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Distribution patterns of deep-sea fish and benthic invertebrates from trawlable grounds of the Hatton Bank, north-east Atlantic: effects of deep-sea bottom trawling

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Distributions of deep-sea fish, benthic invertebrates and the effects of deep-sea bottom trawling were studied based on data collected in 2005 from a joint collaboration survey undertaken between the Spanish Institute of Oceanography and a deep-sea trawler on the Hatton Bank (north-east Atlantic). A total of 163 valid bottom trawl hauls (600–1600 m) were analysed. The main trawlable grounds were located on the sedimentary seabed of the western flank of the bank (Hatton Drift). Grenadiers and smoothheads were predominant in the trawl catches (67% and 11.8% by weight respectively). Both species were abundant along the western flank. Deep-water sharks accounted for 7.4% of weight, and were abundant along the south-eastern slopes. Chimerids, lotids, morids and other deep-sea species were also taken as by-catch. Grenadiers and deep-water sharks dominated the discards. By-catches of cold-water corals were generally associated with the rocky outcrop and were more abundant at the top of the bank. Abundant by-catches of large sponges, characteristic of sponge-dominated biotopes, were taken from the eastern flank.

Keywords: benthic impact, by-catch, bottom trawl, cold-water corals, deep-sea, grenadiers, Hatton Bank, smoothheads, sponges

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INTRODUCTION

Bottom trawl fisheries on the Hatton Bank and their impacts

A multispecies deep-sea bottom trawl fishery has been developed in the Hatton Bank (north-east Atlantic) since the late 1990s, to target roundnose grenadier (*Coryphaenoides rupestris* Gunnerus, 1765) and Baird's smoothhead (*Alepocephalus bairdii* Goode & Bean, 1879). Deep-water sharks (Carchariniformes and Squaliformes), blue ling (*Molva dypterygia* Pennant, 1784), chimerids (Chimaeriformes), black scabbardfish (*Aphanopus carbo* Lowe, 1839) and Greenland halibut (*Reinhardtius hippoglossoides* Walbaum, 1792) are taken as by-catch. The main fishing grounds are located at depths of between 800 and 1600 m on the western flank of the bank (Bensch *et al.*, 2009).

Grenadiers (Macrouridae) are regarded as a long-living, low fecundity and slow-maturing benthopelagic species, and are therefore considered vulnerable to exploitation (Gordon, 2001; Lorance *et al.*, 2008; Shibanov & Vinninchenko, 2008). There is less information available on the life history of smoothheads (Alepocephalidae) but they are also regarded as low-fecundity and slow-maturing species (Allain, 1999, 2001). Deep-water sharks such as *Centroselachus crepidater* (Barbosa du Bocage & de Brito Capello, 1864), captured as by-catch in trawl fisheries, have been considered to be 'of the least concern' (Stevens, 2003) by the International Union for Conservation of Nature (IUCN). However, *Centroscymnus coelolepis* (Barbosa du Bocage & de Brito Capello, 1864) is included under the 'near threatened' category (Stevens & Correia, 2003) and in the list of threatened and/or declining species and habitats of the OSPAR Convention for the protection of the north-east Atlantic marine environment (OSPAR, 2008). The chimerid species *Hydrolagus mirabilis* (Collett, 1904) is also considered as 'near threatened' (Dagit *et al.*, 2007) by the IUCN. Blue ling is a gadoid species which is particularly vulnerable to fishing because spawning aggregations can be targeted (ICES, 2008). In 2003, the European Union (EU) introduced total allowable catches (TACs) for main deep-water species and other regulations for Community vessels fishing in the north-east Atlantic. A ban of fisheries directed towards deep-water sharks has furthermore been implemented (EC, 2010). However, catches of a number of species such as smoothheads still remain unregulated.

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Bottom trawling can be one of the reasons for the decline of cold-water corals and other habitat forming taxa (Gage *et al.*, 2005), which are considered by the FAO (2009) as indicators of vulnerable marine ecosystems (VMEs). Coral reefs and gardens, sea pen fields and sponge aggregations are considered as a 'threatened and/or declining' category by the OSPAR Convention (2008). Distributions of VMEs on the Hatton Bank have been mapped in recent years and extensive seabed areas of the bank (~16,000 km^2) have been closed to bottom fishing since 2007, in order to prevent negative impacts on VMEs, particularly cold-water corals (Durán Muñoz & Sayago-Gil, 2011; Durán Muñoz *et al.*, 2012).

