based on the morphology of the water column backscatter.

The kelp classification was performed by recognizing that the backscatter from the kelp appeared as discrete features, in comparison to sidelobe interference which appeared to be more contiguous. In order to classify the data as either kelp or sidelobe interference, the backscatter data were converted to binary (either above or below an amplitude threshold), and statistical estimates of the co-location of the data above the threshold was ascertained. The ratio of co-occurences of the data divided by the total number of pixels was calculated, and when this ratio was less than 0.05, the data were classified as kelp. This value was derived based on iterative processing, and was determined to be the optimal cut off for discrimination of macrophyte presence and the characterisation of sidelobe interference. The amplitude threshold used for this procedure was set to 20 dB lower than the largest target for the examined data in each ping.

For each ping that was classified as having kelp present, the minimum depth of the amplitude thresholded data was extracted for each beam. The median value of these depths was then retained as the depth of the kelp corresponding to the entire ping. An example of the processing concept is presented in Fig. 3, where Fig. 3a shows the raw datagram plot of depth against range and Fig. 3b shows the effect of the application of the differential threshold, used to separate the signal returned by the bottom detection from that of the kelp canopy.

2.3. Ground-truth data acquisition and processing

Ground-truth data were point sample video stills acquired over the course of three cruises (16 days in total) undertaken during the months of July and August in 2006–2007. Oblique-view HD video cameras were mounted on weighted frames, deployed and recovered from buoy marked lines. Subsequent to recovery, individual frames were extracted from the video footage to determine the presence or absence of benthic macrophytes, which was recorded as one of either of the following categories; *Laminaria* sp. (Lam), *Agarum cribrosum* (Aga), Mixed (Mxd) or Absent (Abs). Positional information was recorded based on vessel position and heading. The distribution of ground-truth effort was focussed around shallow water regions where macroalgae would be expected to occur; based on existing knowledge of macroalgae physiology and supported by the findings of Vadas and Steneck (1988).

2.4. Data integration and analysis

2.4.1. Geospatial distribution of the classifications

All of the data products described above were converted into *ArcMap v.9.2* compatible formats and imported for conventional geospatial analysis. The distribution of the data across each of the classes was recorded in a synoptic table. Classified ground-truth data categories for each station (Lam, Aga, Mxd and Abs) were plotted against the *QTC-Multiview* acoustic class in a contingency table (for both of the original classifications) at the location of each ground-truth station.

The relative composition of interpolated raster cells for the filtered and unfiltered classifications were organised into depth zonations as described by Vadas and Steneck (1988), in order to ascertain if there were any comparable patterns evident in the backscatter classifications. The locations of the ground-truth positions were interrogated to derive depth values for each of the observations. Doing so allowed for the algal classification system to be compared to the expected pattern of zonation at the site and for the observed macrophyte coverage to be evaluated in the context of depth and by specific variation using the predefined terms.

2.4.2. Reclassification of the unfiltered data

Based on the agreement with the ground-truth observations and analysis of the *WCDE*, the classes from the unfiltered classification which were observed to have good agreement with the presence of macrophytes were isolated for further analysis. Additional refinements were based on the relative proximity of these classes in the 3-D vector ordination, as the closer the classes are to one another in the ordination, the more related they are acoustically (Preston, 2009). These data were then reclassified to predicted presence/absence, and were further refined by the application of a depth filter, below which there was no evidence of benthic macrophytes presented in the ground-truth data.

2.4.3. Presence, absence and volume

The vertical extent of the data returns above the seabed were recorded for each observation in the *WCDE*, and these heights were

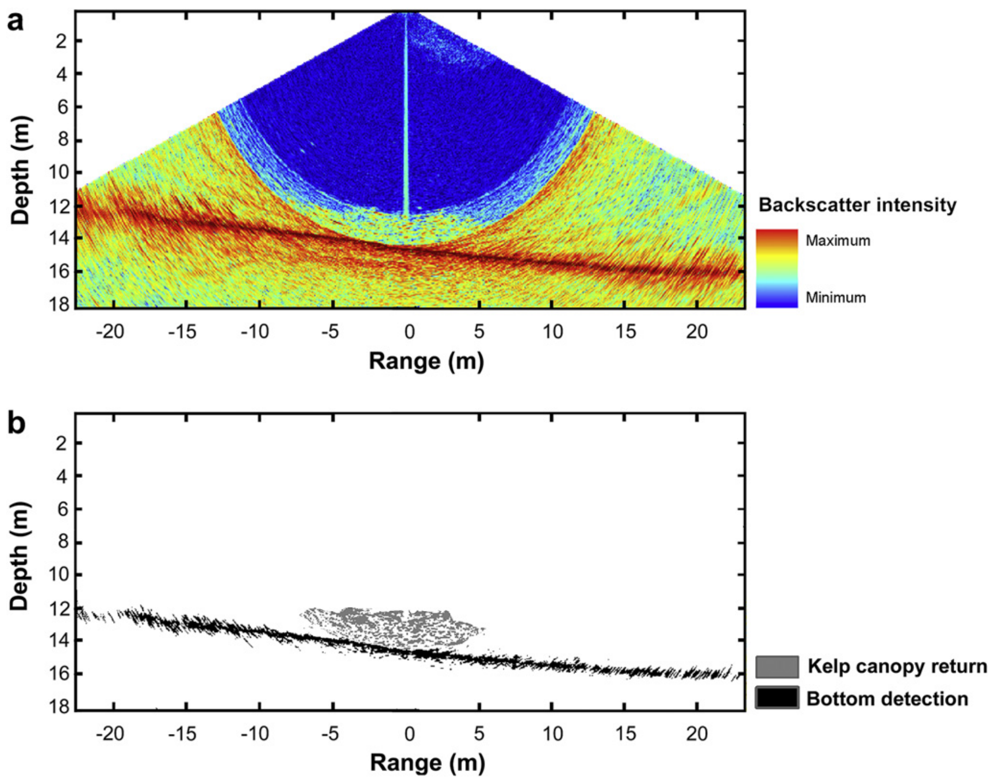

Fig. 3. Example of the process of *WCDE* in *Matlab*. (a) This displays an example of the raw relative backscatter intensity in a plot of depth against range for one datagram from the area <24 m water depth. (b) This displays a figurative example of the differential thresholding of the bottom contact and the kelp canopy.

used to derive an interpolated surface of kelp canopy from the observations. The observed values from the *WCDE* process were buffered to 25 m (line spacing of the original survey), and these polygonal features were used to mask the extent of the interpolated kelp canopy. Surface area and volume within these 3-D polygons was calculated using the difference in volume subtracted beneath a 0 m surface plane, for the interpolated kelp canopy and the bathymetric surface. The 2-D surface area and distribution of the *WCDE* polygons was compared to the *QTC-Multiview* classes which showed evidence of agreement with the ground-truth data. The results of both presence/absence classifications were statistically compared using the *Map Comparison Kit* (Hagen-Zanker et al., 2005). Percentage agreement and *Kappa* coefficients were calculated for the agreement between the different methods of determining presence/absence of macrophytes using the following formula (Landis and Koch, 1977; Hagen, 2002);

$$k = \frac{P(A) - P(E)}{1 - P(E)}$$

where for k (*Kappa*), P (A) is the original fraction of agreement, and P (E) is the expected agreement based on random location subject to the observed distribution (Landis and Koch, 1977; Hagen, 2002). The statistics were further refined by the inclusion of *KLoc* (Pontius et al., 2004) and *KHisto* statistics (Hagen, 2002), which reflect the location and frequency of categories in categorical agreement.

