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The distribution and habitat preference of coastally occurring minke whales (*Balaenoptera acutorostrata*) in the outer southern Moray Firth, northeast Scotland

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Abstract The coastal waters of the Moray Firth in northeast Scotland (57º41'N 2º40'W) provide rich, inshore feeding grounds for minke whales (*Balaenoptera acutorostrata*) during the summer and autumnal months. In order to better understand the habitat selection, movements and feeding ecology of the animals utilising this North Sea region, distribution data from the southern coastline of the outer Moray Firth were subsequently examined with respect to the marine physiography of the area, specifically the environmental variables water depth, slope, aspect and sediment-type. A total of 305 minke whale encounters – collected from dedicated boat surveys conducted between May and October 2001 to 2006 inclusive – were used in the construction of a Geographic Information System (GIS) for the 860 square-km study site. The subsequent analysis revealed a strong spatial preference by whales in this location for water depths between 20 and 50 metres (mean 46.9 m, SD=30.9), steep slopes (mean 75.7 degrees, SD=8.9), a northerly-facing aspect and sandy-gravel sediment type. Kruskal-Wallis tests for variance confirmed that the distribution of *B. acutorostrata* was significantly different across each of these physiographic features examined ($P<0.05$). In particular, water depth and sediment type were shown to be highly correlated with the frequency of whales observed (Spearman's Rank Correlation $P<0.05$ for depth and sediment respectively). From these results, we conclude that sea bottom characteristics may be used to predict the fine-scale distribution of minke whales on their feeding grounds; the physiographic features identified providing valuable proxies for inferring prey distributions in the absence of fisheries data. However, an appreciation of both abiotic and biotic factors (using a combination of GIS and remote sensing outputs) is clearly desirable for ecosystem-based management approaches for the coastal conservation of these whales. The application of GIS capacities to ecological studies based largely on field data of these marine mammals is highly recommended in the present study to cetologists, environmental modellers and conservation managers alike.

Keywords Minke whale · Habitat · Physiography · Environmental factors · GIS · Moray Firth · Conservation

Introduction

The minke whale (*Balaenoptera acutorostrata* Lacépède) is the smallest and most abundant of the baleen whales in European waters. In northwest Europe, it occurs widely along the Atlantic seaboard from Norway to France and throughout the North Sea, although less commonly in the southern North Sea and eastern Channel (Hammond et al. 2006). In UK waters, the species is typically sighted in inshore, shelf and coastal regions less than 200 metres deep (Northridge et al. 1995; Weir et al. 2001; Macleod et al. 2004; Wall et al. 2006), but shows seasonal shifts in latitudinal abundance throughout its range (Stewart and Leatherwood 1985). This is particularly true in the northern North Sea where the whales are usually only seen from April to October (Northridge et al. 1995; MacLeod et al. 2007; Weir et al. 2007), although animals may be found in

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small numbers year-round in some locations (Macleod et al. 2004).

In the outer Moray Firth in northeast Scotland (57º41’N 2º40’W) (Fig. 1), minke whales are commonly recorded between the months of June and October (Robinson et al. 2007a). The heterogeneous inshore waters in this location are thought to provide rich coastal feeding areas for these animals during the summer period at least (Robinson and Tetley 2007; Robinson et al. 2007b). The species subsequently occurs here in considerable numbers at this time (Robinson et al. 2007a; Tetley et al. 2008), whilst sightings in adjacent regional waters are evidently less numerous by comparison (e.g. Mudge et al. 1984; Weir et al. 2007; MacLeod et al. 2007; Canning 2007). Whether the whales utilising the outer Moray Firth represent a significant portion of a larger endemic minke population or not remains to be seen. However, preliminary comparisons of “marked” animals from northeast Scotland with photo-identification records from the Inner Hebrides on the west coast have revealed several possible recaptures of known individuals (KP Robinson unpublished data), suggesting a wider distribution for these whales than the northern North Sea alone. Indeed, Stevick (2007) proposed that the two study populations were most likely connected, with animals relocating between east and west coasts respectively in response to annual shifts in the distribution of target prey, and minke sightings in the outer Moray Firth are certainly seen to be higher during warmer-water front periods when phytoplankton biomass is greatest (Tetley et al. 2008).