The objective of this survey was to study distributions of deep-sea fish and benthic invertebrates on the trawlable grounds of the Hatton Bank and furthermore to describe any effects of deep-sea bottom trawling in relation to conservation measures (areas closed to fishing). Multispecies deep-sea fisheries are often associated with by-catches and discards because trawling is a low-selective fishing method. Bottom trawling can likewise also produce impacts on VME indicator species. Collaborative research with trawl fishermen was therefore carried out as a cost-effective way of gaining valuable insight into the deep-sea trawling techniques. This survey provided an opportunity to target grenadiers and deep-sea species along smooth terrain and muddy–sandy substrate, as well as to study trawl by-catches and discards.

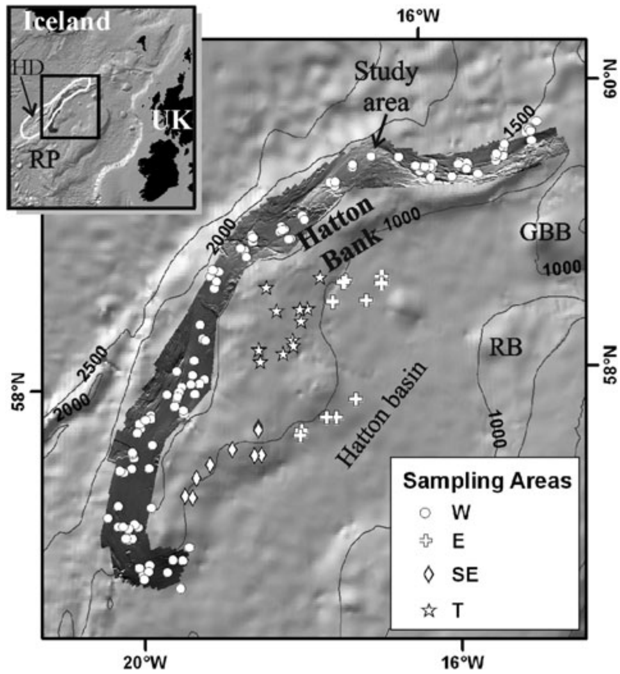

Fig. 1. Map of the study area showing the start position of the trawl hauls using different symbols depending on the sampling areas (W, western slope; SE, south-eastern slope; E, eastern slope; T, top of the bank). Multibeam bathymetry obtained by the Spanish Institute of Oceanography on the western slope of Hatton Bank is also presented (RP, Rockall Plateau; HD, Hatton Drift; GBB, George Bligh Bank; RB, Rockall Bank).

MATERIALS AND METHODS

Study area

The Hatton Bank study area (Figure 1) lies within the North-East Atlantic Fisheries Commission (NEAFC) Regulatory Area, on the high seas of the north-east Atlantic, at depths greater than 600 m. Hatton Bank is one of the three banks (together with the George Bligh and Rockall Banks) which form the Rockall Plateau. The Hatton Bank structure has been described as a bedrock surface composed of flood basalts (Smith *et al.*, 2005). Its western slope is dominated by a contourite drift (sedimentary deposit created by the action of bottom currents and mainly composed of sand and mud) named Hatton Drift (HD) (Ruddiman, 1972). HD overlies the bedrock surface which outcrops at the top of the bank. The study area was divided into four 'sampling areas' according to their location on the bank and based on existing knowledge of the trawl fishery and seabed information (Durán Muñoz *et al.*, 2009): (i) west (W) sampling area (average depth ± SD = 1358.7 ± 137 m), which corresponds to the area where the main trawl fishing grounds for deep-sea species are located (Bensch *et al.*, 2009). This zone is situated along the western slope of the bank, on the HD, where bathymetric and sediment data are available from Spanish multidisciplinary surveys; (ii) east (E) sampling area (average depth ± SD = 1138.0 ± 60 m), which is a medium-depth part located on the eastern slope of the bank, and poorly used by trawlers; (iii) south-east (SE) sampling area (average depth ± SD = 865.9 ± 111 m) located on the upper part of the eastern flank of the bank, and is a fishing ground for blue ling (Large *et al.*, 2010); and (iv) top (T) sampling area (average depth ± SD = 773.1 ± 84 m), located at the top of the Hatton Bank, where trawl fishing effort was historically low.

Survey methodology and data analysis

The experimental survey was developed by the Spanish Institute of Oceanography (IEO) in collaboration with trawl fishermen. The study was undertaken during the second half of 2005, on-board a deep-sea Spanish freezer trawler (1393 gross tonnage capacity; 1420 kw engine power and 61 m length). The objective of the sampling scheme was to study the main trawlable grounds on the Hatton Bank (Figure 1). Trawlable grounds were identified by using: (i) a commercial echo sounder (Simrad ES-500); (ii) any previously available fishery footprint information; and (iii) the skipper's knowledge. A total of 163 valid trawls were analysed. Trawls were carried out using deep-sea bottom trawl gears (Table 1). Two experienced scientific observers travelled on-board the vessel. At each station, they recorded information on: (i) gear characteristics; (ii) location, time and depth at start and end of trawl; (iii) live weight landings and discards; and (iv) by-catch of benthic invertebrates and seabirds. Fish

Table 1. Technical characteristics of the bottom trawl gears used during the survey.