3. Results

3.1. Bathymetry and backscatter

Bathymetric conditions at Cashes Ledge are presented in Fig. 4a, which shows minimum water depths of approximately 10 m in the central western area of the Ledge around the shallowest part of the study area; the Ammen Rock Pinnacle (Figs. 1 and 4a). Fig. 4a shows the 24 m, 30 m and 40 m isobaths, of relevance for the macroalgal zonation patterns described by Vadas and Steneck (1988).

The east flank of Cashes Ledge slopes from 10 m water depth in the west to 140 m in the east over the course of approximately 2.2 km; representing a mean slope of 3.38°. Many localised variations in slope occur at the site (Fig. 4b), with heavily fissured surficial expressions and interstitial recesses of characteristically low levels of slope. Around the eastern-most extent of the site, the slope is less pronounced, although it is frequently punctuated with singular instances of high slope values.

There is a good level of visual agreement with the slope as derived from the bathymetric surface and the backscatter intensity of the substrate (Fig. 4c). Areas of high slope show good spatial correlation with areas of high backscatter. Recesses between fissured areas of high backscatter show a variable response. The distribution of the video ground-truth stations is also displayed superimposed on the MBES backscatter (Fig. 4c).

3.2. QTC-Multiview

3.2.1. Unfiltered classification

The *QTC-Multiview* auto-clustering process (Preston et al., 2004) optimally identified 14 classes based on the processing of the unfiltered data (Fig. 5a and c). As previously described, the classification process is based on the ordination of the classified vectors (FFVs) in 3-D vector space; the ordination is presented for these data in Fig. 5a. The closeness of the class colour is indicative of their acoustic similarity, and these classes form into logical groups of similar composition.

The similarity of these acoustic classes is further confirmed by their distribution on the ground. The geospatial distribution of the classes in the categorical raster is presented Fig. 5c, following interpolation in *QTC-Clams*. It is evident from this classification that

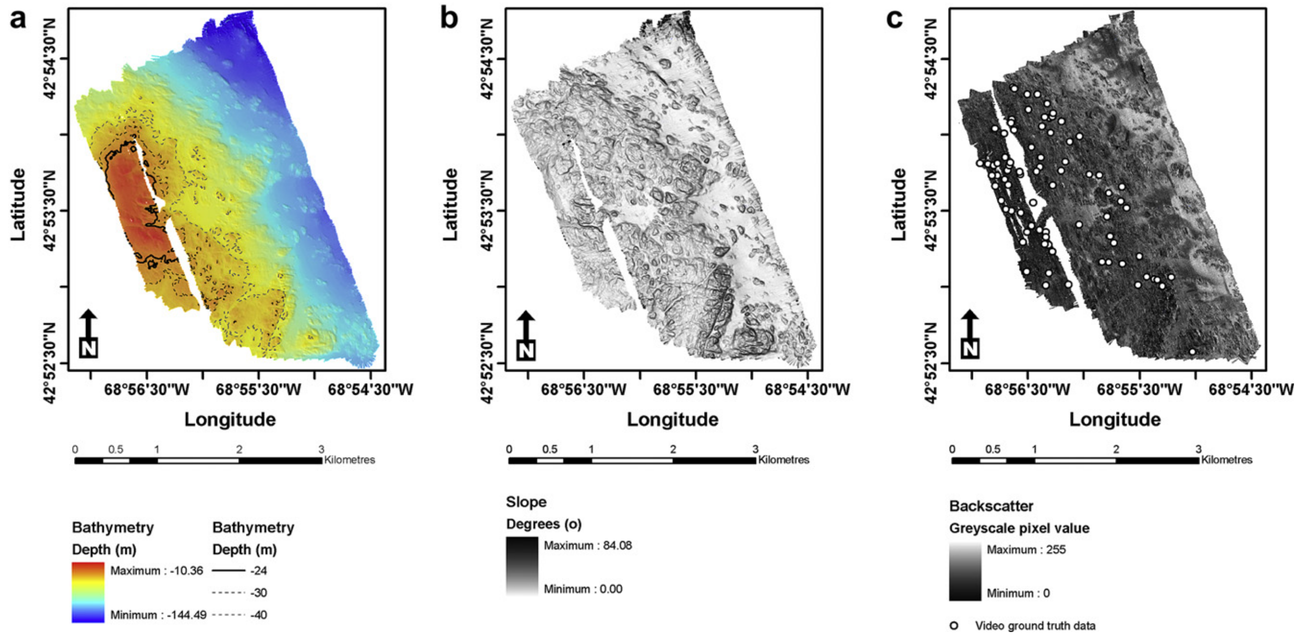

Fig. 4. Geospatial analysis results. (a) Bathymetry (m) as defined by the results of the 400 kHz MBES survey (5 m bin size). The Ammen Rock Pinnacle is the area of shoals defined by the −24 m isobath. (b) Slope in degrees as derived from Fig. 4a. (c) Multibeam backscatter imagery (1 m bin size) as extracted from raw backscatter data, processed using the developer's version of *Geocoder* (Fonseca and Mayer, 2007). The locations of the video ground-truthing stations at Cashes Ledge are indicated by the white circles.

strong linear dependencies remain in the data, and that these are comprised largely by classes 1, 3, 4, 7 and 14. The dominant signature is in the central western section of the study area, where there is a dense aggregation of these classes. This aside, the most significant pattern in the remaining classes is the heterogeneity of classes 5 and 9, and 6 and 11. The remaining classes do not exhibit such definite spatial patterns, do not appear to be depth dependent and tend to be ubiquitous across the study area.

The frequency distribution of all the data types is presented in Table 1. For the unfiltered classification, 52.42% of the interpolated surface belongs to a single class which dominates the classification (class 11). The remainder of classes occupy a smaller proportion of the total classified surface (≥10%).

