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An assessment of the acoustic survey technique, RoxAnn, as a means of mapping seabed habitat

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RoxAnn acoustic surveys of the inner Moray Firth, undertaken in September/October 1995 and January 1996, were used to map seabed habitat on the basis of two sediment characteristics, ‘‘roughness’’ (E1) and ‘‘hardness’’ (E2). The traditional analytical method of fitting a ‘‘box pattern’’ to E1 vs. E2 scatter plots was compared with a more objective method using False Colour Composite Image (FCCI) and cluster analysis. Although both methods produced similar maps, the latter provided greater between survey consistency. Six to seven sediment types were indicated by RoxAnn, however ordination analysis of sediment samples indicated that some of the FCCI clusters could not be separated on the basis of their particle size distributions. This may have been due to a degree of depth sensitivity, but it is also possible that RoxAnn was responding to other physical or biotic seabed features other than just particle size. After combining RoxAnn FCCI clusters where ground-truthing grab samples had shown the particle size distributions to be similar, it was evident that RoxAnn could distinguish three main sediment habitats with certainty. On this basis, the RoxAnn derived maps compared well with maps obtained from British Geological Survey data. Finally we examined the distributions of four flatfish species to determine whether these were in any way related to the different sediment habitats identified by RoxAnn.

Key words: RoxAnn, seabed sediment habitat, mapping, acoustic survey, False Colour Composite Image analysis, habitat selection.

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Introduction

Habitat selection can have important consequences with respect to the fitness of individuals (King and Dawson, 1973; Catchpole, 1974; Holbrook and Schmitt, 1988; Turner, 1996), and ultimately affects fitness at the species level (Werner, 1977; Rosenzweig, 1995). In many instances the distribution of predators is directly related to the distribution of their prey (Fretwell and Lucas, 1970; Milinski and Parker, 1991). However, physical characteristics of the environmental also have an important role to play in determining where individuals of a particular species choose to live (Wecker, 1963; Rand, 1964; Douglass, 1976; Partridge, 1978; Carbone and Houston, 1994). Habitat variability is a key factor in determining the number of species living within defined areas (MacArthur and MacArthur, 1961; Eadie and Keast, 1984; Huston, 1994; Rosenzweig, 1995). Determining habitat variability in particular regions is therefore an important aspect in the assessment of a region’s value with respect to species conservation.

Such assessments are more easily carried out, and consequently are more common and more detailed, where terrestrial landscapes are concerned (see examples in Huston, 1994). They are particularly difficult, and scarce, with respect to marine habitats. Assessment of seabed habitat variation, for example, has traditionaly relied on intensive sediment grab sampling programmes (e.g. BGS, 1984, 1987; Basford and Eleftheriou, 1988; Duineveld *et al.*, 1991; Heip *et al.*, 1992) or diving surveys (Hiscock, 1990), both of which are expensive and time consuming. The recently developed RoxAnn system (Marine Microsystems Ltd, Ireland) provides an acoustic alternative to these labour and time intensive

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techniques, protentially enabling relatively large areas to be surveyed at fine resolution in relatively short periods of time (Chivers *et al.*, 1990; Schlagintweit, 1993; Magorrian *et al.*, 1995). Such acoustic survey techniques have proved to be sufficiently sensitive to detect changes in seabed characteristics following intensive otter and beam trawling (Kaiser and Spencer, 1996; Schwinghamer *et al.*, 1996).

RoxAnn functions by integrating components of the first and second seabed echoes to derive two parameters of the seabed substrate; E1 and E2. E1 is an integration of the tail of the first seabed echo, and is taken to represent seabed roughness. E2 is an integration of the whole of the second bottom echo and provides an index of seabed hardness (Chivers *et al.*, 1990; Schlagintweit, 1993). These data are then presented in an E1 vs. E2 scatter plot. Based on a subjective appraisal of the cluster pattern in the scatterplot, the operator applies a ''box set'' to these data such that each box has a maximum and minimum E1 and E2. Each box is assumed to represent a particular substrate, which is defined based on ground-truth grab samples. There are a number of problems with this technique, most notably that the rectangular boxes are unlikely to be the best representation of each substrate type. An example of such a box set is illustrated in Schlagintweit (1993) and this approach was adopted by Magorrian *et al.* (1995). These previous studies have reported one-off surveys of a particular region, the question of repeatability between RoxAnn surveys of the same area is also a point which requires confirmation.

The spatial distributions and predator–prey interactions of species at various levels in the foodweb (from plankton through to marine mammals and seabirds) have been the subject of a long-term study in the inner Moray Firth in north-east Scotland (e.g. Thompson *et al.*, 1991; Thompson *et al.*, 1996; S. P. R. Greenstreet, SOAEFD Marine Laboratory, unpublished data). As part of this study, habitat variability in the area was assessed in order to distinguish the influence of abiotic physical characteristics of the environment from the effects of biotic interactions on the spatial distributions of various predator species. Since the Moray Firth has also been proposed as a special area of conservation under the European Commission's Habitats Directive, such information is clearly of value with respect to the more wide ranging aspects of marine ecosystem management in the area, and similar approaches are equally valid in other marine regions. Frequently marine surveys adopt a systematic or random design. However, associations of particular species with certain habitat characteristics (e.g. Perry and Smith, 1994; Smith and Page, 1996) suggest that stratified random designs may provide more accurate estimates of abundance (Simmonds and Fryer, 1996). Consequently knowledge of seabed habitat variability provided by RoxAnn may contribute to improved survey design for groundfish and benthic species.

We map spatial variation in seabed sediments and bathymetry using RoxAnn in two acoustic surveys of the same area. Between survey differences in the RoxAnn E1 and E2 data are examined. A novel analytical method is applied to the RoxAnn data which appears robust to between survey variation in E1 and E2 values and provides relatively consistent sediment maps. The sediment maps produced using this method are compared with maps produced using the more traditional subjective box pattern method. We then use sediment grab-sample data to determine what the various sediment types identified by RoxAnn consist of in terms of their particle size distributions. Having done this we compare our RoxAnn derived maps of the Moray Firth with a sediment map produced by the British Geological Survey. Finally we make a preliminary assessment of the biological relevance of the sediment habitats we have identified using RoxAnn by examining their influence on the density and distribution of four flatfish species, common dab (*Limanda limanda*), long rough dab (*Hippoglossoides platessoides*), lemon sole (*Microstomus kitt*), and plaice (*Pleuronectes platessa*), whose diets are dominated by benthic prey (Greenstreet, 1996).

Methods

Two surveys were carried out between 30 September and 9 October 1995 and between 6 and 18 January 1996 in the inner Moray Firth in north-east Scotland using the Scottish Fisheries Research Vessel *Clupea*. An area of approximately 4250 km^2 south of latitude 58°15′N and west of longitude 002°40′W was covered by transects approximately 4 km apart orientated mainly in a north–south direction. Generally, the same transects were steamed in both surveys. However, because of variation in the weather conditions, the two survey tracks were not completely identical, the main differences being along the south coast and along the northern boundary of the study area (Fig. 1).

The RoxAnn system was connected to one quadrant of a 38 kHz split beam transducer run from a Simrad EK500 Scientific Echo-sounder. The transducer was mounted in a towed body and deployed forward of the propeller from a boom mounted near the bow of the vessel. The towed body, towed at a speed of 18 km h^{-1} approximately 4 m below the water surface, provided a more stable platform in rough weather and avoided problems with air bubbles generated under the hull. Data were gathered at 15 second intervals and displayed and stored on an Apple Mac computer running MacSea GIS software.

The data were imported into a spreadsheet and all non-survey sections of the track deleted. RoxAnn data

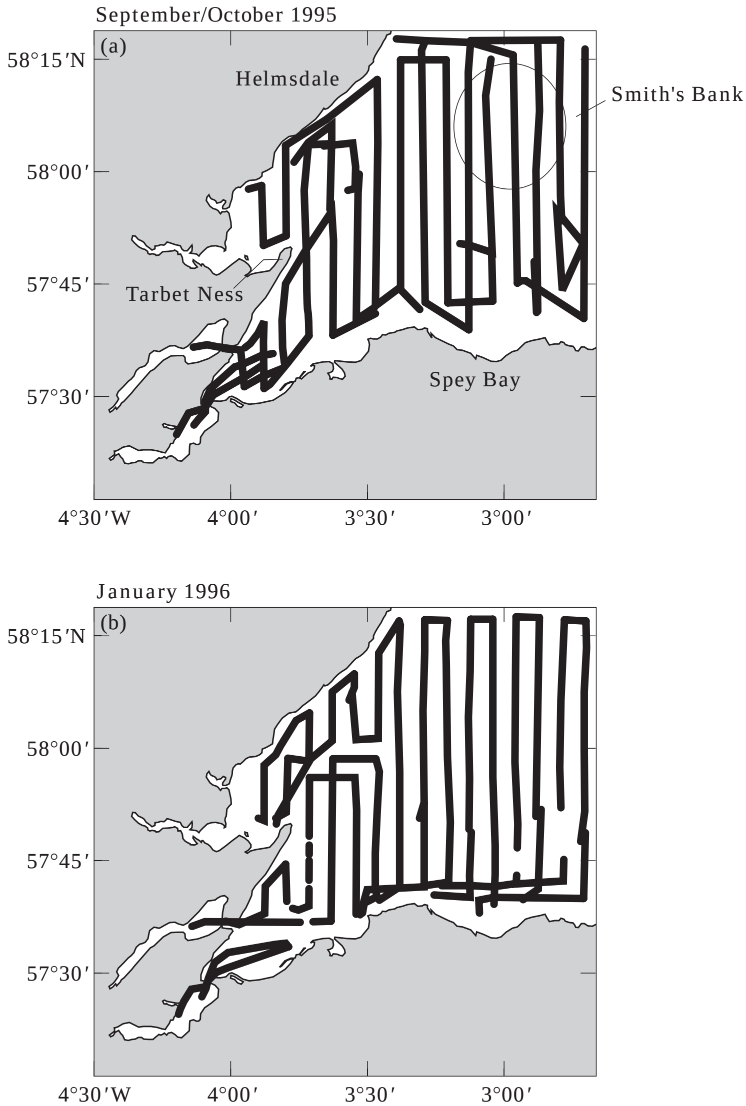


Figure 1. Charts indicating the tracks surveyed using RoxAnn in (a) September/October 1995 and (b) January 1996. Places named in the text are indicated. In all further maps latitude and longitude is given in degrees only (longitude degrees are negative to denote west of the Greenwich meridian).

sets can contain erroneous data, due either to the presence of fish or to interrupt failure in the hardware. These are usually indicated by incorrect depth values. Sample to sample depth changes exceeding 10% of the first sample depth were therefore examined closely. If these occurred as part of a trend of consistent rapid change in depth over several observations, or if they occurred in regions where the seabed was extremely uneven, i.e. where rapid changes in depth were inconsistent, but occurred over several observations within a short time period, then these records were retained. However, single large deviations occurring outside the general run of observations were deleted. As with all data ‘‘cleaning’’ this was a subjective exercise designed to remove all dubious data prior to analysis, and can be seen as being analogous to the ‘‘despiking’’ of Conductivity, Temperature, Depth (CTD) recordings. Following ‘‘cleaning’’ between 13 000 and 14 000 records remained for each survey.