Concentrations of baleen whales on their feeding grounds will ultimately depend upon the distribution and abundance of available prey items (Stevick et al. 2002; Zerbini et al. 2006), and in the case of benthic and pelagic fish species targeted by minkes, the physiography of the marine environment is thought to be particularly important in either limiting or concentrating their distribution accordingly (Macleod et al. 2004). Certainly factors such as water depth, sea bottom sediment and even the extent of sea ice have all been shown to influence minke distributions across a range of different habitats (e.g. Kasamatsu et al. 2000a; Naud et al. 2003; Macleod et al. 2004; Cecchetti 2006), but the interplay between these different factors evidently varies from one geographic region to the next (Tetley April 2007). Consequently fluctuations in both fine and large-scale physiography are believed to be significant for the distribution of minke whales within the Moray Firth, and thus a greater understanding of their habitat preferences in this region is considered to be important not only for the improvement of abundance estimates and interpretations of population trends here, but also for the establishment of protected areas for the long-term coastal management of the species in these waters.

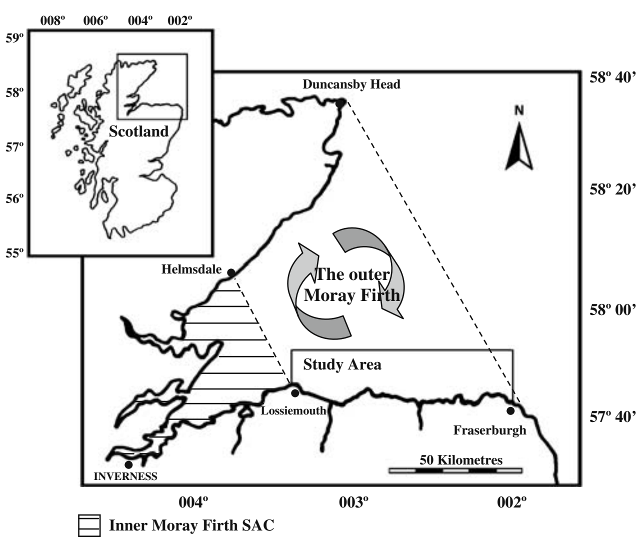

Fig. 1 Map of the Moray Firth showing the position of the 880 km^2 study area along the southern coastline of the outer firth between Lossiemouth and Fraserburgh. The arrows indicate the direction of the Dooley current flow

Within the Moray Firth, the physiography of the ocean floor is seen to be variable and irregular throughout (Eleftheriou et al. 2004). In the “inner” firth, for example, the seabed slopes gently from the shore to a depth of around 50 metres 15 km from the coast, whilst the shoreline of the “outer” firth descends more abruptly to 100+ metres within 8 km (Harding-Hill 1993; Wright et al. 1998). The deepest area of the firth is the Southern Trench, an enclosed basin approximately 220 metres in depth lying just 10 km from the southern shoreline between the coastal ports of Banff and Fraserburgh (Eleftheriou et al. 2004) (Fig. 1). Accordingly, the southern region of the outer Moray Firth encompasses the most topographically complex region of this North Sea coastal embayment, and this is believed to be significant with respect to the remarkable abundance and diversity of cetacean species found here (Robinson et al. 2007a; Robinson and Macleod 2008).

In the following paper, the fine-scale distribution of minke whales from the outer southern Moray Firth was subsequently examined with respect to the physiography of the area to provide a more thorough understanding of the habitat selection, movements and ecology of the animals frequenting this region. The primary objectives of this study aimed to: (i) identify the key habitat preferences shown by the minke whales frequenting this North Sea coastal habitat; and (ii) better define those “critical” areas targeted by the species that might require special attention for their coastal conservation and management. The present study forms part of a larger, on-going project investigating the spatio-temporal distribution of the key cetacean species utilising this North Sea coastal location.