3.2.2. Filtered classification

Based on the application of a threshold filter, *QTC-Multiview* optimally identified 9 classes. In terms of class identity, class 1 is unique in the 3-D vector space ordination (Fig. 5b). Classes 2 and 4 in the ordination are elevated on the positive Q-3 axis whereas Classes 3 and 9 together represent the most positive expression along the Q-2 axis. Classes 5 and 6 represent a class split across the Q1 axis, distinctive from the remainder of gradational classes along the Q-2 axis (Fig. 5b). Classes 7 and 8 represent the most negative values along the Q-2 axis. In a geospatial context (Fig. 5d), Class 1 dominates the results, responsible for 75.97% of the ground coverage post-interpolation (Table 1). There is no evidence of depth dependency within this class, as it occurs throughout the ranges of the final surface from 10 to 140 m. There is, however, an appearance of agreement between this class and the results of the slope and backscatter analysis. The second largest class is 3 which represents 11.14% of the total coverage for the classified surface (Table 1). The third largest class (9) represents 4.74% of the total. The remainder of classes are responsible for >5% of the total interpolated surface area.

3.3. Water column data extraction (WCDE)

The observations from the water column data analysis performed in *Matlab* are presented in Table 1, where the predicted presence of benthic macrophytes is presented in the context of the *Multiview* class in which they occur (*Kelp Obs*.). The mean height of kelp observations was 3.80 m above the seafloor, with a standard deviation of 2.53 m. The maximum density of observations was restricted to shallower waters, typically in the range of 0.005–0.007 *Kelp Obs*./m^2 in the shallower water around the Ammen pinnacle, decreasing to >0.0007 *Kelp Obs*./m^2 in water from 30 to 40 m. For the unfiltered classification, the majority are coincident with class 1 (36.66%), class 3 (18.51%) and class 14 (18.51%) (Table 1). These three classes all occur with the same area in the 3-D vector space ordination (Fig. 5a), and collectively represent 65.62% of the agreement over the 19.71% of the total surface area (Table 1). Furthermore they do not involve the majority class (11), which alone accounts for <50% of the final classified surface. When compared to the level of agreement with the majority class from the filtered classification, 91.98% of the observations predicting kelp occur within the dominant class (1) covering 75.97% of the final classified surface. All remaining classes individually account for >5% of the total number of observations (Table 1).

3.4. Ground-truth data

The ground-truth data observations are presented summarily in Table 2. As a general overview, benthic macrophytes of the genus *Laminaria* were observed in 23 of the 86 clips (26.74% of total). The same number of sequences of video footage documented the presence of macroalgae *Agarum cribrosum* ($n = 23$ [26.74%]), whilst 3.49% of the total number of clips had mixed macrophyte assemblages. The majority observation ($n = 37$ [43.02%]) recorded the absence of macrophytes, however 86.00% of these observations occur below 40 m water depth (Table 2).

Of the video clips which were characterised by the presence of *Laminaria* sp., 96.00% ($n = 22$) occurred in within Zone 1 (0–24 m water depth). The remaining footage ($n = 1$) occurred between 24 and 30 m. A relatively small number of clips within this Zone show mixed macroalgal species ($n = 3$). Of the segments characterised by the presence of *Agarum cribrosum*; 52.00% ($n = 12$) occurred

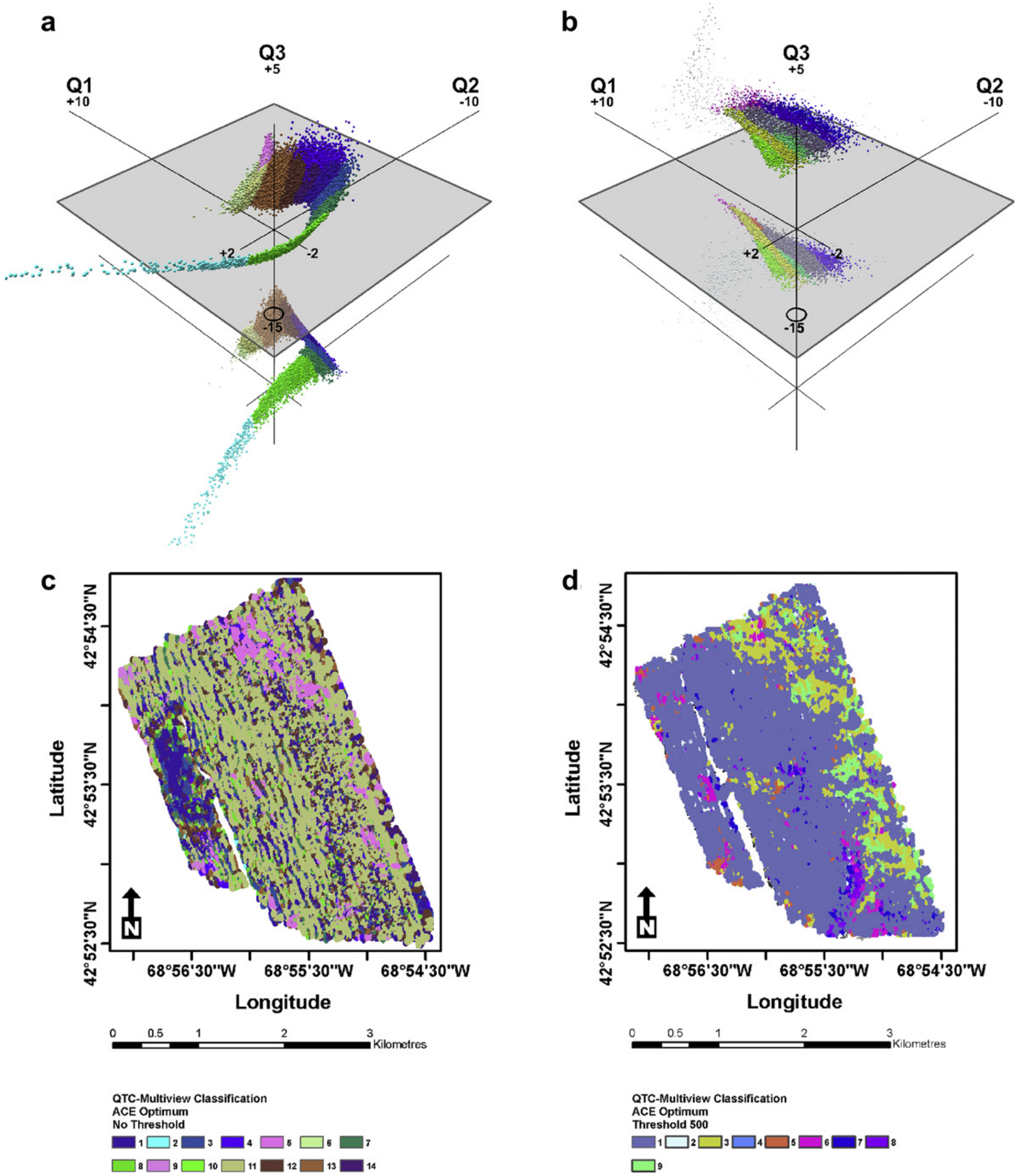

Fig. 5. Results of the *QTC-Multiview* Classification process at Cashes Ledge. (a) 3-D vector space ordination of the unfiltered classification. This represents the original classification prior to interpolation based on geographic occurrence. An inversion of the point cloud is shown underneath the introduced vertical plane. (b) As for Fig. 5a, but for the filtered dataset. (c) Categorically interpolated surface of the unfiltered classification [Fig. 5a]. Interpolation parameters were based on 40 m search radius, with the 5 closest points to the centre of each node at a 5 m bin size. (d) as for [Fig. 5c], but for the filtered dataset.