Categorical data, such as sediment type or category, were mapped using a nearest neighbour algorithm on a high resolution, 250 by 250, grid (SURFER, Golden Software Inc., USA), thus effectively step contouring the data. In such contouring the nearest datum to the grid node is used to fix the node’s value. To prevent rare extreme values from unduly influencing the appearance

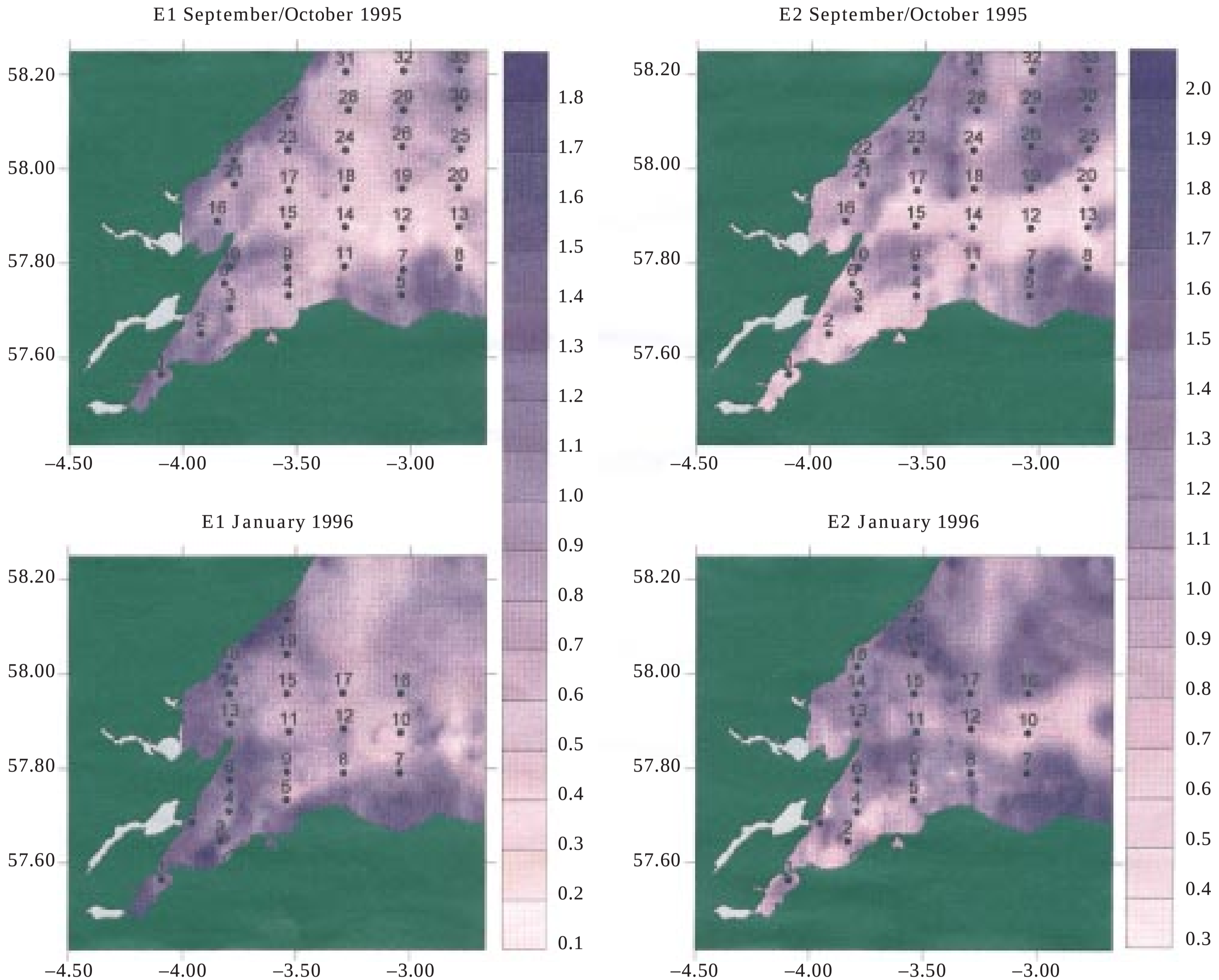
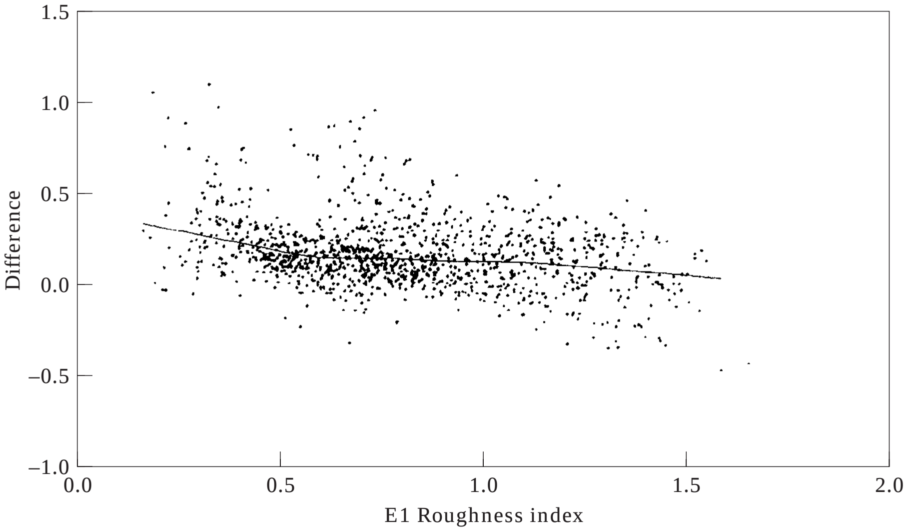


Figure 2. Spatial variation in RoxAnn E1 and E2 parameters in September/October 1995 and January 1996 (see Figure 1 for latitudes and longitudes in degrees and minutes.



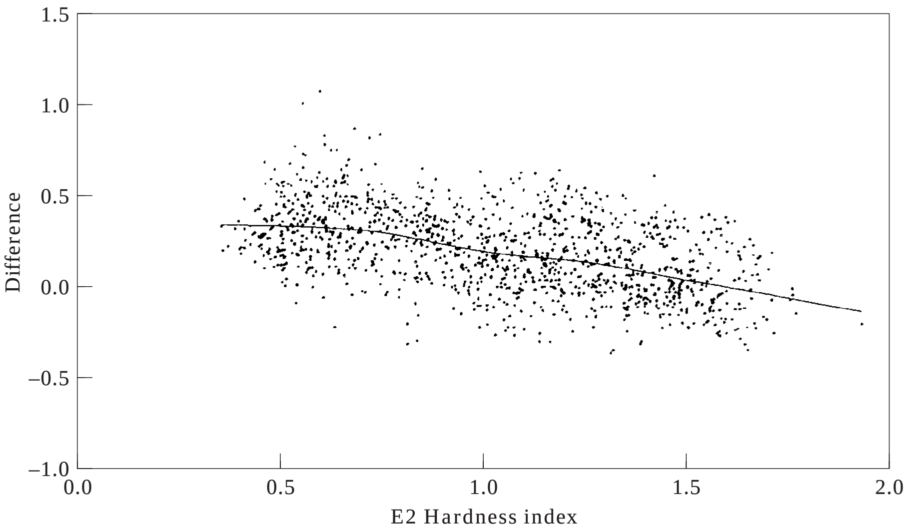


Figure 3. Variation in between survey difference in interpolated grid node E1 and E2 values in relation to the interpolated values of E1 and E2 in September/October 1995. Lines are fitted using a LOWESS smooth (SYSTAT 1992).

of the maps, we averaged the latitude, longitude, depth, E1, and E2 data collected in each minute of survey time (usually between three and four records obtained over a track distance of between 250 and 300 m). This reduced the data sets to 3529 records in September/October 1995 and 3624 in January 1996. These ‘‘minute averaged’’ data formed the basis for all the ensuing analyses.

Continuous data, such as E1, E2, and water depth, were mapped in SURFER by kriging the data (Clark, 1979; Cressie, 1991). Kriging takes into account the difficulties of spatial autocorrelation inherent in data collected continuously along line transects (Cliff and Ord, 1973). Experimental variograms, produced in GEO-EAS (Environmental Monitoring Systems Laboratory, Las Vegas, USA), suggested that the spatial correlation in the data was best fitted by a spherical kriging model. In all cases the variograms passed through the origin, a zero ‘‘nugget effect’’, suggesting little error or micro variance. Grids of 50 rows and 50 columns were generated. Between survey variation in E1 and E2 was examined using the differences calculated at the grid nodes.