Mean of tow speed (kn) ± SD	2.9 ± 0.2
Mean of tow time (hr) ± SD	5.4 ± 1.6
Headrope (m)	52.4
Footrope (m)	70.4
Ground gears	Rubber discs and bobbins
Codend (mm)	100
Liner (mm)	~50
Warps (m)	230
Trawl doors (kg)	2000

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were identified at the lowest possible taxonomic level using available literature. The invertebrates collected were recorded and samples were photographed and taken as 'voucher' specimens for subsequent final identification in the laboratory. These were preserved in 70% ethanol. Length frequencies (pre-anal length in the case of grenadiers; total length in the case of sharks) of fish species were obtained by taking random samples. Landings were estimated by multiplying processed catches with their corresponding conversion coefficients (Cc) (Cc = weight prior to processing/processed weight). Discards were estimated by weighing samples and extrapolating them. Total catch was calculated as the sum of landings plus discards. Discard rates in weight were estimated as a percentage of total catch (discards in kg × 100/total catch in kg). Catch per unit effort (CPUE) was calculated as a relative index of abundance (CPUE = total catch in kg/trawl time in hours). The CPUE dataset was integrated within a GIS and maps were projected in the UTM coordinate system (Zone-27N). Symbols on such maps were marked at the start position of each trawl for better clarification of images (this needs to be taken into account when analysing the actual geographical location of VMEs, since trawls can cover very long distances). Regional bathymetric contours were obtained from the General Bathymetric Chart of the Oceans (GEBCO) database. Species presence was obtained as a percentage of total trawls (number of trawls where the species was encountered × 100/total number of hauls). Average depth of each haul was considered as the arithmetic mean depth at their start and end positions. The Spanish multidisciplinary surveys carried out between 2005 and 2007 on the western slope of Hatton Bank provided the geophysical data used in this study (Durán Muñoz *et al.*, 2009).

RESULTS

Distribution of trawlable grounds

The main trawlable grounds were located on the western slope of Hatton Bank (W sampling area) and corresponded to the seabed of the HD (Figure 1). This contourite deposit (HD) follows the slope trend where average gradients vary between 0 and 3° (Sayago-Gil *et al.*, 2010). Box corer data show that the present day seabed sediments are mainly muddy sands (Durán Muñoz *et al.*, 2009). The outcrop area is described as a non-depositional area at the top of the bank (T sampling area) or the slope area that lies adjacent to the top. It is characterized by an uneven surface with ridges and escarpments (gradients of up to 40°) that was produced as a result of tectonic activity and erosion. Such grounds are generally difficult or impossible to trawl on. In some places, a muddy–sandy deposit covers the outcrop (mainly bedrock), which enables possible use of trawls. The eastern slopes of the bank (E and SE sampling areas) are composed of a contourite deposit (mainly sand and mud) located in the westernmost part of the Hatton Basin. Both trawlable and non-trawlable grounds are located along the eastern slopes.

Catch composition and discards

An estimated total catch of 737,255 kg was recorded. In terms of weight, catch composition was dominated by teleosts (Table 2) and grenadiers were observed to be the dominant taxa (Figure 2). This was mainly due to the predominance of *Coryphaenoides rupestris* (64%) and *Trachyrincus murrayi* (Günther, 1887) (2.4%). Other macrourids including Roughead grenadier (*Macrourus berglax* (Lacépède, 1801) were less represented (<1%). Smoothheads—mainly *Alepocephalus bairdii*—were the next most important component of the catches. Catches of deep-water sharks were dominated by two less marketable species: *Centroselachus crepidater* (3.3%) and *Centroscyllium fabricii* (Reinhardt, 1825) (1.8%). The commercial species *Centroscymnus coelolepis* was poor in the catches at only 0.7%. *Molva dypterygia* was the dominant lotid (Lotidae). Chimerids (Chimaeriformes), morids (Moridae) such as *Lepidion eques* (Günther, 1887), *Aphanopus carbo* (Trichiuridae) and *Reinhardtius hippoglossoides* (Pleuronectidae) were others that were taken as by-catch. Appendix 1 shows a list of the identified deep-sea fish. Echinoderms (Echinodermata) and sponges (Porifera) were the clearly dominant invertebrates in terms of weight. This was due to large by-catches being concentrated in a few trawls. One seabird (*Fulmarus glacialis* Linneaus, 1761) was captured during hauling operations. It was later freed and survived. No marine mammals were taken as by-catch.