Materials and methods

Data collection

Data used in the present study were collected during dedicated boat surveys carried out between May and October 2001 to 2006 inclusive. The surveys were conducted along an 80 km length of the outer southern Moray Firth coastline lying between the coastal ports of Lossiemouth and Fraserburgh. Four standardised boat routes were used, each positioned parallel to the shore, consisting of three outer routes (approximately 1.5 km apart in latitude) and an inner coastal route (Fig. 2) and covering a total survey area between them of approximately 860 km^2. The surveys were carried out using 5.4 m outboard boats at mean vessel speeds of 7 to 10 knots and during Beaufort Sea States ≤3 (Robinson et al. 2007a). A crew of 2 experienced and up to 4 additional trained observers searched the water using a continuous scanning method (after Mann 1999). To ensure animals were sighted before they reacted to the presence of the boat, binoculars were used from an eye height of approximately 3.5 metres above the water (using a 2 metre observation platform) to scan far from the vessel. The remaining crew searched closer to the boat with the naked eye.

The choice of survey route was primarily dictated by the daily weather / sea conditions in the study area. Boat tracks were usually determined each morning according to the direction and speed of the wind. As sea conditions were typically more inclement with increasing distance from shore, a higher number of surveys were inevitably carried out along the innermost survey routes. Thus, whenever conditions allowed, priority was typically given to the outermost survey routes.

Environmental parameters were monitored throughout the survey trips, and if the sea state increased above Beaufort 3 or the visibility decreased below 1.5 km the observer effort was either suspended or aborted respectively. Cues used to locate the whales during surveys included the presence of feeding birds in addition to direct observations of the animals themselves when surfacing (Fig. 3a-c). Once a sighting was confirmed, the time, GPS position of the animal (corrected for distance) and the water depth were recorded. When two or more animals were sighted in close proximity (<50 metres apart), a single GPS position was typically taken as the closest point to the whales where first sighted and the total number of individuals noted. Whenever possible, opportunistic photographs of the whales were taken for use in ongoing mark capture-recapture studies. These images subsequently provided useful controls ensuring duplicate sightings of the same animals did not occur during boat trips, particularly when multiple survey routes were covered in any one day by one or more survey vessels. Positions of the whales and counts were also cross-checked at the end of each day to avoid double sightings/recounts.

Environmental data

A Geographic Information System (GIS) of the study area was constructed using ArcView 3.3 (Environmental Systems Research Institute, USA). A rectangular grid (11×80 cells) was prepared with cells measuring 1 km^2 using a Mercator projection and the designated cells were assigned