In order to obtain an objective sediment type classification, the interpolated grid mode E1 and E2 data were stretched by linearly scaling between a specified minimum (0) and maximum (255) and forcing the extreme

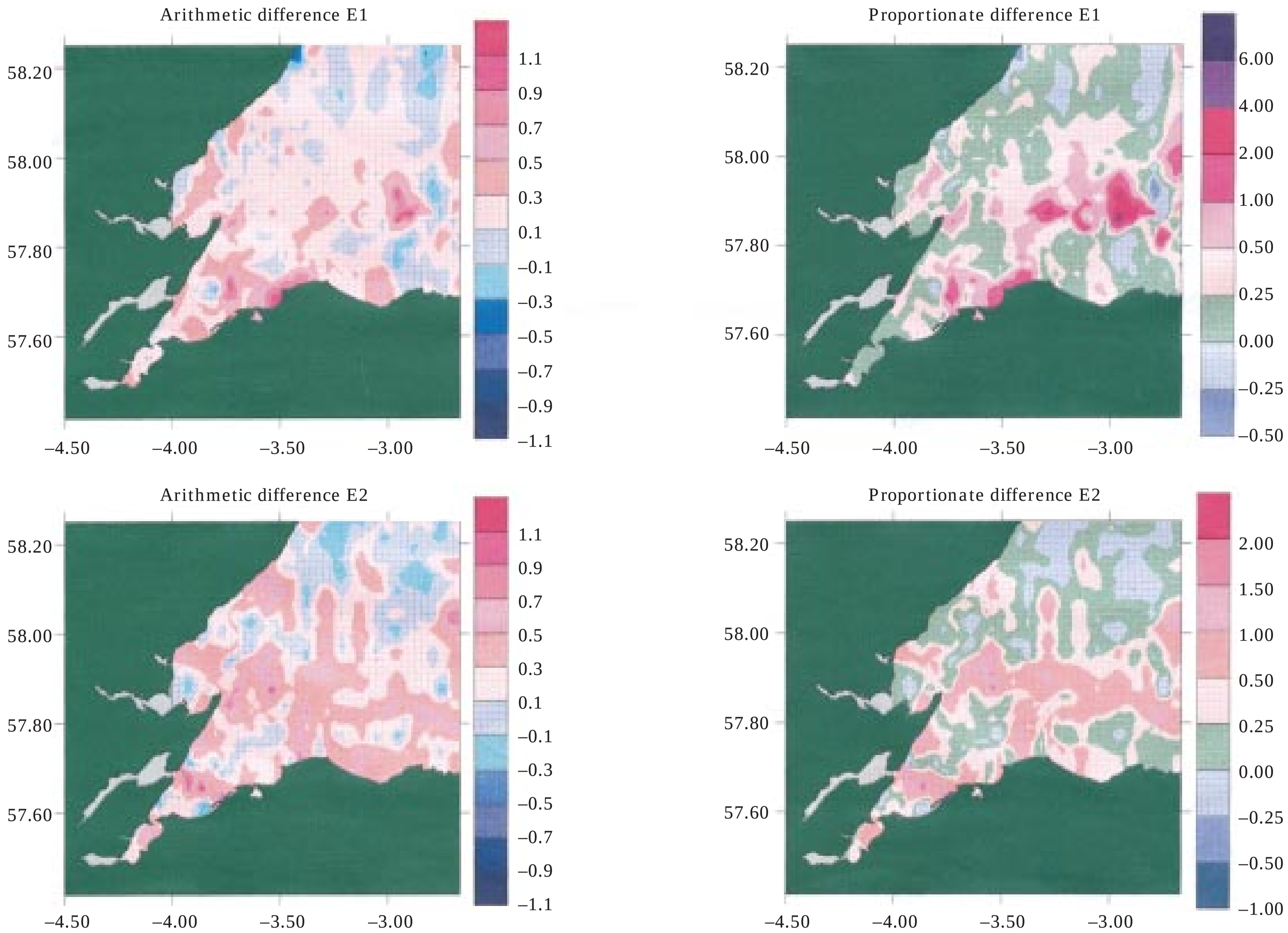


Figure 4. Spatial variation in the between survey difference in interpolated grid node E1 and E2 values expressed as the arithmetic difference and as a proportion of the September/October 1995 values (see Figure 1 for latitudes and longitudes in degrees and minutes).

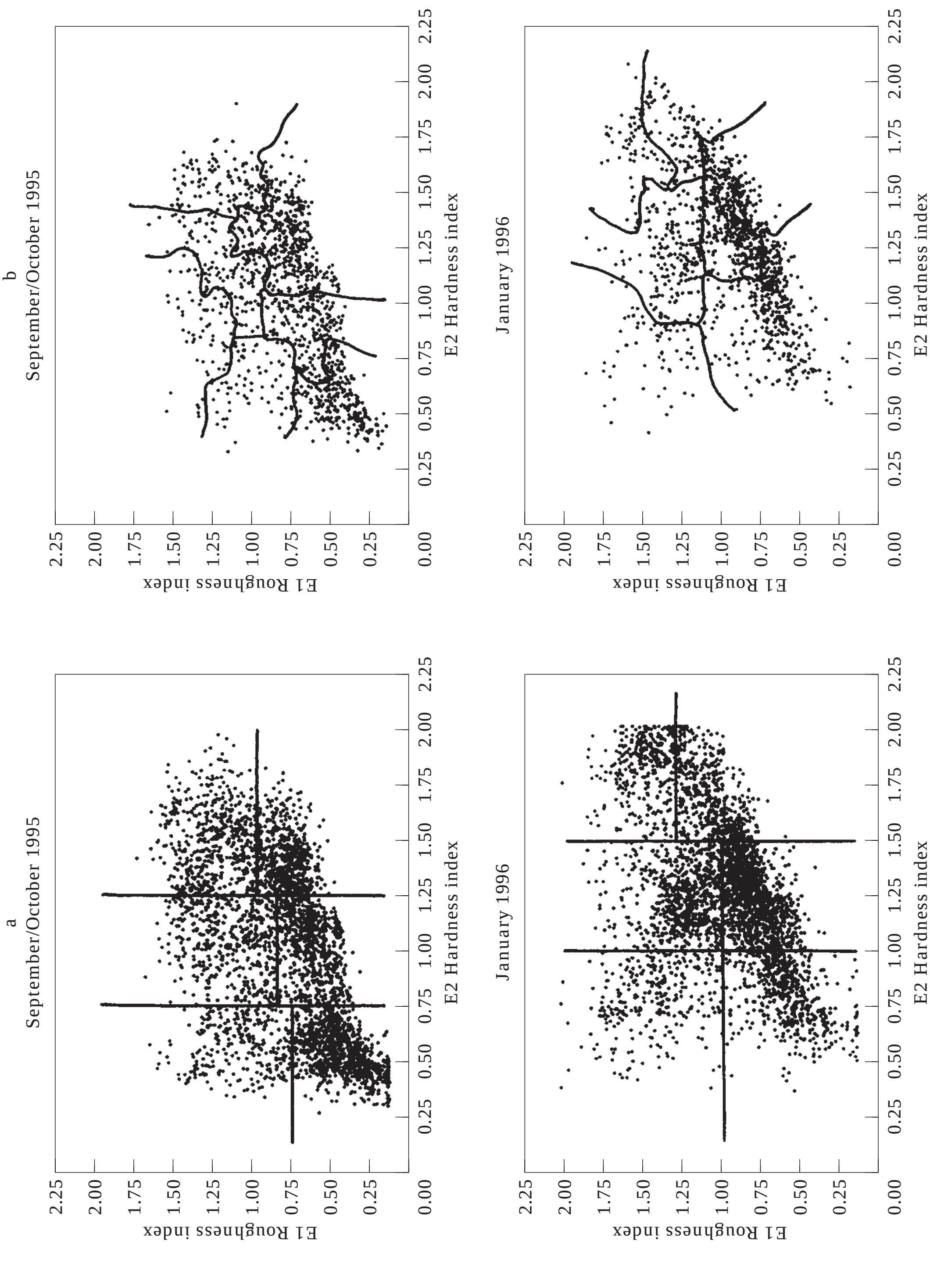


Figure 5. Scatterplots of E1 against E2: a, minute averaged data with box sets used in the subjective analysis; and b, interpolated grid node data with objective clustering pattern obtained following False Colour Composite Image and cluster analysis of the data collected in each survey.

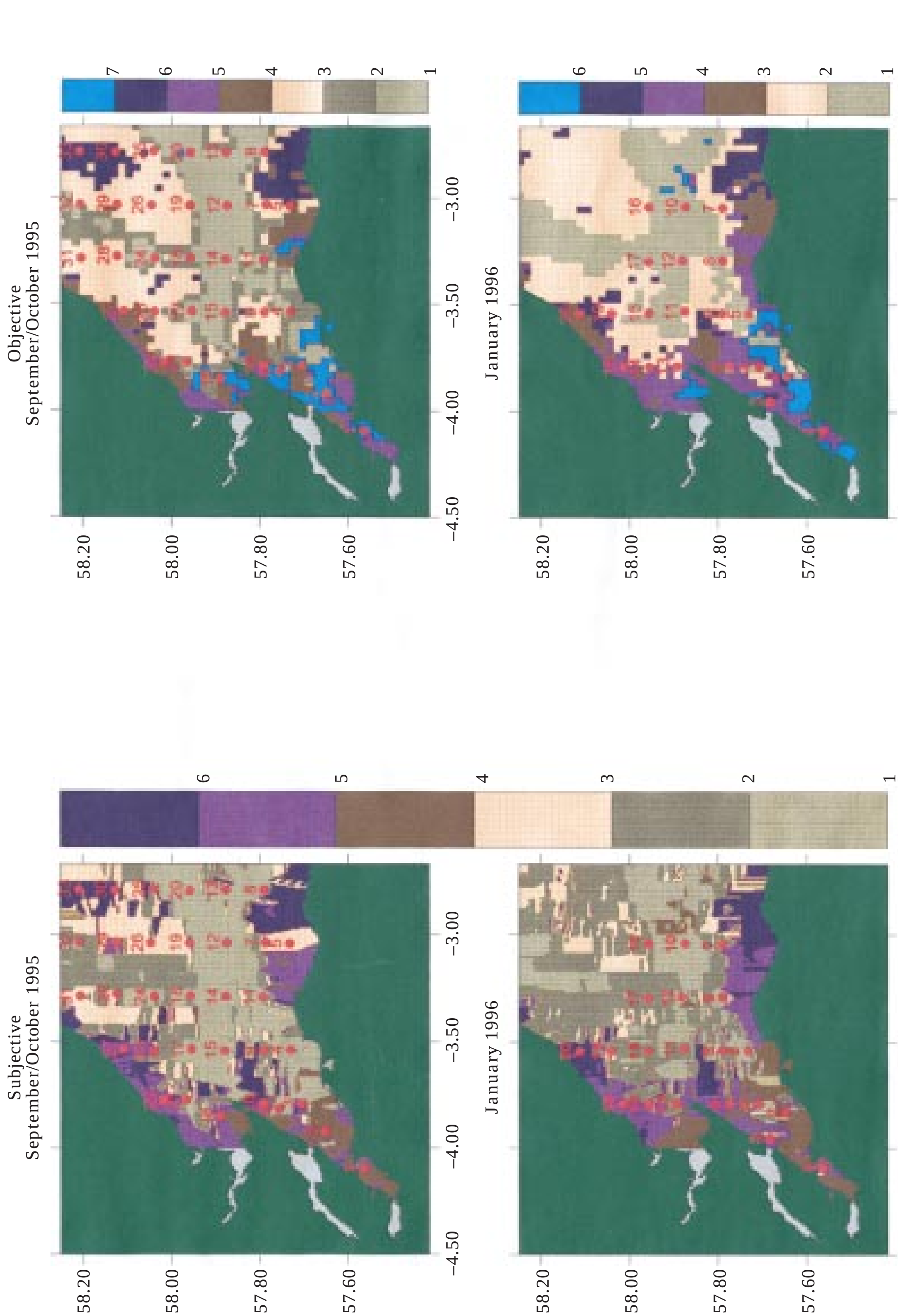


Figure 6. Seabed habitat maps of the inner Moray Firth following subjective box set and objective False Colour Composite Image and cluster analysis of the RoxAnn E1 and E2 data. Positions of day grab samples are shown, numbers relate to the sediment descriptions given in Table 1. (See Figure 1 for latitudes and longitudes in degrees and minutes.)