Discards were generally dominated by grenadiers and deep-water sharks (Figure 3). They represented 38% of the total catch in terms of weight (Table 2) and were composed of non-commercial/less marketable species and small or damaged individuals of commercial species. Morids and most catches by weight of elasmobranchs and chimerids were discarded. Discards of *Molva dypterygia* were negligible. There were no discards of *Reinhardtius hippoglossoides* or *Centroscymnus coelolepis*. Most catches of *Coryphaenoides rupestris*, *Alepocephalus bairdii* and *Aphanopus carbo* were landed. The estimated discard rates for these species were 28%, 18% and 4% by weight respectively. All invertebrates were discarded.

Distribution patterns of deep-sea fish on trawlable grounds

Table 2 presents CPUE values for main deep-sea fish taxa in each sampling area. Figure 4 shows the values by depth strata. Grenadiers and smoothheads were widely distributed: *Coryphaenoides rupestris* and *Trachyrincus murrayi* were found in 99% and 86% of the trawls respectively, while *Alepocephalus bairdii* was found in 94% of the trawls. Both species were quite abundant along the western slope of the Hatton Bank (Figure 5). The abundance of grenadiers increased with depth and apparently with latitude. *Centroselachus crepidater* and *Centroscyllium fabricii* were widespread in the study area (73% and 82% of presence respectively). The former was more abundant along the south-eastern slope while the latter was mainly caught on the western and eastern slopes, preferably at a mid-depth range. The commercial species *Centroscymnus coelolepis* (27% of presence) was more abundant along the western slope, and also at mid-depths. Skates (Rajiidae) were clearly less abundant than sharks. *Hydrolagus mirabilis* were present in 50% of the trawls. In general, the highest abundances of chimerids were obtained on shallow grounds such as at the top of the bank. The highest abundances of *Lepidion eques* (56% presence) and *Molva dypterygia* (74% presence) were found

Table 2. Catch per unit effort (kg/hr) obtained on the Hatton Bank with bottom trawls, by taxa and sampling areas (W, western slope; SE, south-eastern slope; E, eastern slope; T, top of the bank). The percentage contribution to the total catch (TC), the retained (R) and discarded fractions (D) expressed as percentages of the total catch, and the percentage of presence in the trawls (P) are shown for each taxa. Values <0.1 are represented as +. Taxa are listed by weight.

		CPUEs (kg/hr)							
		W	SE	E	T	TC	R	D	P
Teleosts	Grenadiers	648.5	74.5	206.9	18.2	67.0	69	31	99
	Smoothheads	105.3	93.7	84.2	19.0	11.8	79	21	96
	Lotids	23.2	41.4	31.0	16.3	2.9	100		80
	Morids	8.1	101.4	37.2	29.7	1.8		100	88
	Black scabbardfish	11.2	18.9	30.2	4.4	1.5	96	4	53
	Greenland halibut	5.9				0.6	100		34
	Others	10.2	5.4	3.6	23.1	1.2	10	90	93
Elasmobranchs	Deep-water sharks	56.9	111.7	91.1	75.8	7.4	10	90	97
	Skates	1.6	1.7	2.0	0.1	0.2		100	43
Holocephals	Chimerids	3.8	100.6	112.2	219.1	3.0	19	81	91
Total fish		**874.6**	**549.3**	**598.4**	**405.7**	**97.2**	**63**	**37**	**100**
Echinoderms	Sea urchins	0.6	2.5	7.5	169.0	1.1		100	86
	Sea stars	0.4	+	1.1	0.1	0.1		100	85
	Sea cucumbers	0.1	0.3	3.2	0.3	+		100	57
	Brittle and basket stars	+	+	+	+	+		100	6
Sponges		0.1		124.9	1.8	0.8		100	19
Molluscs	Cephalopods	1.9	7.4	4.1	10.6	0.3		100	94
	Others	+		+	+	+		100	4
Arthropods	Deep-sea crabs	2.0	1.0	0.1	0.4	0.2		100	86
	Others	+	0.1	0.1	0.2	+		100	86
Cnidarians	Actinians	0.5	0.8	2.0	5.8	0.1		100	83
	Zoanthideans(1)	0.4	0.1	0.4	0.3	+		100	82
	Jelly fishes	0.1	0.1	+	1.1	+		100	75
	Stony corals	+	+	0.3	1.0	+		100	11
	Sea pens	+	+	+	0.1	+		100	29
	Gorgonians	+	0.1	+	+	+		100	8
	Cup corals	+				+		100	22
	Black corals	+			+	+		100	2
	Others	+		+		+		100	1
Other invertebrates		+	+	0.1	+	+		100	25
Total invertebrates		**6.3**	**12.5**	**143.9**	**190.8**	**2.8**		**100**	**94**
Total							**62**	**38**	

(1), associated with *Parapagurus pilosimanus* Smith, 1879.

along the shallowest part of the south-eastern flank of the bank. *Reinhardtius hippoglossoides* (34% of presence) was abundant in the deepest part of the western slope, and was absent in other grounds. *Aphanopus carbo* was found in 53% of the trawls. It was mainly caught at intermediate depths, on the eastern flanks of the bank. All other species were pooled into a group called 'others', and were more abundant at the top of the bank. Most of them had no commercial value.