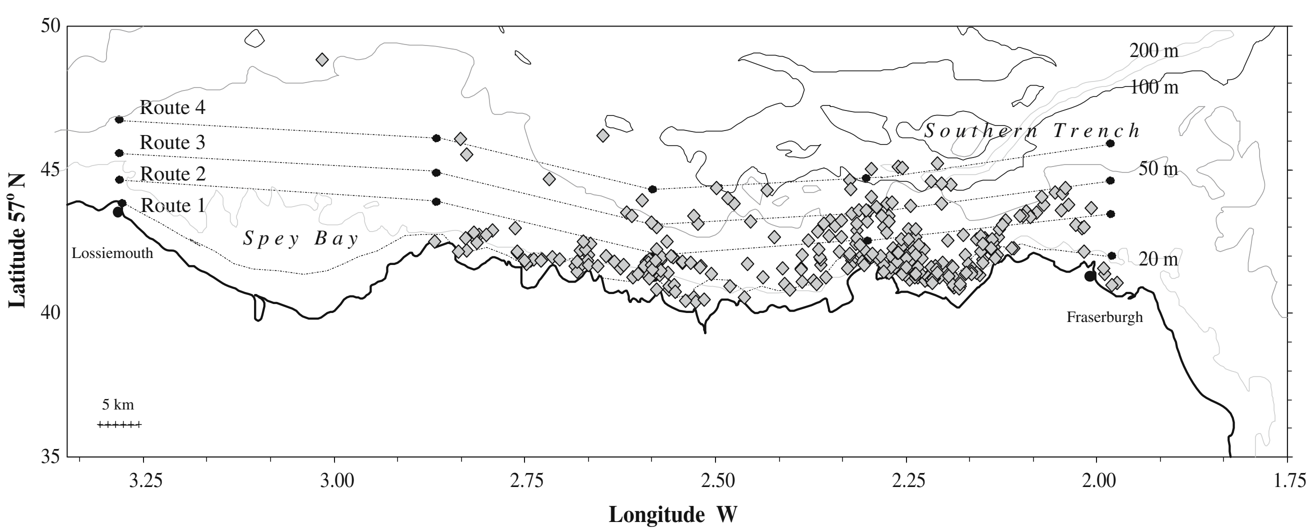

Fig. 2 Showing the spatial distribution of minke whale encounters in the southern outer Moray Firth between May and October 2001 to 2006 inclusive (n=305). The survey routes, comprising three outer transects (routes 2 to 4 respectively) plus an inner coastal transect (route 1), are also depicted here for reference

Fig. 3 Cues used to locate minke whales during surveys included the presence of feeding birds at the water's surface (**a**), in addition to direct observations of the animals when surfacing (**b**) and/or feeding (**c**)

a value for each of the physiographic characteristics: water depth, slope, aspect and sediment type respectively. The values for water depth were obtained from Admiralty charts of the Moray Firth using a digitising tablet and were re-interpolated so as to provide a continuous raster of the survey area (No. of neighbours = 12, Power = 2) (after Tetley 2004). Slope (as a percentage rise) and aspect were subsequently derived from the depth data using the Spatial Analyst tool in ArcView 3.3. For the sediment class, a digital map of the survey area was obtained from the British Geological Survey, and this was similarly interpolated to fit the grid extent and interpolated 1 km^2 depth raster as before (Tetley 2004).

Data values for the whale encounters were extracted using the XYZ Point Theme function within ArcView Grid Analyst version 1.1. As the main aim of this study was to relate the spatial distribution of whales to the physiography of the marine environment, the encounter data for all months and years were subsequently pooled, and therefore any seasonal / annual variations in occurrence or habitat utilisation were not considered in the following analysis. With respect to the frequency of occurrence of *B. acutorostrata* in relation to each of the physiographic classes examined, the variance between classes was examined using a Kruskal-Wallis non-parametric test for variance. Spearman's Rank Correlation coefficients were further used to test these relationships.

Results

Between 2001 and 2006, a total distance of 12,571.6 km was covered during boat surveys on 314 survey days, resulting in 305 encounters with 323 whales (Table 1). The whales were encountered throughout the survey area but were more generally distributed towards the central and eastern areas of the study site, with a notable absence of encounters to the western region both within and adjacent to Spey Bay (Fig. 2). A greater number of encounters were recorded on the innermost survey route 1, but once corrections for survey effort had been made, a considerably higher abundance of animals was resolved for each of the outer survey routes 2 to 4 respectively (Table 2). Throughout the study period, however, considerable variation in the frequency of encounters was observed from one year to the

Table 1 Showing the annual survey effort and total number of minke whale encounters recorded between May and October 2001 to 2006 during dedicated surveys in the outer Moray Firth

Year	No. survey days	Survey effort in km	Total no. encounters	No. of whales km
2001	45	1514.20	16 (16)	0.011
2002	67	2518.55	40 (52)	0.021
2003	60	1946.00	53 (53)	0.027
2004	35	1886.80	0	0
2005	43	1797.55	78 (79)	0.044
2006	64	2908.50	118 (123)	0.042
Total	314	12571.6	305 (323)	0.026

The total number of animals is given in parentheses to the right of the encounter numbers, and the number of minkes per km was derived from these latter values.

Table 2 Showing the total number of minke whales recorded between 2001 and 2006 on each of the survey routes covered with respect to the cumulative survey effort (in km) per route

Survey route	Route 1	Route 2	Route 3	Route 4
Total no. of whales encountered	99	103	90	31
Survey effort in km	7378.20	2511.05	1893.40	788.95
Derived no. of minkes per km	0.013	0.041	0.048	0.039

next (Table 1). In 2004, for example, no sightings were made in the study area, whereas peak numbers of encounters and abundances of whales were recorded during 2005 and 2006.