between 30 and 40 m water depth, 35.00% ($n = 8$) between 24 and 30 m and 13% occurred >24 m ($n = 3$: Table 2). For the absent category (*Abs.*), three occurred in the 30–40 m (Zone 3), with only two sequences recorded in less than 24 m water depth (depth Zone 1; Table 2).

The average depth of observed *Laminaria* sp. is 17.00 m ($n = 23$) (Table 2). The minimum observed depth is 12.43 m, and the maximum is 24.65 m with an interquartile range of 3.12. Mixed algal species are observed occurring at an average depth of 19.95 m water depth, a maximum of 24.84 m and a minimum depth of 17.27 m. Of additional note, *Agarum cribrosum* is observed to occur at an average depth of 29.61 m, with a minimum of 15.66 m, a maximum of 35.59 m and an interquartile range of 7.08. The absence of macroalgal species is observed to occur in 37 instances at an average depth of 46.24 m, with a 15.66 m minimum, a maximum of 58.19 m and an interquartile range of 7.99.

3.5. Data integration and analysis

3.5.1. Geospatial distribution of the classifications

The results for the unfiltered classification show that there is variation in the relative class composition by depth, with Zone 1

Table 1
Distribution and percentage contribution for each of the data types within the study area for both of the original *QTC-Multiview* classifications at Cashes Ledge. Key to column headers: Clams (# of 5 m raster cells [% of total]); Video (# of clips [% of total]); and, Kelp Obs. (# of datagrams predicting presence of macrophytes [% of total]).

Class	Clams # [%]	Video # [%]	*Kelp Obs.* # [%]
Unfiltered classification			
1*	31400 [9.61]	24 [27.91]	1238 [36.66]
2	368 [0.11]	–	6 [0.18]
3*	16634 [5.09]	4 [4.65]	625 [18.51]
4*	3983 [1.22]	1 [1.16]	39 [1.15]
5	15416 [4.72]	1 [1.16]	6 [0.18]
6	588 [0.18]	–	–
7*	10354 [3.17]	6 [6.98]	255 [7.55]
8	8529 [2.61]	2 [2.33]	164 [4.86]
9	8224 [2.52]	–	32 [0.95]
10	2391 [0.73]	–	67 [1.98]
11	171271 [52.42]	36 [41.86]	179 [5.30]
12	26780 [8.20]	4 [4.65]	290 [8.59]
13	14075 [4.31]	5 [5.81]	123 [3.64]
14*	16699 [5.11]	3 [3.49]	353 [10.45]
Total	326712 [100]	86 [100]	3377 [100]
Filtered classification			
1	248311 [75.97]	69 [80.23]	3106 [91.98]
2	1725 [0.53]	1 [1.16]	21 [0.62]
3	36414 [11.14]	1 [1.16]	8 [0.24]
4	17 [0.01]	–	–
5	6031 [1.85]	–	45 [1.33]
6	7946 [2.43]	7 [8.14]	147 [4.35]
7	5446 [1.67]	7 [8.14]	31 [0.92]
8	5475 [1.68]	1 [1.16]	19 [0.56]
9	15485 [4.74]	–	–
Total	326850 [100]	86 [100]	3377 [100]

* Denotes the classes which were determined to be indicative of the presence of benthic macrophytes.

(0–24 m water depth) exhibiting a difference when compared with Zones 2 (24–30 m) and 3 (30–40 m) (Fig. 6). However, the relative proportions of classes in Zones 2 and 3 are representative of the distribution across the entire area (Fig. 6: Total). The area covered by classes 1, 3, 4, 7 and 14 in the unfiltered classification covers significantly more surface area in Zone 1 than in any of the other Zones. Conversely, classes 6 and 11 are responsible for a significantly smaller area than at any other Zone in the classification.

In contrast, for the unfiltered classification, it is immediately apparent that there is markedly less variation between the three depth Zones; however, the relative proportions of classes 3 and 9 over the study area as a whole are markedly greater than any equivalent pattern in the unfiltered classification.

Table 2
Distribution and percentage contribution of ground-truth data effort for each of the categories at depth zones described by Vadas and Steneck (1988). Lam = *Laminaria* sp., Aga = *Agarum cribosum*, Mxd. = Mixed Macrophytes and Abs. = Macrophytes Absent.

Depth zone (m)	Lam # [%]	Mxd # [%]	Aga # [%]	Abs # [%]	Total # [%]
1 (0–24)	22 [95.65]	2 [66.66]	3 [13.04]	2 [5.41]	29 [33.72]
2 (24–30)	1 [4.35]	1 [33.33]	8 [34.78]	–	10 [11.68]
3 (30–40)	–	–	12 [52.17]	3 [8.10]	15 [17.44]
4 (>40)	–	–	–	32 [86.49]	32 [37.21]
Total # [%]	23 [100.00]	3 [100.00]	23 [100.00]	37 [100.00]	86 [100.00]
Average	−17.00	−19.95	−29.61	−46.24	−33.06
Minimum	−12.43	−17.27	−16.43	−15.66	−12.43
Maximum	−24.65	−24.84	−35.59	−58.19	−58.19
Interquartile range	3.12	–	7.08	7.98	29.00

3.5.2. Biological significance of the classifications: ground-truth validation

In the case of the filtered classification, the largest numbers of observations for *Laminaria* sp. (78.26%), *Agarum cribrosum* (69.57%), *Mixed* (66.66%) and *Absent* (89.19%) all occur within the same class identity (class 1) (Table 3). In contrast, the unfiltered classification shows significant variation in class identity in relation to the presence, and to an extent, by specific variation between the classes (Table 3). The filtered classification was determined to be more sensitive to variation in substrate, and less influenced by the presence of scattering material in the water column; this is supported by the low level of agreement observed with the ground-truth data. This supports the hypothesis that the filtered classification does not have the sensitivity to determine presence or absence of benthic macrophytes, and was taken to be significant justification not to pursue the comparison further.