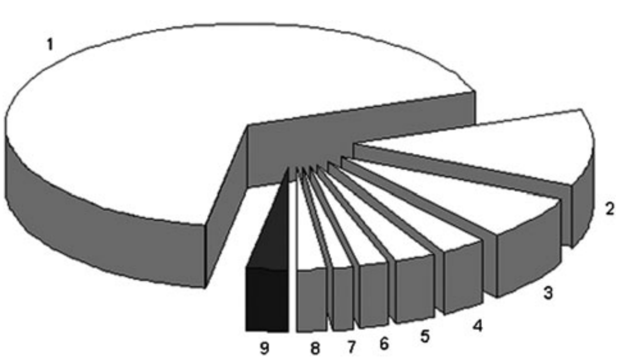

Fig. 2. Pie chart showing the percentage composition of estimated catches by weight (white sectors, fish; black sector, invertebrates). (1) Grenadiers (67%); (2) smoothheads (11.8%); (3) deep-water sharks (7.4%); (4) chimerids (3%); (5) lotids (2.9%); (6) morids (1.8%); (7) black scabbardfish (1.5%); (8) other fish including Greenland halibut (2%); (9) total invertebrates (2.8%).

Distribution patterns of benthic invertebrates on trawlable grounds

Table 2 presents CPUE values for main invertebrate taxa in each sampling area. The presence frequency of VMEs indicator species (FAO, 2009) is shown in Table 3. Distribution and abundance maps for each category of VME are shown in Figure 6, and some records of these species are shown in Figure 7. Echinoderms (Echinodermata) were quite common on trawlable grounds (91% presence) especially sea stars (Asteroidea) and sea urchins (Echinoidea). Large by-catches of *Spatangus raschi* (Lovén, 1869) mixed with species belonging to the family Echinoturidae (e.g. *Calveriosoma* sp.) were present in two trawls carried out at the top of the bank (>1000 kg per trawl). Cephalopods (Cephalopoda) were present in 94% of the trawls. They were abundant in the shallow parts of the south-eastern slope and at the top of the bank. Deep-sea crabs were

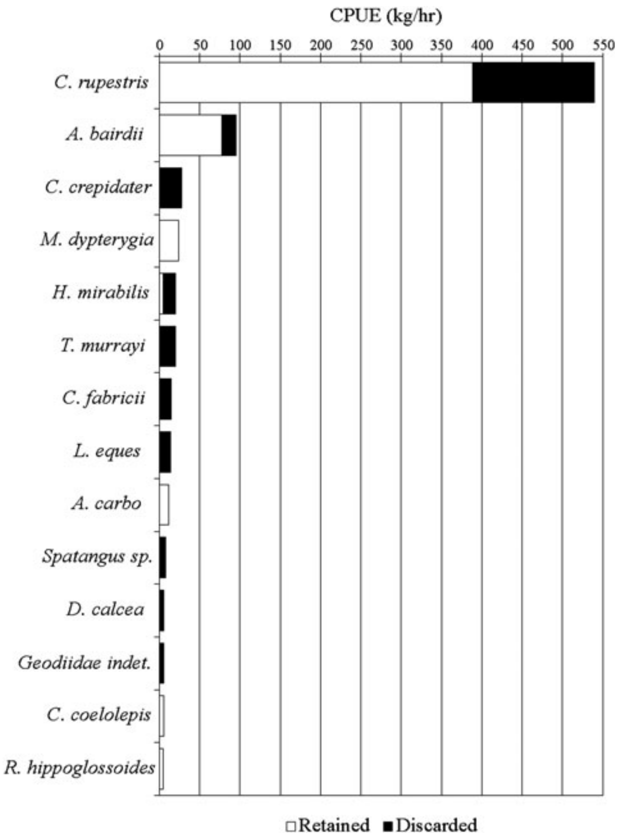

Fig. 3. Estimates of discarded (black) and retained (white) fractions for the main species in terms of weight (catch per unit of effort >5 kg/hr). Species are listed by catch per unit effort (kg/hr).

present in 86% of the trawls: Geryoniidae (71%) and Lithodidae (45%) were the most common families found, and showed highest abundances on the deep western slope of the bank. Actinians (Hormathiidae and Actinostolidae) and zoanthideans (*Epizoanthus paguriphilus* Verrill 1883) were found along the study area (83% and 82% respectively).