Whilst minkes were encountered during all survey months, May to October inclusive (Fig. 4), the animals were more typically seen from mid June onwards and with a peak in annual occurrence from July to August. The distribution of whales showed a progressive inshore movement of animals across the summer and autumnal months, with the species being solely recorded in deeper waters (on routes 3 and 4) when first seen each year, followed by increasing numbers of sightings in shallower inshore waters (on routes 1 and 2) and then a progressive return to offshore waters again towards the end of the study period at which time whales were evidently less abundant. Whilst the timing of this inshore-offshore movement was clearly variable from one year to the next, this general trend can be seen in the pooled annual sightings results (after corrections for survey effort) in Fig. 5.

GIS

The GIS resolutions for the environmental variables depth, slope, aspect and sediment type are presented in Fig. 6. Figure 6a shows a general land to offshore increase in water depth as expected, however the depth to the western region of the study area (within and adjacent to Spey Bay) is considerably shallower than to the east where depths descend to over 100 metres within 5 to 8 km from the shore. Slope gradients are also seen to be pronounced throughout much of the study area, with the exception only of Spey Bay to the west (Fig. 6b). Being the southern coastline, the inshore slopes predominantly face north, although further offshore along the Southern Trench the aspect shows more variability (Fig. 6c). Finally, the sediment type within the study area varies from sand or gravel type classes within Spey Bay, to sandy-gravel composites within most of the remaining inner shelf waters, to sandy and muddy composites with further distance from the shore and in proximity to the Southern Trench (Fig. 6d).

The subsequent data analyses for depth, slope, aspect and sediment type revealed a non-uniform distribution of minke whales with respect to each of these physiographic variables. However, an apparent preference was shown by the whales for habitats with water depths between 20 and 50 metres (mean depth 46.9, SD=30.9), a steep slope (mean 75.7 degrees, SD=8.9), northerly facing aspect and sandy-gravel sediment type (Fig. 6, a–d). Kruskal-Wallis tests for variance confirmed that the spatial distribution of animals was significantly different across each of these parameters (Table 3). However, only water depth and sediment type were correlated with the occurrence of minkes in the present study area (Spearman's Rank

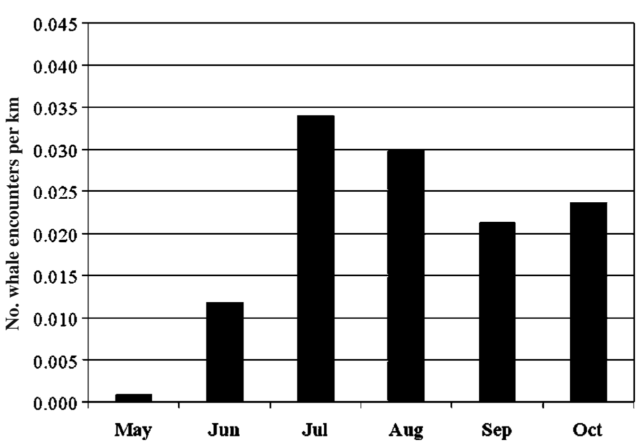

Fig. 4 Graph showing the abundance of minke whales per km of survey effort in the study area between the months of May and October