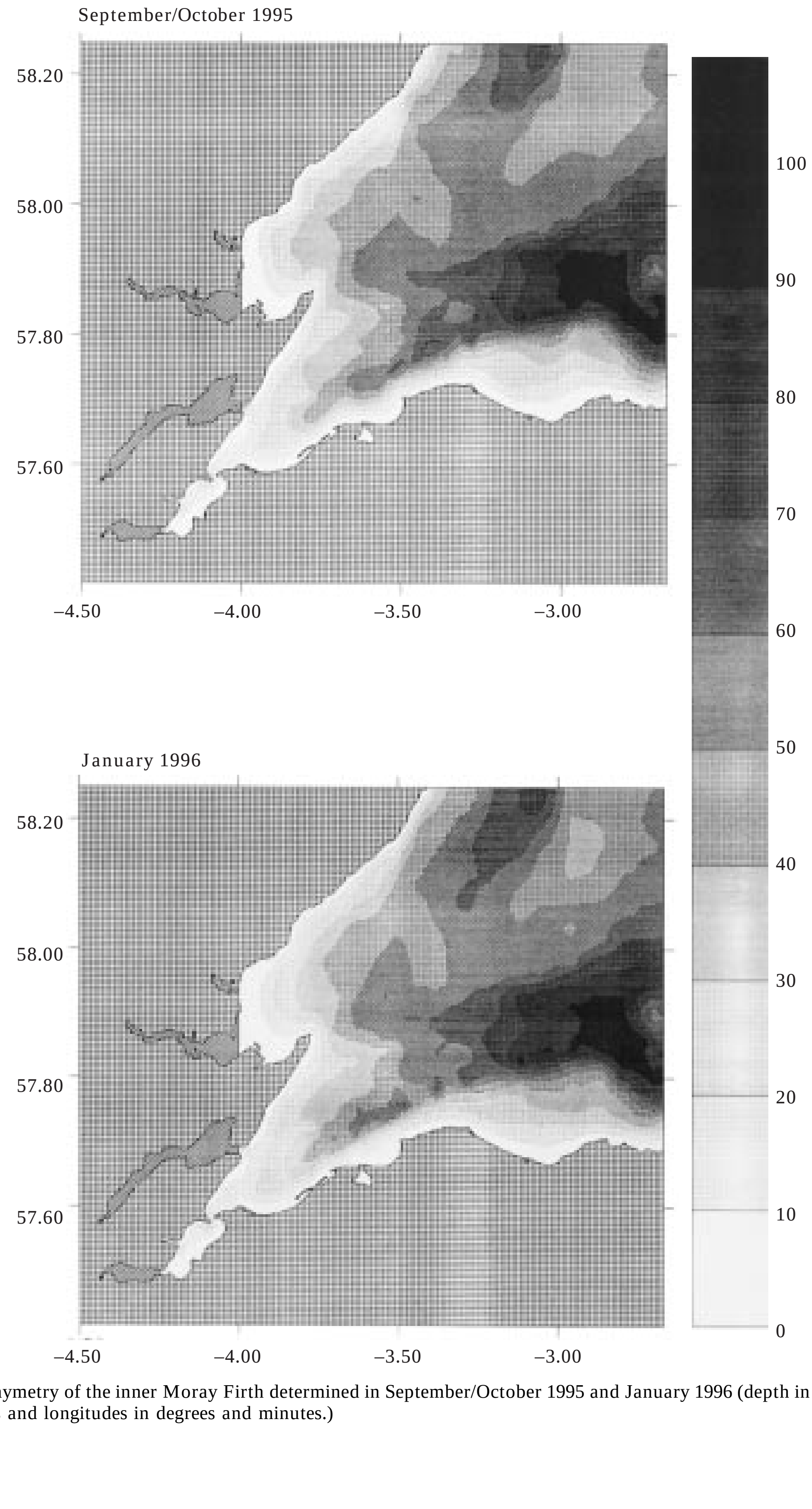


Figure 7. Bathymetry of the inner Moray Firth determined in September/October 1995 and January 1996 (depth in m). (See Figure 1 for latitudes and longitudes in degrees and minutes.)

Table 1. Visual descriptions of the sediments obtained in Day grab samples in each survey. The top section of the table lists samples collected at the same locations in both surveys.

September/October 1995		January 1996	
Sample no.	Sediment description	Sample no.	Sediment description
3	Gravel/coarse sand	4	Small stones/gravel/sand
4	Mud/fine sand	5	Fine mud
7	Sand	7	Fine sand
9	Fine sand/mud	9	Sand/mud/shell gravel
12	Mud	10	Mud
14	Fine sand/mud	12	Fine sand/mud
15	Mud/fine sand	11	Mud/fine sand
17	Fine sand/mud	15	Fine sand/mud
18	Fine sand/mud	17	Fine sand/mud
19	Fine sand/shell gravel/stones	16	Sand/mud/shell gravel
23	Sand/shell/gravel	19	Sand
27	Boulder/rock	20	Boulder/rock
1	Sand/shell gravel	1	Shell gravel/mussels/sand
2	Mud/sand	2	Fine mud
5	Stones	3	Fine sand
6	Mud/sand	6	Fine sand
8	Mud/fine sand	8	Fine mud/sand
10	Sand/small gravel/shell gravel	13	Mud/sand
11	Mud/fine sand	14	Mud/fine sand
13	Mud/fine sand	18	Fine sand/mud
16	Mud/sand/coarse shell gravel		
20	Mud/fine sand		
21	Mud/fine sand		
22	Sand/mud/shell gravel		
24	Fine sand/mud		
25	Fine sand		
26	Sand/fine sand/shell gravel		
28	Stones/mud/sand		
29	Shell gravel/sand		
30	Fine sand/shell gravel		
31	Sand/mud/shell gravel/tunicates		
32	Fine sand/mud		
33	Sand/small pebbles/shell gravel		

5% at each end of the scale to be saturated (i.e. to take the extreme class values of 0 and 255). A default file was created with the same grid node spatial location parameters but with a data parameter value of zero. A false colour composite image (FCCI) was then produced, specifying the E1, E2, and default data as blue, green, and red band components respectively. The composite image was then subjected to an unsupervised classification to divide the survey area into clusters with similar E1 and E2 values. The unsupervised classification was carried out using an algorithm modified from a histogram peak technique (Richards, 1986), and the least significant (by area) 1% of clusters were dropped. This analysis was carried out in IDRISI (Clark University). The categorical data obtained were mapped using the nearest neighbour algorithm as described above.

A number of sediment samples were taken in each survey using a 0.1 m^2 Day Grab. These samples were collected immediately following completion of the acoustic survey and were spaced more or less evenly throughout the study area in September/October 1995. In January 1996 severe weather prevented sampling at the stations in the extreme north and east of the study area. Grab sample stations were located without reference to the RoxAnn data although in the main they were located on or very close to the RoxAnn survey track. Grab samples were examined on the boat and a visual description of each sample recorded.

The sediment samples collected in September/October 1995 were also retained for particle size analysis in the laboratory in order to verify the accuracy and value of the visual descriptions, and to provide a more objective method for ground-truthing the RoxAnn maps. The fraction of each sample with particle size less than 0.5 mm was analysed by laser granulometry using a Malvern Mastersizer/E granulometer (Malvern

Table 2. The number of grab samples with a particular description associated with each RoxAnn sediment cluster.

Survey date	Sediment description	RoxAnn sediment clusters 1	2	3	4	5	6	7
September/ October 1995	Mud	1						
	Mud/fine sand	5*	1	1				
	Fine sand/mud	5†		1				
	Fine sand			1				
	Sand			1				
	Sand/mud/shell gravel/tunicates			1				
	Sand/fine sand/shell gravel			1				
	Fine sand/shell gravel/stones			1				
	Shell gravel/sand			1				
	Stones/mud/sand			1				
	Sand/shell gravel			1‡		1		
	Sand/small gravel/shell gravel					1¶		
	Stones				1§			
	Mud/sand/coarse shell gravel				1			
	Sand/mud/shell gravel				1			
	Gravel/coarse sand				1			
	Boulder/rock				1			
	Fine sand/shell gravel						1	
	Sand/small pebbles/shell gravel						1	
	Mud/sand							2
January 1996	Small stones/gravel/sand	1						
	Fine mud/sand	1						
	Mud	1						
	Fine mud	1			1			
	Fine sand/mud	2	1		1			
	Fine sand	1	1		1			
	Mud/fine sand		2					
	Mud/sand		1					
	Sand		1					
	Sand/mud/shell gravel		2					
	Shell gravel/mussels/sand			1				
	Boulder/rock			1				

*One sample on the border between sediment clusters 1 and 2.
†One sample on the border between sediment clusters 1 and 2 and one sample on the border between sediment clusters 1 and 3.
‡On the border between sediment clusters 3 and 4.
§On the border between sediment clusters 3 and 4.
¶On the border between sediment clusters 4 and 5.

Instruments), while the fraction with larger particle size was analysed using a sieve shaker. Seven sieves were used with pore size ranging from 1Φ (0.5 mm) to −2Φ (4 mm) at half Φ intervals (where pore size in mm is $1/2^{\Phi}$). The sieves were shaken for 15 min and the weight of sample in each fraction noted. The resulting distribution was then combined with the granulometer distribution to produce the full particle size range from 11Φ to −2Φ (0.0005 mm to 4 mm) at half Φ intervals. Similarity in the distribution of sample material over the 26 particle size fractions was determined using the Bray–Curtis similarity index. Non-metric multidimensional scaling (MDS) ordination analysis was used to examine sample clustering (Clarke and Ainsworth, 1993; Warwick and Clarke, 1993). The significance of any clustering of grab samples associated with different RoxAnn habitat types was examined using one way Analysis of Similarity (ANOSIM) randomization tests (Clarke, 1993).