3.5.3. Reclassification of the unfiltered data

In order to progress with the unfiltered classification, it was necessary to simplify the class structure to its maximum biological validity. From this point forward, the classes from the unfiltered classification which showed positive agreement with the presence of macrophytes (1, 3, 4, 7 and 14) were reclassified to a binary condition. This additionally facilitated comparison with the results of the *WCDE* results, which had already been reduced by this criterion.

3.5.4. Presence, absence and volume

The classes exhibiting an agreement with the presence of macrophytes (1, 3, 4, 7 and 11) from the original unfiltered classification were isolated, and restricted to their occurrence above 40 m water depth (Fig. 7a). These were compared to the spatial distribution of the original kelp observations (+25 m buffer) from the *WCDE* (Fig. 7b). This size of the buffer was chosen to reflect the lane spacing of the original survey design.

The classified ground-truth data stations are displayed with the presence/absence images (Fig. 7). The results of the classifications are also presented as a depth stratified contingency table showing the interrelationship with the ground-truth data in the context of the Zones described by Vadas and Steneck (1988) (Table 4). Comparison of these data demonstrates that for the *QTC-Multiview* classification in Zone 1 (0–24 m), 81.80% of the recorded observations of *Laminaria* sp. agreed with the predicted value (1; Table 4). The *WCDE* technique produced a comparable agreement of 77.30%. Encompassing the observations from Zone 2 increased the agreement of the *QTC-Multiview* to 82.60% (Table 4), and the *WCDE* to 78.30%; both of these values remained the same when the range was increased to cover the full range of potential depths (0–40 m; Table 4). The mixed category of macrophyte coverage (Mxd) co-occurred 100.00% with the predicted presence in the case of the *QTC-Multiview* derived classification at all depth Zones (Table 4), as opposed to the 100.00% predicted absence from the *WCDE* method. Overall, both techniques performed less well for the predicted detection of *Agarum cribrosum* (Aga), although there was some variation in this respect in terms of depth. In Zone 1 (0–24 m), there were only three observed instances of *A. cribrosum*, and both methods successfully predicted 66.6% of them. However, as the depth range increased (Zone 2), the number of observations increased to 11 and the predictive efficiency decreased to 63.60% in the case of the *QTC-Multiview* method, as opposed to 45.50% agreement with the *WCDE* technique (Table 4). When the full range of depths was considered, this effectiveness

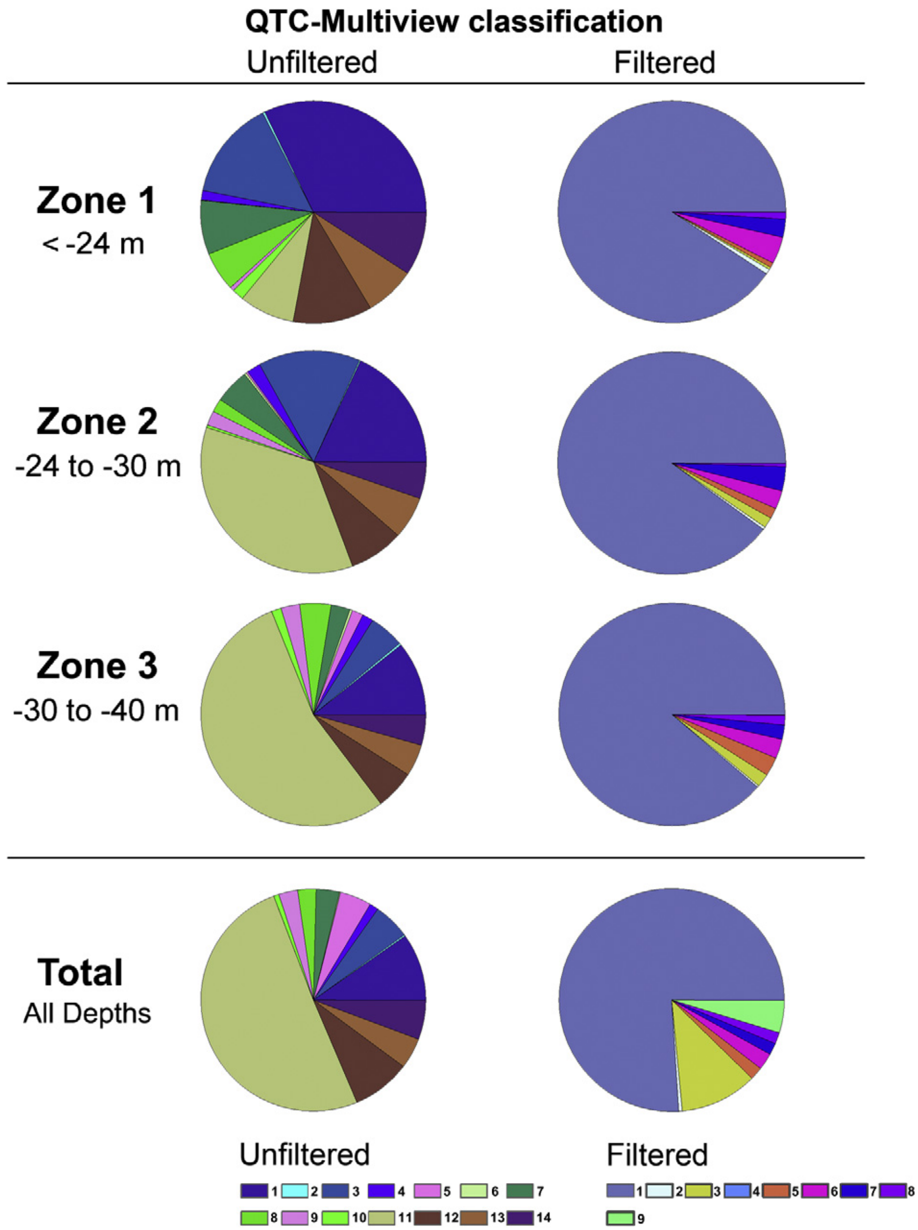

Fig. 6. Results of the *QTC-Multiview* Classification process at Cashes Ledge. This figure demonstrates the relative composition of the classification results (filtered and unfiltered) at each of the three depth Zones expected to contain macrophytes, as described by Vadas and Steneck (1988).

had further decreased for both methods, with 39.10% and 30.40% prediction rates for the *QTC-Multiview* and *WCDE* techniques respectively.