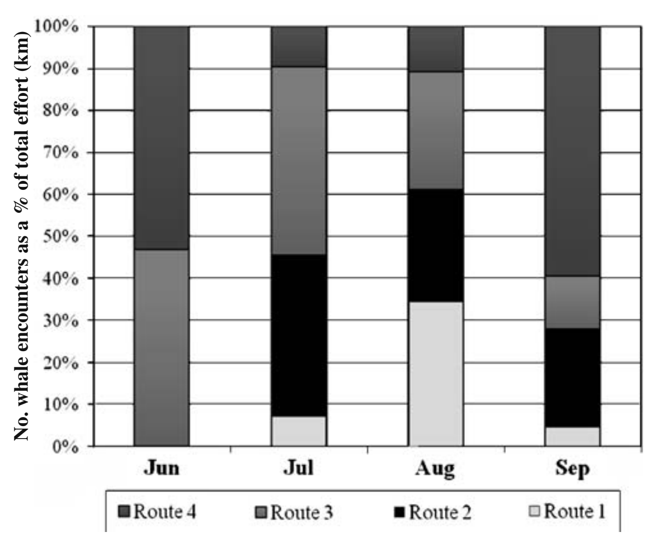

Fig. 5 Stack histogram illustrating the temporal inshore-offshore movements of minke whales in the outer southern Moray Firth between the months of June and September