Data on seabed sediment composition from two British Geological Survey (BGS) sediment charts (sheets 57N 04 W and 58N 04 W) were digitized using the sample station positions and their corresponding modified Folk (1954) seabed classification. The data were digitized using TOSCA (version 2.12, Clark University) and converted to SURFER format using IDRISI. A

Table 3. Classification of the sediment grab sample descriptions associated with each false colour composite image cluster by particle size approximation and variability.

Survey	Cluster	Particle		Other notes
		Size	Variability	
September/ October 1995	1	Very fine	Low	Mud or fine sands
	2	Very fine	Low	Mud or fine sands
	7	Very fine to fine	Intermediate	Intermediate of 1/2 and 3, particle size more variable
	3	Fine–medium	Intermediate	Sands to very fine gravel
	5	Fine–medium	Intermediate	Similar to 3, more shell gravel
	6	Medium	Intermediate	Similar to 5, larger particle size
	4	Medium–large	High	Coarse hard sands to boulder/rock
January 1996	1	Very fine	Low	Mud or fine sands
	4	Very fine to fine	Intermediate	Intermediate of 1 and 2, particle size more variable
	2	Fine–medium	Intermediate	Sand to very fine gravel
	3	Medium–large	High	Coarse hard sands to boulder/rock

sediment map of the inner Moray Firth BGS data was produced in SURFER by constructing a grid of 250 columns by 250 rows and fixing the grid node values to that of the nearest neighbouring BGS datum.

Immediately following the acoustic survey in October 1995, samples of demersal fish were taken at 21 locations in the study area using a Jackson Rockhopper trawl fitted with a 10 mm mesh codend (see Fig. 12 for haul locations). The gear was fished for 30 min contact with the seabed, except for one location at the mouth of the Inverness Firth where a tow of only 15 min duration was possible because of the confined area. The fishing gear was fitted with net monitoring equipment (SCANMAR, Norway) which recorded wing-spread and headline height at 30-second intervals. The ship's position was obtained simultaneously from the Global Positioning System (GPS). These data allowed the area of seabed swept by the gear during each tow to be determined. The numbers of common dab, long rough dab, lemon sole, and plaice caught at length at each location were determined from a subsample of the catch. Numbers-at-length were converted to weights-at-length using published length–weight relationships (Coull *et al.*, 1989). Summing weights-at-length over all length intervals provided a total catch weight estimate for each species and dividing these by the swept area provided density estimates (g m^{-2}). The four flatfish distributions were mapped by kriging these density data after first examining experimental variograms to determine the most suitable kriging model and appropriate model parameters (see above). Differences between the spatial distributions were examined using the two methods proposed by Syrjala (1996), one a modification of the Cramer–von Mises test, the second approach involving a Kolmogorov–Smirnov test.

Results

The patterns of spatial variation in E1 and E2, although not identical, were essentially similar in each of the two surveys (Fig. 2). Much of the difference between the patterns, particularly close to the south coast, can be explained by differences in survey coverage (see Fig. 1). However, the darker contour shading of the January 1996 maps also suggests that the recorded E1 and E2 values were generally higher in the later survey.

Between survey differences in E1 and E2 were examined by comparing the interpolated grid node values (Fig. 3). Over much of the E1 range the difference between the two surveys was more or less constant, but at the extreme low end of the range of E1 values the difference increased. For E2 the difference was not a simple constant variation, but was instead negatively related to E2. At high E2 values the difference was minimal while at low values it was considerable with January 1996 values being on average nearly twice those of the September/October 1995 data. The pattern of spatial variation in the difference in E2 values between surveys closely followed spatial variation in E2 itself (Fig. 4), and this was especially obvious when the difference was expressed as a proportion of the September/October 1995 E2 value. Positive differences were apparent in regions of softer sediment, while zero or negative differences were observed where the sediments were harder. No such spatial relationship was apparent for E1. Instead positive differences were noted over most of the study area and were greatest in two regions (Fig. 4); one on the south coast which could be attributed to variation in coverage, and the second in the middle of the deeper area of smoother softer sediment in the south-east quadrant of the area associated with the

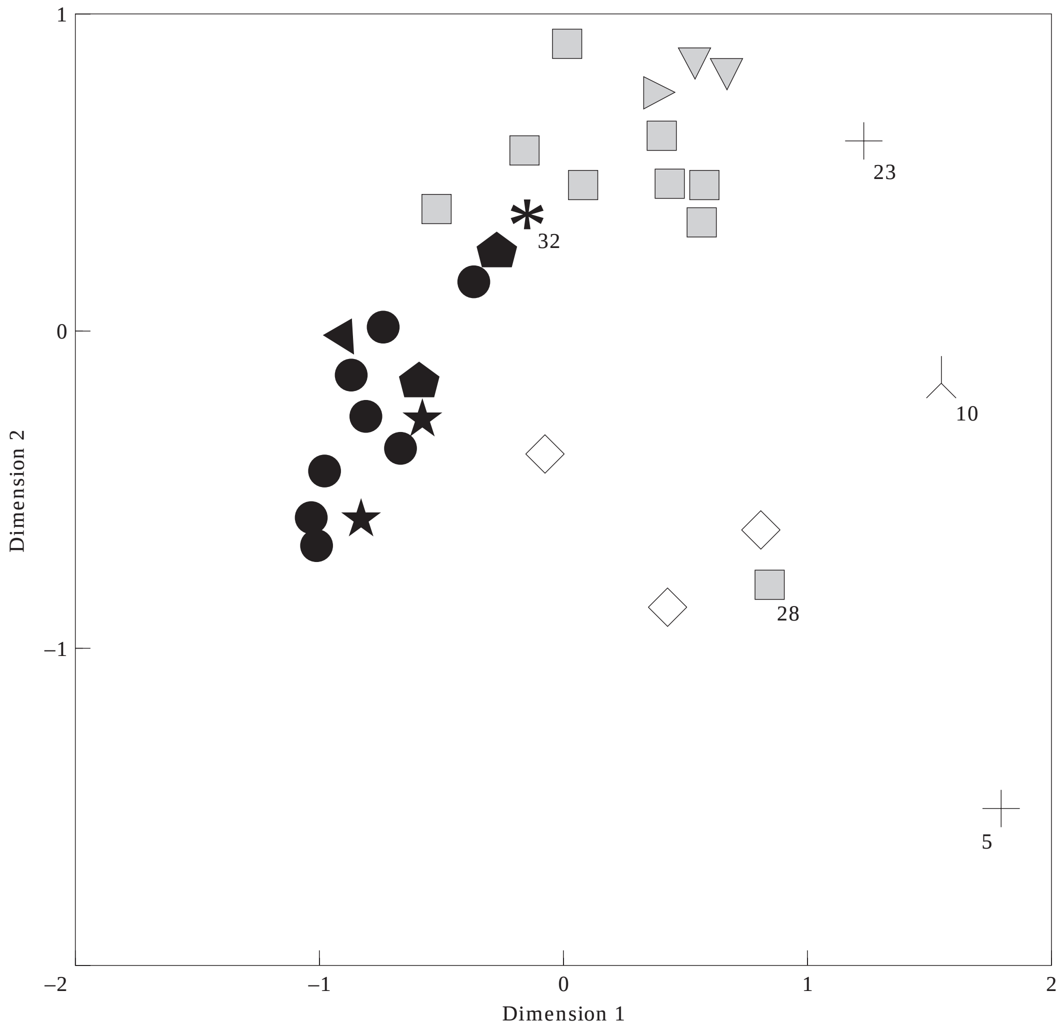


Figure 8. Multi-dimensional scaling ordination of the grab samples based on Bray-Curtis similarity of the particle size distributions. The three main clusters used in the Analysis of Similarity are indicated by the black (finest particle size), white (coursest particle size) and grey (intermediate particle size) filled symbols. The line symbols are samples on the boundaries between the major habitat types. Samples associated with particular RoxAnn habitat type clusters, and boundaries between them, are indicated as follows: type 1 ●; type 2 ◀; type 3 ■; type 4 ◇; type 5 ➤; type 6 ▼; type 7 ★; boundary type 1 and 2 ⬟; boundary type 3 and 4 +; boundary type 4 and 5 ⅄; boundary type 1 and 3 *.

presence of dense shoals of pelagic clupeid fish (S. P. R. Greenstreet, unpublished data).

Plots of E1 against E2 indicated that over 60% of the data in each survey were closely correlated falling in a diagonal band running across the lower part of each plot (Fig. 5a). Above this band fall data with higher E1 values than data of similar E2 value which lie in the main band. A ‘‘box set’’ consisting of six boxes was set on these data by first looking for apparent clusters in the main band of data and assigning three E2 band widths, and then in each E2 band width group, the outliers were separated from the main band of data. As suggested by the previous analysis, the data clouds in each of the plots clearly differ, with higher E1 and E2 values occurring in the January 1996 survey, consequently the positioning of the six boxes differed between surveys (Fig. 5a).