Statistical comparison of these binary images was undertaken (Hagen, 2002) using the depth Zones described (Vadas and Steneck, 1988) as an analysis mask (Table 5). The results of the *WCDE* (+25 m buffer) showed a consistently larger surface area for all depth Zones than the results of the *QTC-Multiview* analysis, with 2.97×10^5 m^2 as opposed to 4.42×10^5 m^2 in the first 24 m (Zone 1) water depth (*QTC-Multiview* and *WCDE* respectively), and this represents 63.05% and 55.13% of the total canopy surface area as determined by both approaches (Table 5). In contrast, in the surface area including Zone 2 increases to 3.93×10^5 m^2 as opposed to 6.04×10^5 m^2, representing 73.11% and 86.07% (*QTC-Multiview* and *WCDE* respectively). Finally, when considered as the entire 0–40 m potential area, the predicted surface area was 5.38×10^5 m^2 (*QTC-Multiview*) compared to 7.01×10^5 m^2 (*WCDE*) (Table 5).

The results of the statistical comparison of the two binary images showed that whilst the percentage agreement remained consistently high (66.00–70.00%), there was an increase in the *Kappa* significance from slight ($k = 0.17$), to fair ($k = 0.28$ and $k = 0.35$) as the surface area of the Zones increased through Zones 1–3 respectively (Table 5). More detailed examination of the component statistics *KHisto* and *KLoc* shows that this is due to an increase in the histogram shape of categorical agreement as opposed to being based on location. In this respect *KHisto* showed the strongest improvement increasing from $k = 0.43$ (fair) to $k = 0.95$ (almost perfect agreement) through Zones 1–3 (Table 5).

The estimated volume of the canopy was derived based on interpolated surface heights of the kelp canopy from the *WCDE* (Fig. 7b; Table 5). The volumetric estimate of the presence of benthic macrophytes was calculated differentiated by depth to be between 1.21×10^6 m^3 (<24 m), 1.82×10^6 m^3 (<30 m), and 2.45×10^6 m^3 <40 m water depth. The ratio of surface area to

Table 3
Contingency table showing the cross-tabulated results of the ground-truth data against the *QTC-Multiview* classifications for filtered and unfiltered classifications. Agreements which are discussed in the text are annotated with symbols in the table. Summary statistics for these are presented below. Key to column headers: # of positive identifications of Lam., Mxd., Aga. and Abs. from the video data [% of total].

Class	Lam # [%]	Mxd # [%]	Aga # [%]	Abs # [%]	Total # [%]
Unfiltered classification					
1*	13 [56.52]	–	6 [26.09]	5** [13.51]	24 [27.91]
2	–	–	–	–	–
3*	1 [4.35]	1 [33.33]	–	2* [5.41]	4 [4.65]
4*	–	1 [33.33]	–	–	1 [1.16]
5	–	–	1 [4.35]	–	1 [1.16]
6	–	–	–	–	–
7*	4 [17.39]	1 [33.33]	1 [4.35]	–	6 [6.98]
8	–	–	–	2 [5.41]	2 [2.33]
9	–	–	–	–	–
10	–	–	–	–	–
11	2 [8.70]	–	11 [47.83]	23* [62.16]	36 [41.86]
12	1 [4.35]	–	1 [4.35]	2 [5.41]	4 [4.65]
13	1 [4.35]	–	1 [4.35]	3* [8.11]	5 [5.81]
14*	1 [4.35]	–	2 [8.70]	–	3 [3.49]
Total	23 [100.00]	3 [100.00]	23 [100.00]	37 [100.00]	86 [100.00]
Filtered classification					
1	18 [78.26]	2 [66.66]	16 [69.57]	33**** [89.19]	69 [80.23]
2	1 [4.35]	–	–	–	1 [1.16]
3	–	–	1 [4.35]	–	1 [1.16]
4	–	–	–	–	–
5	–	–	–	–	–
6	–	1 [33.33]	4 [17.39]	2 [5.41]	7 [8.14]
7	4 [17.39]	–	1 [4.35]	2** [5.41]	7 [8.14]
8	–	–	1 [4.35]	–	1 [1.16]
9	–	–	–	–	–
Total	23 [100.00]	3 [100.00]	23 [100.00]	37 [100.00]	86 [100.00]

* Indicates the number of instances where the absence of kelp occurred >40 m water depth. For example: * indicates the occurrence on a single instance, whereas **** indicates the absence of kelp (>40 m) on four occasions.

volume showed an increase within each of the decreasing depth Zones, with 25.65% of the total canopy volume originating from 13.93% of the surface area above 40 m.

4. Discussion

This research demonstrates that:

(1) Benthic macrophytes can be successfully mapped using multibeam echosounders; and
(2) The presence of benthic macrophytes in the water column has the capacity to significantly affect the results of image-based classification of acoustic data.

4.1. Agreement between approaches

The results of these analyses led to the production of two independent classifications predicting the presence of benthic macrophytes at Cashes Ledge; one using *QTC-Multiview*, and the other using water column data extraction technique in *Matlab*. The similarity between the two classifications recorded 66.00–70.00% agreement, with a *Kappa* significance of slight to fair (Landis and Koch, 1977). The *WCDE* technique is undoubtedly more focussed on the research objective than the image-based classification process, although the results of both techniques show a degree of similarity when reduced to presence/absence categories, which helps to increase confidence that their comparison is relevant.

The *Kappa* significance of agreement consistently improved as a result of increasing the size of the sample area (Table 5). The *KLoc* (Pontius et al., 2004) and fraction correct (% agreement) remain similar although there is an increase in the value of *KHisto* (Hagen, 2002); it is the interrelationship between these values which is driving the improvement in the *Kappa* significance overall (Visser and de Nijs, 2006; Table 5). When this agreement is considered in terms of overall surface area, the relative percentages show significant variation by method (Fig. 7a and b; Table 5).

Potentially, the agreement between methods could have been improved by the inclusion of classes 8, 10, 12 and 13 from the unfiltered classification, but it is likely that while this may have improved agreement in Zone 1 (and possibly 2) it would have the effect of decreasing agreement in Zone 3 as these classes were consistently present in sufficient quantity in deeper water (Figs. 5b and 6). Co-examination of Figs. 5a and 7 shows the variation in extents within Zone 3 between the original unfiltered classification and the *WCDE*. Therefore, the inclusion of additional classes would go some way to equalise the difference in observed surface area (and potentially the significance of agreement) between the methods in shallow water (Table 5). However, this is not supported by the results of the ground-truth data which were analysed (Table 3). Where ground-truth observations were made, the dominant record was the absence of any macrophytic species in classes 8, 10, 12 and 13 (Table 3). Where positive identification was made, it was in insufficient number to warrant inclusion with the remaining acoustic classes.

4.2. Agreement with the ground-truth data

When examined in the context of the ground-truth data, the presence of the macrophytes appears to agree comparably well with the results of both techniques (Table 5). This supports the findings of other researchers who have reported success in detecting and quantifying macroalgal abundance and distribution using MBES (Komatsu et al., 2003; Kruss et al., 2008). However, there appears to be specific variation in terms of the level of agreement observed, which is reflected in the reported values (Table 4). The results of both techniques were demonstrated to be more effective at accurately predicting the occurrence of *Laminaria* sp. than *Agarum cribrosum*, although this is understandable knowing something of each individual species physiology and regional distribution (Vadas and Steneck, 1988).