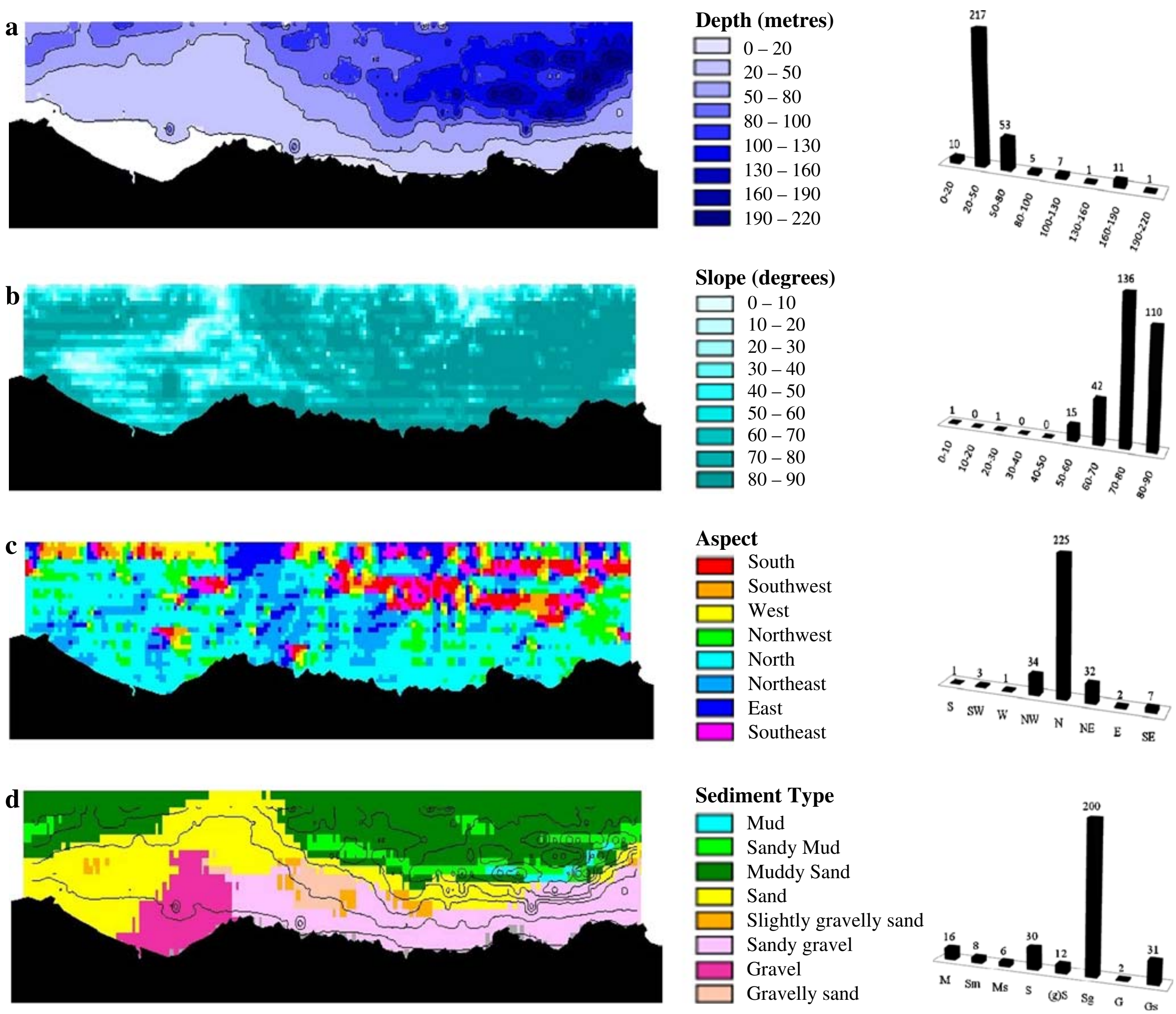

Fig. 6 ArcView maps of the southern outer Moray Firth region showing (**a**) depth (**b**) slope (**c**) aspect and (**d**) sediment type within the study area. The whale encounter frequencies are shown for each of the respective variables in the histogram plots to the right

Correlation for depth R^2=2.04, P<0.05 and sediment class R^2=2.23, P<0.05), with whale numbers showing a significant increase with respect to decreasing depth and sediment grain sizes.

Discussion

In the present investigation, minke whales were encountered throughout the summer months – the main feeding period for rorqual whales in this region (Camphuysen and Winter 1995; Robinson et al. 2007b) – but were seen to be highly variable and non-uniform in their spatial and temporal distribution. Consequently, monthly encounter rates were largely inconsistent from one year to the next, with annual encounter frequencies ranging from 0 to 123 whales across the 6-year study period, although such variability is evidently commonplace in studies of baleen whales on their feeding grounds (e.g. Whitehead and Carscadden 1985; Payne et al. 1990; Friedlaender et al.

Table 3 Results of Kruskal-Wallis tests (test statistic, degrees of freedom and probability values) used to determine differences in the distribution of whales respective to each of the variables depth, slope, aspect and sediment type examined

Variable	H	df	*P*
Depth	71.0	70	0.049
Slope	305.0	37	<0.001*
Aspect	302.5	89	<0.001*
Sediment type	217.9	17	<0.001*

*results significant when P<0.05

2006) and especially where research effort is geographically restricted (e.g. Tscherter and Morris 2007) as in the present study. From the GIS analyses, however, over 70% of the whales recorded in the Moray Firth study area occurred in steeply sloped areas at depths of between 20 and 50 metres. Such topographic relief is known to promote up-wellings in nutrient-rich currents, which would be expected to heighten local productivity and, in turn, provide enhanced feeding opportunities for these and other marine predators and their prey (Franks 1992; Yen et al. 2004). Indeed, Lynas and Sylvestre (1988) proposed that minke whales in the St Lawrence Estuary, Canada utilised currents modulated by the sea bottom topography whilst feeding, and this has subsequently been demonstrated for other rorqual whale species to date, including the fin whale (*Balaenoptera physalus*) (Woodley and Gaskin 1996; Panigada et al. 2005) and the blue whale (*Balaenoptera musculus*) (Schoenherr 1991; Kasamatsu et al. 2000b). In the Moray Firth study area, our field observations of feeding minkes certainly support this behaviour too (Robinson and Tetley 2007), although factors other than topography alone appear to be significant in the spatial distribution of the whales observed here.

The sediment type, for example, also showed a very strong correlation with the distribution of whales in the present study (Spearman's Rank Correlation $P<0.05$). Sea bottom sediments evidently provide integral habitats for a number of benthic and nectobenthic fish species targeted by minkes in Scottish waters, and are therefore thought to be important in habitat prediction (Macleod et al. 2004). In the North Sea, for example, lesser sandeels (genus *Ammodytes*) – constituting 62 to 87% by weight of the diet here (Olsen and Holst 2001; Pierce et al. 2004) – require sediments of coarse sand and fine gravel for burrowing and protection (Macer 1966), whereas pelagic herring (*Clupea harengus*) select gravel beds within 50 km of the coast for spawning (Saville and Bailey 1980; Blaxter 1990). The arrival of whales in the study area each year appears to be synchronised with the emergence of sandeels into the water column to feed (FRS 2004), and in the GIS results over 66% of the whale encounters showed a clear spatial preference for sandy-gravel sediments, i.e. optimal sandeel habitat.