Figure 6 compares these subjective ‘‘box set’’ derived sediment maps with maps derived from the more objective false colour composite image and cluster analysis. Interestingly, the unsupervised cluster analysis determined seven clusters in the September/October 1995 data set and six clusters in the January 1996 data set, numbers remarkably similar to the six boxes subjectively fitted by eye to the data clouds shown in Figure 5a. The grouping determined by the cluster analysis on equivalent scatterplots of grid node E1 on E2 data is shown for

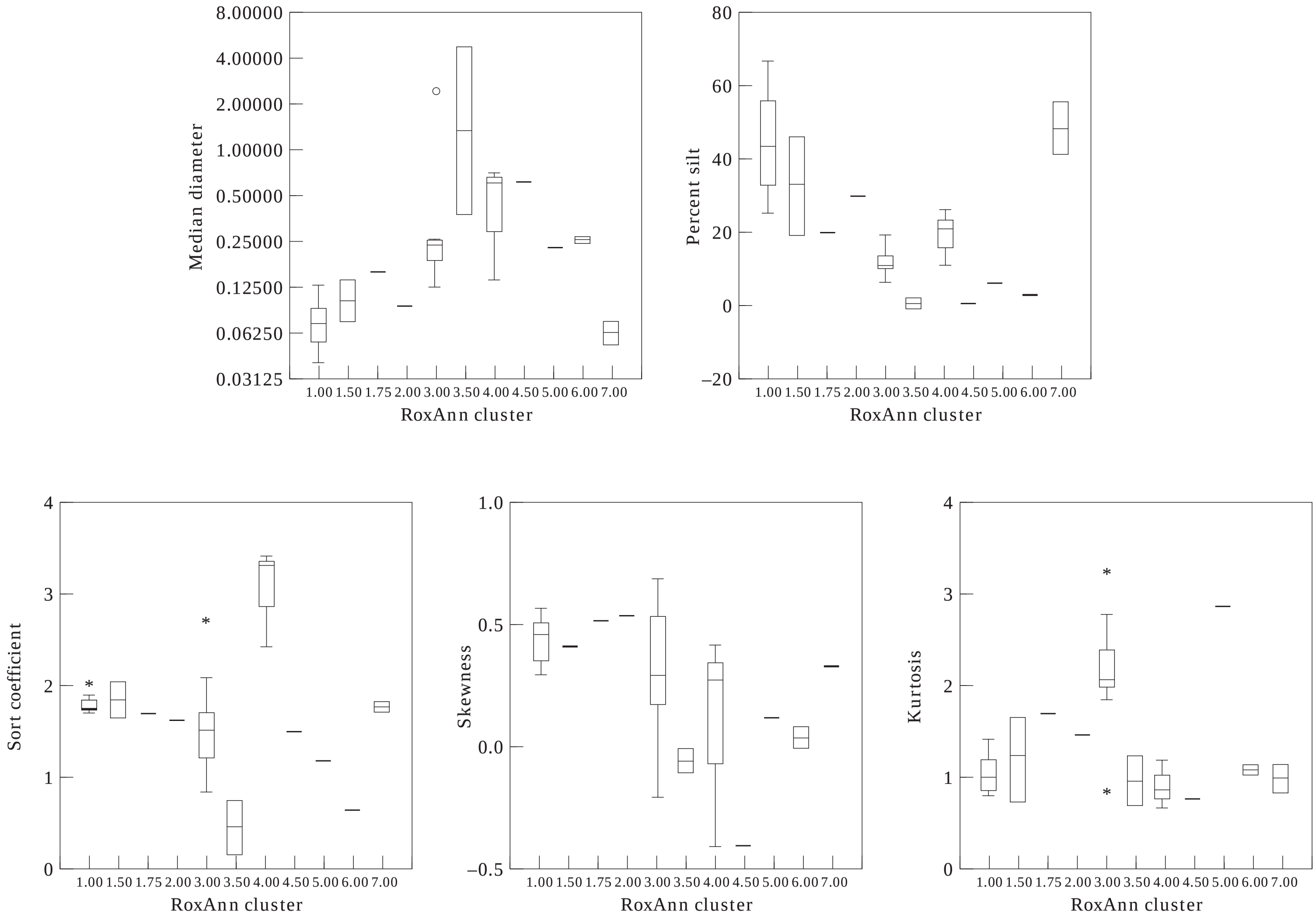


Figure 9. Box plots of five particle size parameters, median diameter, percent silt, sort coefficient, skewness and kurtosis, for grab samples associated with different RoxAnn habitat type clusters. Samples falling on boundaries between RoxAnn habitat type clusters are shown as 1.50 (boundary between clusters 1 and 2), 1.75 (boundary between clusters 1 and 3), 3.50 (boundary between clusters 3 and 4) and 4.50 (boundary between clusters 4 and 5).

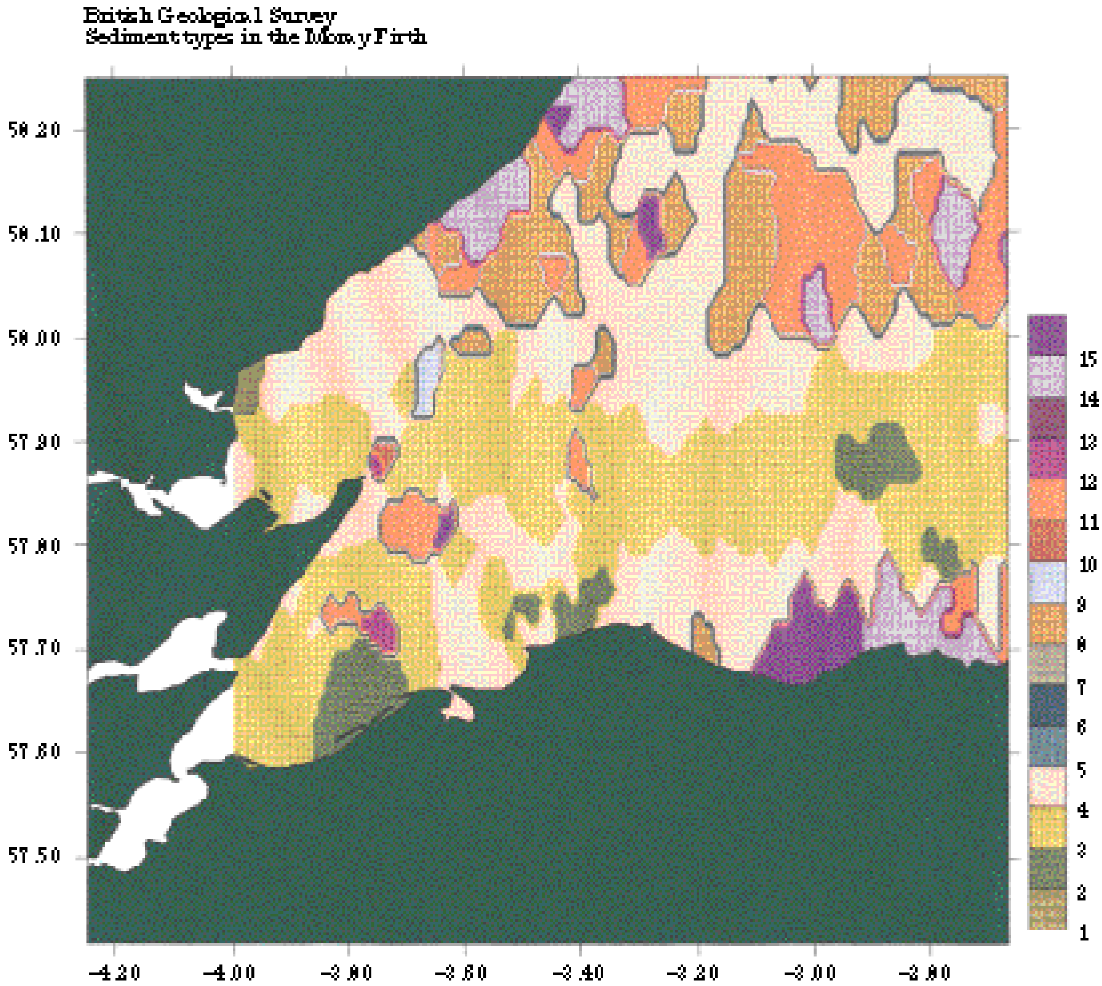


Figure 10. Sediment map of the inner Moray Firth obtained from the British Geological Survey data (see Figure 1 for latitudes and longitudes in degrees and minutes). 1 Mud; 2 Sandy mud; 3 Muddy sand; 4 Sand; 5 Slightly gravelly mud; 6 Slightly gravelly sandy mud; 7 Slightly gravelly muddy sand; 8 Slightly gravelly sand; 9 Gravelly mud; 10 Gravelly muddy sand; 11 Gravelly sand; 12 Muddy gravel; 13 Muddy sandy gravel; 14 Sandy gravel; 15 Gravel (in BGS, 1984, 1987, after Folk, 1954). Reproduced with permission from the NERC.

comparison in Figure 5b. Both the subjective and objective methods of sediment classification result in maps which are very similar (Fig. 6). However, the objective method results in maps which are more consistent between surveys. In particular, the location of boundaries between the different sediment types is less variable.

Bathymetry maps of the inner Moray Firth recorded in the two surveys are almost identical (Fig. 7), with any discrepancies explained by survey coverage differences and tide state variation. There is a close relationship between depth (Fig. 7), the E1 and E2 values (Fig. 2), and sediment type (Fig. 6). In the deeper water, sediments tended to be softer and smoother, while in the shallower coastal water the sediments were harder and rougher. The shallower water in the north-east corner of the study area, the south-west edge of Smith's Bank, shows up as a distinct harder and rougher sediment type.

Day Grab sample stations are shown on each of the sediment maps and the sediment descriptions recorded at each station are given in Table 1. At 12 locations grab samples were obtained from almost the same position in both surveys and the descriptions recorded on each occasion were reasonably consistent (Table 1). Table 2 shows the number of times particular sediment descriptions were associated with each sediment type identified by the false colour composite image and cluster analysis of the RoxAnn E1 and E2 data. Initially the RoxAnn sediment type FCCI clusters seem quite distinct, however, closer examination of the descriptions suggests considerable overlap between them. The sediment

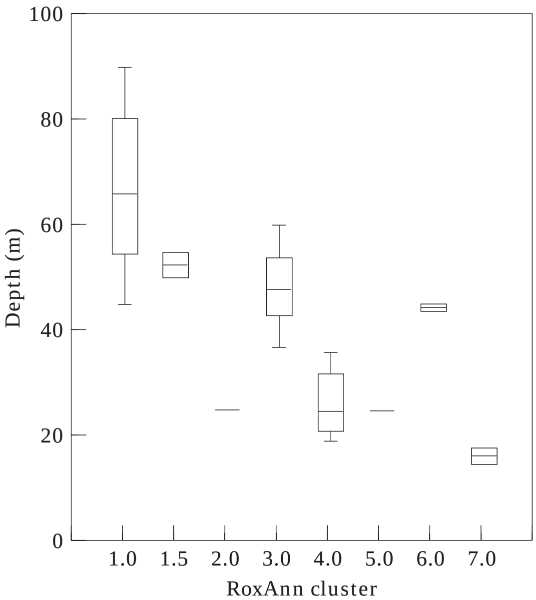


Figure 11. Box plots of grab sample depths for grab samples associated with different RoxAnn habitat type clusters.

descriptions were used to provide a habitat type classification based roughly on particle size and variability, and on this basis three distinct habitats were apparent (Table 3). The first of these consists of muds or very fine sands, the second consists mainly of more sandy substrates, while the third habitat consists of a broad range of substrates ranging from coarse sands or gravels to boulders or bedrock. Table 3 shows the grouping of the RoxAnn FCCI clusters into each of these habitat types for each survey.