When viewed in light of the patterns of macroalgal zonation which have been previously described around the Ammen Rock Pinnacle (Fig. 4), the implications for this research are apparent (Vadas and Steneck, 1988). The zonation within the first 40 m water depth is described as being dominated by three leathery macrophytes (*Laminaria* sp., *Laminaria longicruris* and *Agarum cribrosum*). The distribution of species varies by depth, with *Laminaria* sp. described as forming an open park-like canopy from 24 to 30 m water depth, and *A. cribrosum* occurring as isolated individuals to depths of 40 m. Intuitively, the density of macroalgal species could be expected to diminish below 30 m as depth increases to 40 m, below which there was no evidence of macrophytes reported, either in the literature or through ground-truth observation. Vadas and Steneck (1988) additionally report localised variations in distribution with broad clear 'halos' of bare substrate around many of the individual macrophytes, inferred to be due to the whiplash effects of the fronds.

4.3. Interpretation of results

In the context of these observations, the results of this study can be interpreted in two interrelated ways; firstly that the results of both techniques are more appropriate for detection of *Laminaria* sp., and secondly that they are more appropriate for use in shallow water. However, the distribution of *Laminaria* sp. is typically

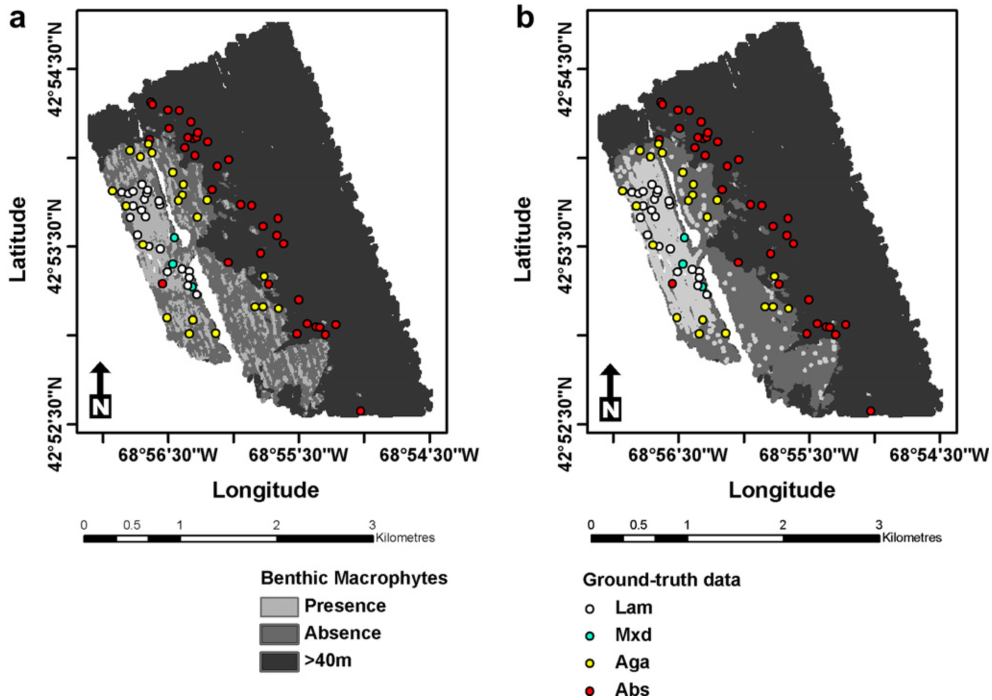

Fig. 7. Results of the presence/absence comparative analysis. (a) This figure displays the Classes 1, 3, 4, 7 and 14 of the unfiltered classification in *QTC-Multiview* representing the predicted presence category. (b) *WCDE* points buffered to 25 m representing predicted presence, converted to raster for comparative analysis in *Map Comparison Kit* (Visser and de Nijs, 2006).

restricted to the shallow waters (<30 m), where it also tends to occur in dense aggregations (Steneck et al., 2002), which have a greater chance of being detected using acoustic remote sensing techniques. The results suggest that both methods have been successful in the acoustic detection of the park-like canopies of *Laminaria* sp., occurring between 24 and 30 m water depth around the summit of the Ammen Rock Pinnacle (Figs. 2 and 4a; Vadas and Steneck, 1988).

The reliability of either technique for determination of the presence of *Agarum cribrosum* has not been demonstrated effectively by the results of this study, particularly in the deeper waters specific to Zone 3. This is further reflected in the volumetric estimates derived using the interpolated canopy heights from the *WCDE* technique. The surface area of Zone 1 has 49.40% of the canopy volume (1.21×10^6 m^3) based on 63.00% (4.42×10^5 m^2) of the total surface area (Table 5). In contrast, the difference between Zones 2 and 3 shows that 25.65% of the canopy volume is based on 13.93% of the total surface area. In terms of the ground-truth agreement, there was no evidence of *Laminaria* sp. below 30 m water depth (between Zones 2 and 3) that could account for this predicted volume, and furthermore, where *A. cribrosum* was observed, it occurred predominantly as solitary individuals, or in small groups that did not form a canopy like structure. Therefore, irrespective of the lack of agreement with the ground-truth data already demonstrated for Zone 3 (Table 4), this is taken as further indication that the volumetric estimates below 30 m should be regarded with a degree of caution (Table 5).

This has implications for the relatedness of the two methods of classification, as although the quantity of categorical agreement did increase as a result of the increase in surface area (into deeper

Table 4
Contingency table showing the summary of relationship between the ground-truth data, unfiltered binary classification and the water column data extraction (*WCDE*).