In agreement with the visual observations by Robinson and Tetley (2007), these results suggest that sandeels are highly targeted by minke whales in the Moray Firth. That said, offshore populations of pelagic herring and sprat (*Sprattus sprattus*) may also be equally or sometimes even more accessible to foraging whales at certain periods across the summer or from one year to the next, and this would certainly explain the seasonal inshore-offshore movements and inter-annual variability of animals observed in the present results. Ultimately, a threshold response by the whales to the seasonal occurrence of available fish prey would be hard to prove in this case, since quantitative fisheries data is clearly absent for these "non-commercial" prey species in this North Sea region (ICES 2006; Maravelias 1997). However, the skewed spatial distribution of whale sightings towards the southern central and eastern parts of the study area could reasonably be accounted for by the underlying sediment type here, thereby corroborating the importance of sandeels in the diet of these icthyophagous predators in the coastal Moray Firth.

In area-based coastal conservation, site selection is typically based upon unchanging physical features of the marine environment (Cañadas et al. 2002). Yet the non-random distributions of predators and their prey are invariably determined by physiographic and oceanographic variables within the marine environment (Cañadas et al. 2002; MacLeod et al. 2004; Yen et al. 2004; Panigada et al. 2008). Thus, whilst the physical factors identified in this study may be fundamental parameters for managers attempting to define the coastal occurrence of *B. acutorostrata* in potential areas of importance, a broader appreciation of the oceanography in this region (e.g. Tetley et al. 2008) is clearly desirable to any ecosystem-based management approach for the long-term coastal conservation of this species. Furthermore, prospective managers will need to consider the increasing number of anthropogenic threats affecting these animals in UK coastal waters at this time. In the Moray Firth, for example, detrimental impacts may include direct / indirect interactions with fisheries, boat strikes, exposure to anthropogenic noise, ingestion of contaminants and debris, and inevitably the loss or degradation of critical habitat (Gill et al. 2000; Gubbay and Earll 2000; Nautilus 2001; Edwards et al. 2002; MFP MFP 2003; Williams et al. 2006; Parsons et al. 2007; Robinson et al. 2007a; Stone and Tasker 2007; Dolman et al. 2008).

Since oceanographic variables are fluid features that quickly change over time (even from day to day), while physiographic features remain constant and unchanging, from a practical point of view the present results provide the first "fixed" reference on which to base currently sought-after conservation measures for the protection of *B. acutorostrata* along the northeast Scottish coastline. In agreement with previous studies by Naud et al. (2003) and Macleod et al. (2004), the present findings suggest that both sea floor topography and geomorphology may be used as underlying predictors for the fine-scale distribution of the species within the heterogeneous Moray Firth. Moreover, features such as the topographic relief, sediment type, time of year and even distance from shore, as identified herein, may provide previously unconsidered proxies for inferring the distributions of prey in the absence of regional fisheries data (as discussed by Torres et al. 2008).

Comparable studies over a larger geographic range might further be interesting as a measure of the stability of the parameters identified in this study. Certainly, ongoing studies will continue to provide a better understanding of the ecology of this small, coastally-occurring baleen whale in our inshore North Sea waters. Additional work aims to consider the behaviour of these animals – i.e. feeding/foraging versus travelling/resting behaviours – with respect to the physiography and oceanography of the study site. Since as many as 60% of the minkes encountered in the study area are seen to be juvenile animals (determined from their smaller body size and lighter colouration), an additional consideration might also be measurable with respect to the age class of the animals recorded.

With increasing demands for greater focus on our oceans and coastal zones in recent years from different scientific and management communities (discussed by Halpern et al. 2008), GIS techniques provide a range of cost-effective approaches for monitoring the marine environment and collecting environmental data that can be applied across a range of spatial and temporal scales. The application of these techniques in the design and development of ecological studies based largely on field data is subsequently highly supported in the present study, and the integration of both GIS (present study) and remote sensing capacities (e.g. Tetley et al. 2008) is thereby wholly recommended in this respect to cetologists, environmental modellers and conservation managers alike.

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