MDS ordination of the particle size distribution Bray–Curtis similarity matrix suggested the same grouping of RoxAnn sediment clusters (Fig. 8. Although the overall ANOSIM based on the all RoxAnn sediment clusters was highly significant (actually clusters 2 and 5 were excluded because only one grab sample was associated with each; samples located on the borders between sediment clusters were also excluded), this was mainly due to the separation of samples associated with sediment clusters 1 and 3. The remaining nine pairwise comparisons were not significant at a significance level of $p<0.005$ (Bonferoni adjusted for multiple, i.e. 10, comparisons). The ANOSIM was then repeated, but with grab samples associated with RoxAnn clusters 1, 2, and 7 (including samples on the boundary between clusters 1 and 2), and samples associated with clusters 3, 5, and 6 combined and treated as two separate entities (as suggested by Table 3). Samples associated with cluster 4 continued to be treated separately. Now, not only was the global test highly significant, but all three pairwise comparisons were also significant at $p<0.017$ (Bonferoni adjusted for three comparisons). Samples 23 and 5 were located on the border between clusters 3 and 4, while sample 10 lay on the border between clusters 4 and 5. The interesting point to note here is that the MDS ordination suggests that these borderline samples consist of unique particle size distributions. This contrasts with sample 32, located on the border between clusters 1 and 3, whose particle size distribution appears to be intermediate between those characteristic of the two neighbouring RoxAnn clusters. Sample 28 is simply an ‘‘odd’’ sample, probably taken from a patch of sediment more characteristic of RoxAnn FCCI cluster 4, which was located within a larger area of cluster 3 type sediment, and which just happened by chance to be hit by the grab.

Particle size analysis of the grab samples retained in September/October 1995 also confirmed the broader habitat type classification outlined in Table 3 (Fig. 9). Samples associated with RoxAnn FCCI clusters 1, 2, and 7 had the highest silt content and smallest median grain diameter, they tended to be poorly sorted and their grain size distributions were strongly positively skewed. Samples associated with RoxAnn clusters 3, 5, and 6 had the lowest silt content and moderate median grain diameter; they were moderate to poorly sorted. Samples associated with RoxAnn cluster 4 held intermediate silt content, but had a higher median grain size and were extremely poorly sorted.

When viewed in this light there was broad agreement between the objective sediment maps produced from the RoxAnn data (Fig. 6) and the sediment map derived from the BGS data (Fig. 10). The harder coarser substrates off Helmsdale, east and south of Tarbet Ness and in Spey Bay are clearly distinguished in both the RoxAnn and the BGS maps. That the bulk of the region’s seabed is covered by muds and fine sands is also apparent in both sets of maps, with the softest finest substrates found in the deep water in the southern part of the region and between the north-west Moray Firth coast and the shallower Smith’s Bank in the north-east of the study area. The coarser sandy substrate of Smith’s Bank is also clearly evident in both sets of maps. The main difference between the two maps lies in the apparent differentiation by RoxAnn of the muddy/sandy sediments in the shallower waters close to the coast line in the western parts of the study area from apparently similar sediments further offshore and to the east. While analysis of the grab samples presented above suggests that this differentiation may not actually be related to differences in sediment particle size distribution, it could however be related to variation in depth (compare the maps in Figs 6 and 7). For example, the grab samples associated with RoxAnn sediment types 1, 2, and 7 in September/October 1995 all consisted of mud or fine sands, but the depth at which these samples were collected varied considerably (Fig. 11).

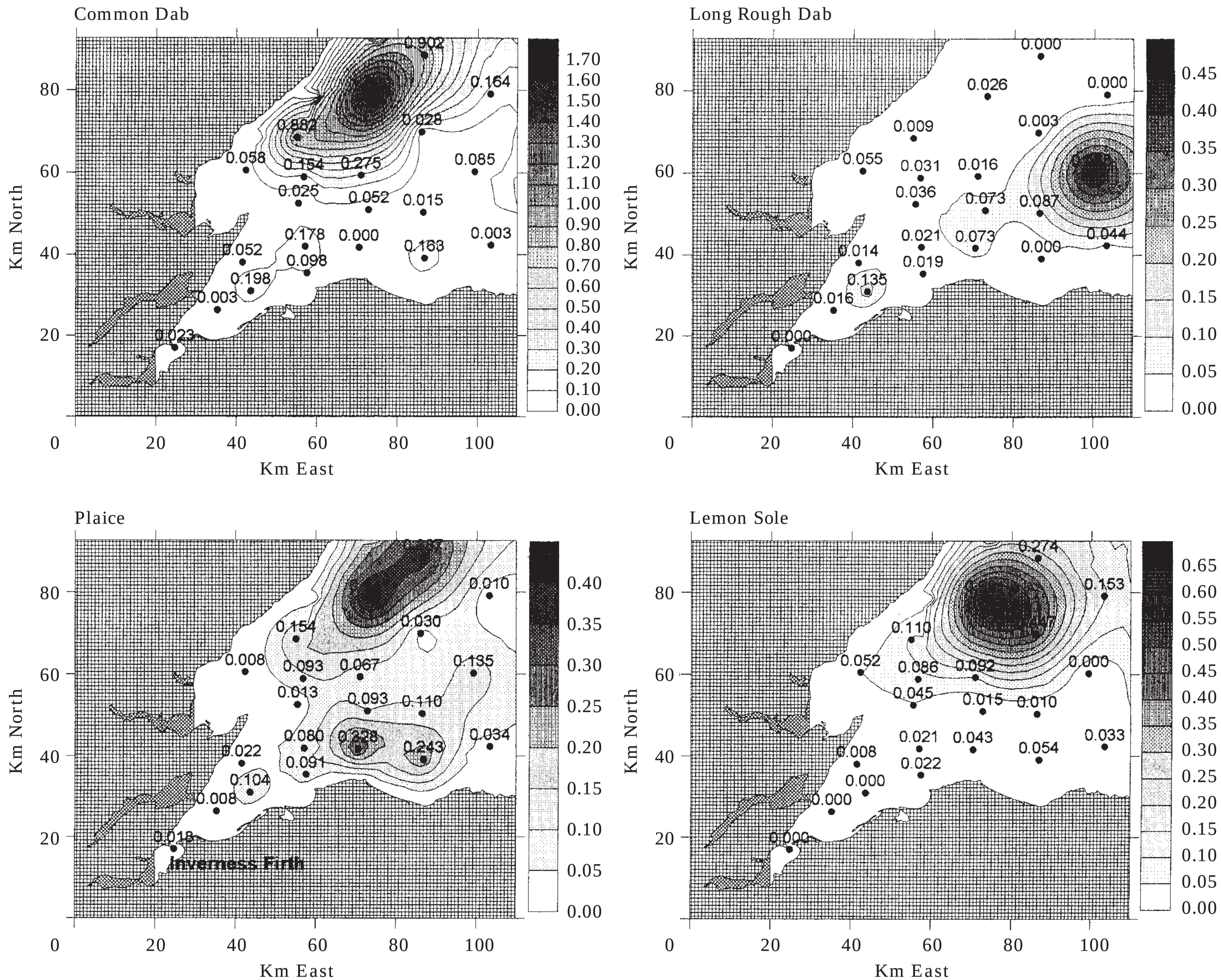


Figure 12. The spatial distributions of four flatfish species in the Moray Firth. Points show trawl locations and values give recorded density at each location. Contour maps were derived after kriging these data using a spherical model with zero nugget and sill and range parameters equal to 0.270 and 40 for common dab, 0.013 and 30 for long rough dab, 0.036 and 32 for lemon sole and 0.018 and 35 for plaice. The origin was located at 57°25′N and 004°30′W.

Table 4. Results of Syrjala's (1996) tests for significant differences between the spatial distributions of common dab, long rough dab, lemon sole and plaice in the Moray Firth in October 1995. Lower left section gives results obtained from the modified Cramer-von Mises test, upper right section shows results of the Kolmogorov-Smirnov approach.

	Common dab	Long rough dab	Lemon sole	Plaice
Common dab	–	0.007**	0.405	0.007**
Long rough dab	0.225	–	0.002**	0.406
Lemon sole	0.372	0.046*	–	0.007**
Plaice	0.006**	0.637	0.007**	–

Significance levels indicated by *($p<0.05$) and ** ($p<0.01$).

Figure 12 shows the spatial distributions of common dab, long rough dab, lemon sole, and plaice in October 1995. With the exception of common dab and lemon sole, these distributions appear quite dissimilar. However, formal testing indicated that there was also no significant difference between plaice and long rough dab. Furthermore, the difference between the distributions of common dab and long rough dab was only statistically significant when using the Kolmogorov–Smirnov test and this test can be unduly influenced by large single point deviations. The three remaining comparisons were all significant no matter which test was used (Table 4). Most of the demersal hauls occurred in areas of Very Fine to Fine or Fine to Medium particle size (see Table 3). Only two hauls were located in the third, coarser, sediment habitat type; we therefore combined these with the trawl samples taken from the Fine to Medium sediment habitat. Comparison between Figures 12 and 7 suggests that the highest densities of each species were to be found in areas of deeper water. In examining the possible effect of the two sediment habitat types on flatfish density therefore, we also took variation in water depth into account by considering two depth strata, 0–35 m and >35 m. This gave a total of four habitats, shallow with fine sediment, shallow with coarse sediment, deep with fine sediment, and deep with coarse sediment. The Box and Whisker plots suggest that each species responded differently to various combinations of sediment habitat and depth (Fig. 13). Common dab were most abundant in coarser sediments at both depth strata. Long rough dab appeared to prefer fine sediments in deeper water, while lemon sole tended to be most abundant in coarse sediments in deeper water. Plaice appeared to avoid fine sediment habitat in shallow water. These patterns should however be treated with some caution since analyses of variance (on the root-transformed data) were not statistically significant (p values for the sediment habitat variable for example ranged from 0.09 to 0.21). We believe that the small samples sizes involved are largely responsible for our failure to produce statistically significant results in this instance. Given our small sample sizes, the relatively small probabilities may well be indicative that the sediment habitats detected by RoxAnn influence the spatial distributions of the four flatfish species.