Sponges (Porifera) were present in 19% of the trawls and were more abundant on the eastern slope at a mid-depth range (Figure 8). Of the 11 trawls carried out in the E sampling area, 10 trawls (average depth ± SD = 1131.5 ± 59 m) contained by-catches of large sponges: massive by-catches of demosponges—such as *Geodia* and *Isops* species (Geodiidae)—were obtained in eight trawls, while the hexactinellid *Pheronema carpenteri* (Thomson, 1869) was obtained in just one trawl. Their estimated weights ranged from between 100 and 3000 kg per trawl. *Pheronema* species was also found in a trawl conducted at the top of the bank. Sponges were absent along the south-eastern slope of the bank (<1000 m depth). However, sponges were present on the western slope, in 20 of the 131 trawls carried out and by-catches were lower (ranging from 0.1 to 25.1 kg per trawl).

Cold-water corals (Scleractinea, Pennatulacea, Gorgonacea and Antipatharia) were generally more abundant at the top of the bank (Figure 8). Stony corals (colonial Scleractinea) were present in 11% of the trawls. *Solenosmilia variabilis* (Duncan, 1873) was more abundant on the eastern slope and at the top of the bank: 27% of the trawls conducted on the eastern slope and at the top of the bank contained by-catches that ranged from 0.1 to 25.7 kg per trawl. However, only 7% of the trawls conducted along the western and the south-eastern slopes revealed by-catches that were generally lower (ranging from 0.1–2.8 kg per haul). *Lophelia pertusa* (Linnaeus, 1758) was recorded exclusively in two hauls conducted on the shallow top of the bank (1.2 and 7.7 kg respectively). Cup corals (solitary Scleractinea) were present in 22% of the trawls (<1.0 kg per trawl), distributed mainly along the deep western slope. The most common species found was *Flabelum alabastrum* (Moseley in Thomson, 1873). Sea pens (Pennatulacea) were captured in 29% of the trawls (≤1.2 kg per trawl). The most common species belonged to the family Anthoptilidae. Gorgonians (Gorgonacea) were present in 8% of the trawls (≤2.2 kg per trawl). The main species found was *Callogorgia verticillata* (Pallas, 1766) which appeared in seven trawls conducted at the top of the bank. Black corals (Antipatharia) were the least represented taxa (2% presence). Appendix 2 shows a list of the VME indicator taxa recorded.

DISCUSSION

Relationship between seabed geomorphology and trawl footprint

Two main geomorphological domains can be differentiated in the Hatton Bank: (i) outcrop area, mainly located at the top of the bank and composed of a bedrock surface (Smith *et al.*, 2005) with certain areas slightly covered by sediments; and (ii) sedimentary seabed (HD areas) that cover the majority of the slopes and are mainly composed of muddy–sandy deposits. The limit between the two domains was located at ~1100 m water depth (Figure 9), except in the ridge areas described by Sayago-Gil *et al.* (2010), where part of the outcrop was found deeper.

Benn *et al.* (2010) reported that the spatial extent of the trawl footprint is mainly concentrated along the western slope of the Hatton Bank. Seabed geomorphology is an important variable that determines extent of the spatial fisheries footprint wherein fishing gear contacts the seafloor during fishing operations (e.g. towed gears). However, there are several reasons that may explain why trawl footprint is preferably located along the western slope between ~1000 and 1500 m depth, namely: (i) the highest abundance of two main target species (Figure 5); (ii) a gentle seabed that forms an extensive good trawling area (HD) from the boundary between both domains (~1100 m depth) towards deeper waters; and (iii) the common fishing practice of deep-sea trawlers—only a few long tows per fishing day to minimize number of shooting and hauling operations, and also to optimize towing opportunity (Durán Muñoz *et al.*, 2009). This suggests that in the Hatton Bank the deep-sea bottom trawl technique is particularly applicable where there are large slopes with smooth sediment covered surface (e.g. HD) (Figure 9). These may be the reasons why trawling preferably occurs on the extensive areas of the HD. But trawling is also feasible in other places of the outcrop area where the rock is covered by a thin sediment veneer or ‘ponded deposits’ (Figure 9A) which is a mixture of sediment with coral rubble trapped by the ridges acting as barriers. This suggests that benthic communities on the sedimentary slopes of the HD may have been strongly influenced by trawling, at least when compared with the communities on the rough outcrop