	Class	Lam # [%]	Mxd # [%]	Aga # [%]	Abs # [%]	Total # [%]
Unfiltered binary						
Zone 1 (0–24)	0 (Predicted absence)	4 [18.2]	–	1 [33.3]	–	5 [17.2]
	1 (Predicted presence)	18 [81.8]	2 [100.0]	2 [66.6]	2 [100.0]	24 [82.8]
Zone 2 (0–30)	0 (Predicted absence)	4 [17.4]	–	4 [36.4]	–	8 [20.5]
	1 (Predicted presence)	19 [82.6]	3 [100.0]	7 [63.6]	2 [100.0]	31 [79.5]
Zone 3 (0–40)	0 (Predicted absence)	4 [17.4]	–	14 [60.9]	2 [40.0]	20 [37.1]
	1 (Predicted presence)	19 [82.6]	3 [100.0]	9 [39.1]	3 [60.0]	34 [62.9]
(>40 m)	Null	–	–	–	32 [100.0]	32 [100.0]
Water column data extraction						
Zone 1 (0–24)	0 (Predicted absence)	5 [22.7]	2 [100.0]	1 [33.3]	1 [50.0]	9 [31.0]
	1 (Predicted presence)	17 [77.3]	–	2 [66.6]	1 [50.0]	20 [69.0]
Zone 2 (0–30)	0 (Predicted absence)	5 [21.7]	3 [100.0]	6 [54.5]	1 [50.0]	15 [38.5]
	1 (Predicted presence)	18 [78.3]	–	5 [45.5]	1 [50.0]	24 [61.5]
Zone 3 (0–40)	0 (Predicted absence)	5 [21.7]	3 [100.00]	16 [69.6]	4 [80.0]	28 [51.8]
	1 (Predicted presence)	18 [78.3]	–	7 [30.4]	1 [20.0]	26 [48.2]
(>40 m)	Null	–	–	–	32 [100.0]	32 [100.0]
	Total	23 [100.00]	3 [100.00]	23 [100.00]	37 [100.00]	86 [100.00]

Table 5
Statistics for the surface area of the macrophyte canopy, based on comparison of the two approaches. *Kappa* statistics are included for comparison of the binary rasters showing predicted presence/absence of macrophytes within each of the zones described by Vadas and Steneck (1988). Volumetric calculations are based on interpolated canopy heights as determined by *WCDE* in *Matlab*.

Predicted macrophyte canopy	Zone 1 [0–24 m]	Zone 2 [0–30 m]	Zone 3 [0–40 m]
QTC-Multiview m^2 [%]	296554 [55.13]	393330 [73.11]	537961 [100.00]
WCDE m^2 [%]	442172 [63.05]	603601 [86.07]	701263 [100.00]
Canopy volume (based on *WCDE*) m^3 [%]	1211617 [49.38]	1824326 [74.35]	2453706 [100.00]
Kappa	0.17	0.28	0.35
KLocation	0.40	0.40	0.37
KHisto	0.43	0.71	0.95
Fraction correct	0.67	0.66	0.70

water), the location (*KLoc*) of the agreement remains fair (Table 5; Landis and Koch, 1977). This signifies that although both techniques may be more effective at predicting presence in waters less than 30 m, the *Kappa* significance of their relationship does not increase. In order to investigate the validity of these approaches more fully, more representative ground-truth data from all classes, and a wider range of depths would need to be obtained to substantiate the predictions. As it stands, the distribution of ground-truth data left several classes from the original classifications underrepresented or not represented at all (Tables 2–4). This would need to be addressed to more definitively qualify surface area and volume estimates, and determine the distribution of macrophytes relative to the measured acoustic signatures. It is envisaged that such an approach could be the focus of future research.

Using the *WCDE* technique, the height of the canopy is recorded as an empirical value as opposed to being inferred or based on field observations as would be the case when using optical remote sensing techniques for mapping macroalgae (e.g. Armstrong, 1993; Simms and Dubois, 2001). It is also significantly more resolute than single beam echosounder approaches to the mapping of aquatic vegetation, as the canopy has been insonified by ±10 beams either side of nadir, as opposed to being based on a single measurement (Quintino et al., 2010). However, the relatively large proportion of the canopy occurring between depths of 30 and 40 m suggests that this approach may be more valid in shallower waters.

4.4. Refining benthic mapping

It is increasingly accepted that the key to refining habitat models is more complicated that just using abiotic proxies as a direct approximation for habitat (Stevens and Connolly, 2004; Zajac, 2008). For example, geological maps cannot simply be ground-truthed and labelled, as organisms and communities do not necessarily behave according to geologically imposed segmentations (Diaz et al., 2004). Increasingly, seabed scientists are realising that in order to truly understand complex multidimensional habitat structures, it is counter-productive to think of a two-dimensional planar surface. Instead, sub-surface and water column parameters need to be included in these habitat models. For example, sub-bottom stratigraphy has the capacity to affect the acoustic response from the surficial sediments (Jackson and Richardson, 2007) and the presence of material in the water column such as macrophytes, bubbles, fish, ambient noise etc. can also have an impact on acoustic data (Cutter and Demer, 2007; Kruss et al., 2008; Gurshin et al., 2009; Weber et al., 2009). In order to successfully map and understand these complex multidimensional ecosystems, it is necessary to think more inclusively of these spatial components. Ultimately, this will lead to an increasingly more sophisticated means of predicting habitat, as opposed to ignoring complex factors which may initially appear to present confounding variables (Anderson et al., 2008; Zajac, 2008).

Although multidimensional environmental data are increasingly being implemented in a GIS software environment (Mayer et al., 2002; Mayer, 2006a; Anderson et al., 2008), this practice has not yet filtered down into mainstream scientific use. There is now more than ever a need to move beyond static, display-based GIS into a fluid dynamic analysis environment, which is ultimately more representative of the system(s) we are trying to understand (Mayer, 2006a). Understanding spatially and temporally variable components of marine habitats and their controlling mechanisms is perhaps the most vital stage in enhancing our understanding. This research highlights the value of re-processing extant geophysical data with variable parameters in order to extract maximum value from a product which is expensive and time-consuming to acquire in the first instance.

5. Conclusions

The physical extent of an area of macrophyte canopy at Cashes Ledge in the Gulf of Maine has been successfully examined using two independent techniques for the detection of benthic macrophytes (*QTC-Multiview* and *WCDE*). In contrast to the *WCDE* technique, the image-based approach (*QTC-Multiview*) was not designed for the prediction of benthic macrophytes; however, it has been demonstrated to do so remarkably well. This represents a novel diversification of the image-based technique, which shows considerable promise for this type of application. In the context of the specific aims and objectives defined in the Introduction, this research has demonstrated:

(1) The presence of benthic macrophytes has significant capacity to affect the results of image-based classification of multibeam backscatter;
(2) The results of both methods have demonstrated a positive agreement with the ground-truth data in the context of existing work;
(3) The significance of the degree of similarity between the methods was shown to be between 66.0% and 70.0%, with *Kappa* coefficient increasing with depth ($k = 0.17–0.35$);
(4) Both methods were more effective at detecting the presence of *Laminaria* sp. (82.60–77.30%) than *A. cribrosum* (66.60–30.40%) and the efficiency of prediction decreased with depth;
(5) The predicted canopy volume of benthic macrophytes at Cashes Ledge was determined to be between 1.21×10^6 m^3 (at <24 m), 1.82×10^6 m^3 (at <30 m), and 2.45×10^6 m^3 (at <40 m water depth); and
(6) The significance of the water column in terms of its ability to affect the results of seabed classification process.

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