Discussion

The present paper highlights some important aspects in the analysis and application of RoxAnn data for habitat discrimination. There were systematic differences in the E1 and E2 values recorded at the same locations between the two surveys. Although it is impossible to be certain why this should be, a number of suggestions can be made. The most likely cause of differences is variation in the attitude of the transducer. The theoretical basis of RoxAnn (Chivers *et al.*, 1990) assumes that the transducer is generally horizontal. The values of both E1 and E2 are likely to be affected when this assumption is violated. The towed body used in this survey (and in most similar situations) is actively hydrodynamic. Even slight accidental damage of the fins (e.g. bending) will cause the towed body to take up a subtly different attitude. However, for this type of survey the towed body is generally preferable to the hull mounted option despite these potential drawbacks. Provided the towed body is protected from damage during a survey, it is reasonable to assume that its attitude will remain relatively constant. In addition, variation in the towed body's attitude can be monitored with heel and pitch sensors and corrective action taken in the event of a significant change. The greatest advantage of towed bodies is that their performance is relatively independent of the weather. It is almost impossible to ensure that the trim of a vessel does not change constantly during a survey, not only due to wave action, but also through fuel and water use. Systematic differences could also arise as a result of seasonal changes. At 38 kHz sound can penetrate a considerable distance into the seabed, perhaps up to 1 m depending on sediment density and water content. It is likely therefore that the infaunal as well as epifaunal benthic biota may affect the values of E1 and E2 (e.g. Magorrian *et al.*, 1995). There are likely to be seasonal changes in the abundance and distribution of such organisms, which may modulate the RoxAnn parameters.

These observations highlight the requirement to ground truth any RoxAnn survey data on the same survey, and to conduct the analysis on the basis of these samples. The false colour and clustering technique described here is particularly useful in this context, as it does not work on the basis of a fixed relationship between E1, E2 and a specific substrate. This technique also avoids the problem associated with the ''box set''.

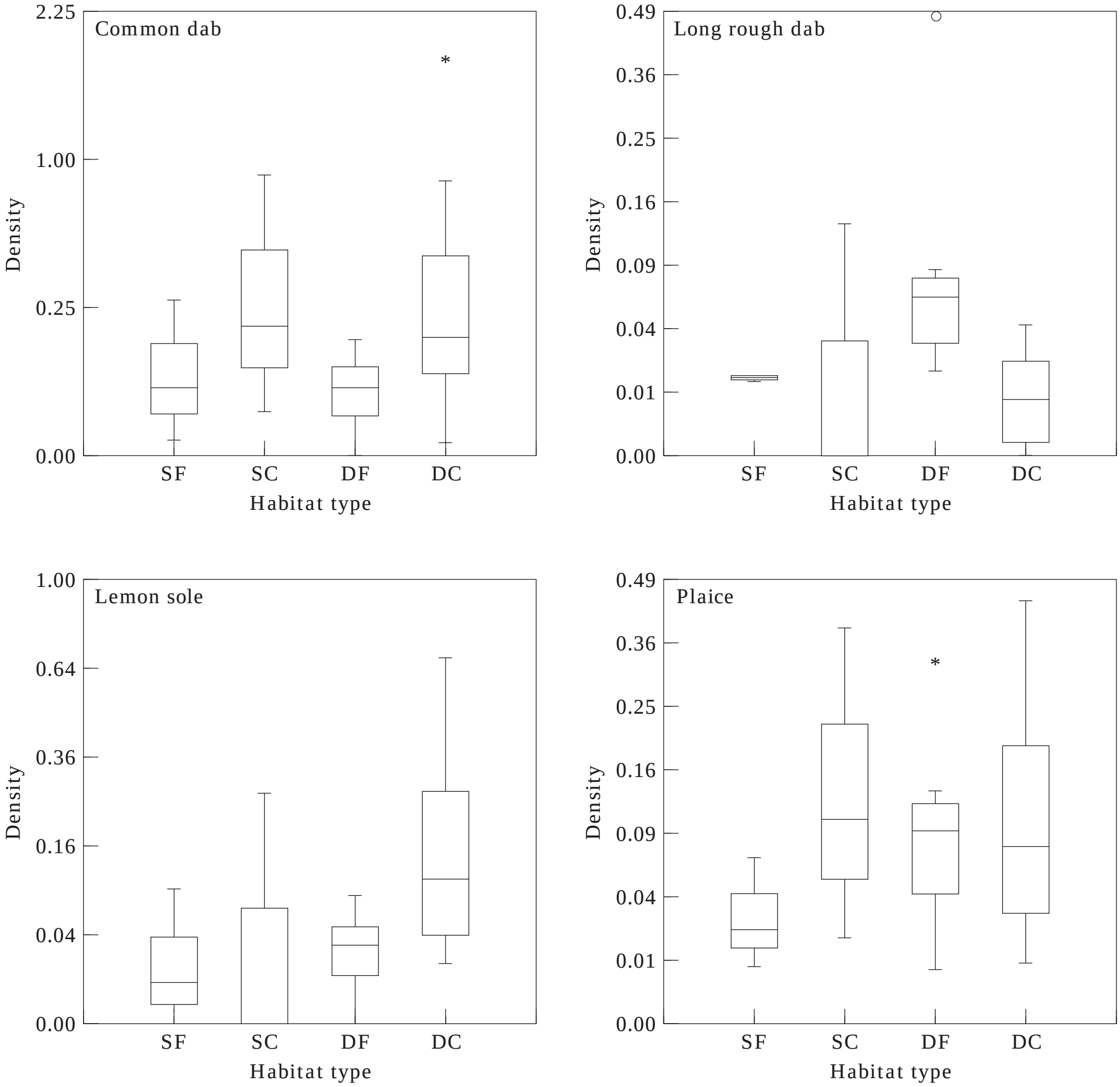


Figure 13. Box and Whisker plots of the density of four flatfish species in four habitats; shallow with fine sediment (SF, n=3), shallow with coarse sediment (SC, n=3), deep with fine sediment (DF, n=8) and deep with coarse sediment (DC, n=7). Density values were square root transformed, but the plots show the original values on a √ transformed scale.

The rectangular boxes are a very crude way of grouping the data and will tend to result in more mis-identification at the edges of the boxes than is apparent with the false colour approach. This is substantiated by the greater clarity and repeatabiltiy of the maps derived by this approach.

Subjective examination of the data suggested a box pattern delimiting six clusters in the data. This was in close agreement with the more objective False Colour Image and cluster analysis which discriminated seven clusters in September/October 1995 and six in January 1996. The BGS sediment maps use a modified Folk (1954) diagram which gives 15 distinct sediment types, only seven of which were present in our Moray Firth study area. Thus all three sets of sediment maps suggest between six and seven different sediment types. Distinguishing between this number of sediment types using simple descriptions of the appearance of the sediments in grab samples proved difficult however. Various factors contributed to the problem. Firstly, the grab sample locations were relatively evenly spaced throughout the study area, but much of the area was dominated by only two of the sediment types. Consequently, these sediment types were frequently sampled, while the remaining sediment types were rarely sampled. In future ground-truthing activities in the study area we will adopt a more stratified sampling regime to ensure equal sampling of the less common sediment types. Secondly, actually describing in words the appearance of a grab sample was not simple, consequently most samples acquired a unique description and relating these numerous various descriptions to the six or seven RoxAnn FCCI clusters was not easy. Refinement of the grab sample visual appearance descriptions, and MDS ordination analysis of particle size distributions, suggested that, on the basis of the data available to date, we could only resolve three sediment habitats with certainty in the inner Moray Firth using RoxAnn.

Analyses of both RoxAnn surveys indicated substrate differences in inshore areas which were not apparent in either the grab samples or the BGS data. However, RoxAnn is not only sensitive to physical abiotic characteristics of the sediments; E1 and E2 can also be influenced by biotic features associated with the seabed such as the abundance of particular benthic organisms (Magorrian *et al.*, 1995). The apparently different habitats defined by RoxAnn in the inner Moray Firth were restricted to shallower water of generally less than 30 m depth. It is entirely possible that some biotic feature, such as the presence of seaweed, may have been responsible for this habitat distinction, rather than any variation in sediment type (e.g. Schlagintweit, 1993). Alternatively, water depth, or perhaps closer proximity to freshwater outflows, might affect the performance of RoxAnn or influence characteristics of the seabed, such as sediment compaction, water content and large-scale ‘‘roughness’’, e.g. sand ripples, to which RoxAnn is sensitive, but which do not show up in simple visual examination of the grab samples or in particle size analysis. One final possible explanation is that the top layer of soft mud/sand substrates sampled by the grab is less thick in the shallower water exposed to stronger tides, and that RoxAnn is responding to denser harder substrate layers below the surface of the seabed. In general, it is recommended by Marine Microsystems (RoxAnn's manufacturers) that different box settings be used in water shallower than 30 m. The results of this survey emphasize the importance of treating shallow subtidal areas differently to more offshore areas.

To conclude, RoxAnn provided an efficient means of distinguishing differences in seabed habitat that were repeatable, particularly when the E1 and E2 data were analysed using False Colour Image and clustering techniques. However, when compared with simple visual examination and particle size distribution analysis of sediment grab samples, RoxAnn appeared oversensitive. Some of the different sediment types resolved by RoxAnn could not be characterized in terms of difference in sediment grain size. It remains entirely possible however, that RoxAnn is identifying real differences in habitat and that it is responding to other characteristics of the seabed that sediment grab sampling cannot detect. Even if we can, at this point, identify with certainty only three different sediment habitats in the inner Moray Firth, this in itself is no mean achievement when one considers that these habitats only range from muddy sands to fine gravels. The finer muds and the coarser, harder sediments are almost absent from our study area, or are restricted to close inshore regions which were not easily covered by the survey vessel. Our results suggest, therefore, that the use of RoxAnn, combined with False Colour Image and cluster analysis, to map seabed habitat variation would be highly effective in areas containing more varied sediment habitats. The flatfish density data suggest that the sediment habitats discerned by RoxAnn may hold biological significance in influencing the distribution of fish species strongly associated with the seabed. If further work confirms the statistical significance of this result, then RoxAnn surveys of regions such as the North Sea may provide valuable information which would allow surveys of groundfish and benthic invertebrate species to be designed on a stratified random basis. Such designs, where they can be realistically applied, generally provide more precise estimates of species abundance (Simmonds and Fryer, 1996).

The final point to make concerns the cost-effectiveness of mapping sea bed habitat in this manner. The amount of effort required to produce the maps shown in Figure 6, in terms of shipboard sea-time and time in the laboratory necessary for grab sample analysis, is considerably less than the resources required to produce similar maps using more traditional methods, such as the BGS grab survey (Fig. 10). Furthermore, the RoxAnn data can be collected while the vessel is occupied in other activities. In this instance, RoxAnn was deployed while *Clupea* was engaged in acoustic surveys of pelagic fish and visual count transect surveys of seabirds and marine mammals.

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