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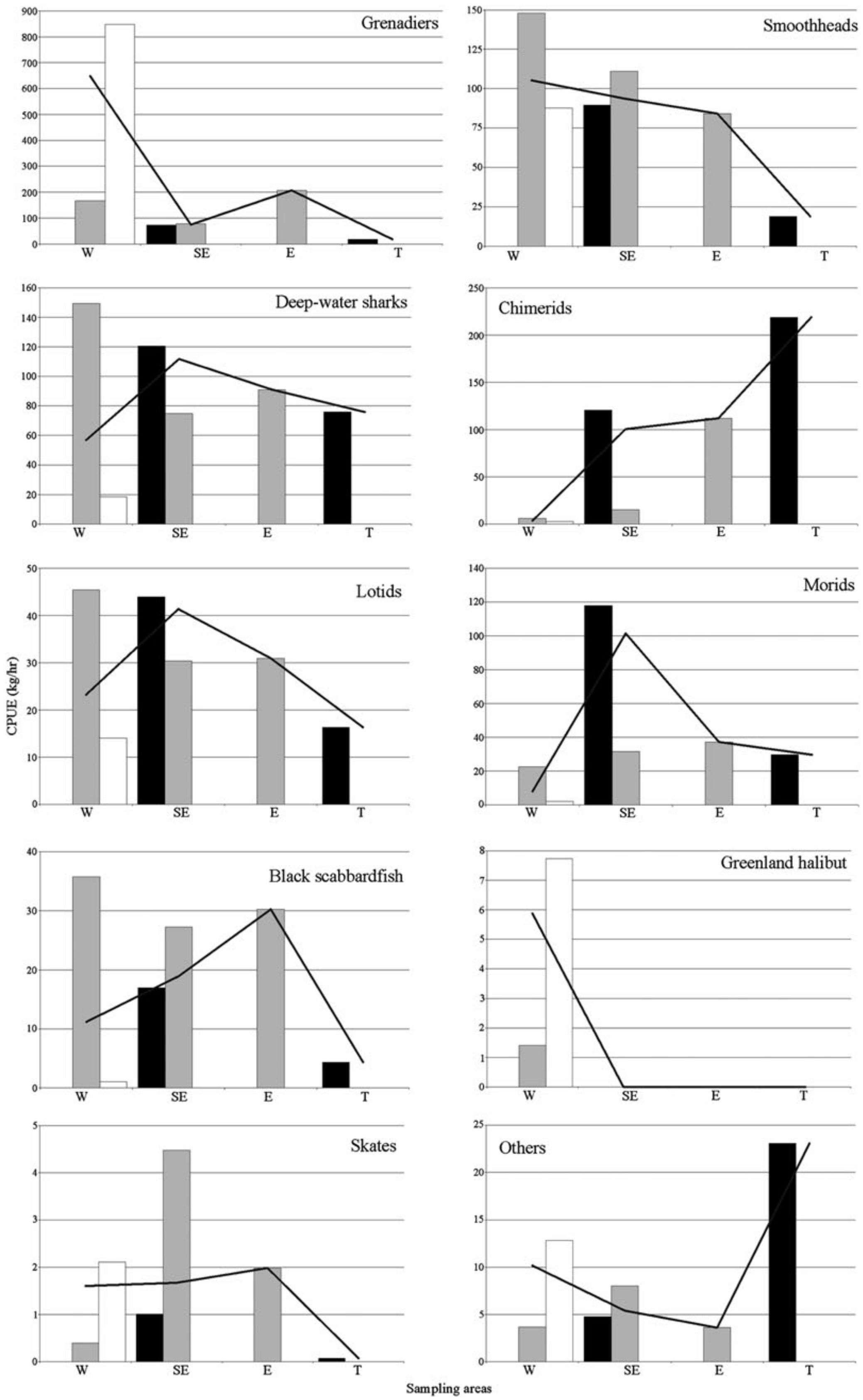

Fig. 4. Catch per unit effort (kg/hr) for the main taxa of deep-sea fish, by depth (black bars, <1000 m; grey bars, 1000–1300 m; white bars, >1300 m, black line, total) and sampling areas (W, western slope; SE, south-eastern slope; E, eastern slope; T, top of the bank).

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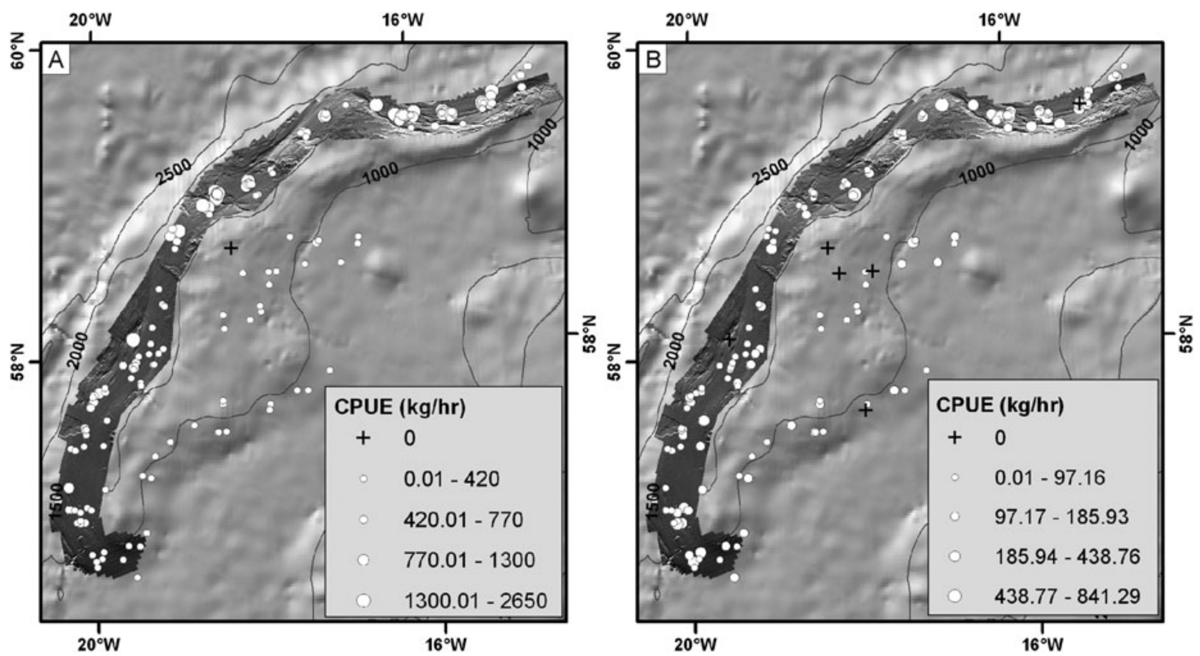

Fig. 5. Maps of the study area showing the distribution and abundance of main deep-sea fish ((A) grenadiers; (B) smoothheads). The size of the symbols (white dots) represents the catch per unit effort (kg/hr) on a haul by haul basis (symbols are associated with the start position of the trawl hauls). Note that the scale of the symbols is not the same in the maps. Values = 0 are represented as +.

and at the top of the bank, where less trawlable grounds are available.

Effects on target and by-catch fish species

In the present case, and just as in previous studies (Connolly & Kelly, 1996; Allain & Kergoat, 1997; Clarke *et al*., 2005), trawl catch composition was clearly dominated by deep-sea teleosts, particularly grenadiers and smoothheads (Figure 2). Both fisheries resources were more abundant along the deep western slope (Figure 5). This suggests that they have high catchability to bottom trawling, especially in soft sedimentary deep-sea habitats such as the HD. Length distributions of the two main grenadier species, when compared with minimum size at sexual maturity, indicated that bottom trawl appears to be a low-selective gear: both juvenile and adult grenadiers were captured on the same grounds, although mature fish were predominant. The commercial grenadier *Coryphaenoides rupestris* ranged in length from 5 to 26 cm (mantle length (ML) = 14.3 cm, N= 6021) and 89% of the individuals recorded were larger than 11.5 cm in length—their size at maturation (Allain, 2001). The rate of discards and length

Table 3. List of vulnerable marine ecosystems indicator taxa (sponges and cold-water corals) captured with trawls on the Hatton Bank. For each sampling area, the presence of each taxon is presented expressed as a percentage of the trawls conducted in the area and the total number of hauls (W, western slope; SE, south-eastern slope; E, eastern slope; T, top of the bank).

		W	SE	E	T	Total
Porifera	Porifera indeterminate			9.1		0.6
	Geodiidae indeterminate	13.7		81.8		16.6
	Axinellidae indeterminate	2.3				1.8
	Pheronema carpenteri (Thomson, 1869)			9.1		0.6
	Pheronema sp.				9.1	0.6
Gorgonacea	*Anthothela grandiflora* (M. Sars, 1856)				9.1	0.6
	Paragorgia sp.		20.0			1.2
	Paragorgia arborea (Linnaeus, 1758)	1.5		9.1		1.8
	Paramuricea biscaya Grasshoff, 1977	0.8	10.0			1.2
	Callogorgia verticillata (Pallas, 1766)			9.1	63.6	4.9
Pennatulacea	Pennatulacea indeterminate	0.8	10.0			1.2
	Anthoptilidae indeterminate	17.6	30.0	90.9	72.7	27.0
	Anthoptilum murrayi Kölliker, 1880	0.8	10.0			1.2
	Halipteris finmarchica (Sars, 1851)	0.8				0.6
Antipatharia	Antipatharia indeterminate	2.3			9.1	2.5
Scleractinea	Caryophyllidae indeterminate	0.8				0.6
	Lophelia pertusa (Linnaeus, 1758)				18.2	1.2
	Solenosmilia variabilis Duncan, 1873	6.9	10.0	18.2	36.4	9.8
	Stephanocyathus spp.	3.1				2.5
	Flabellum alabastrum Moseley in Thomson, 1873	25.2				20.2

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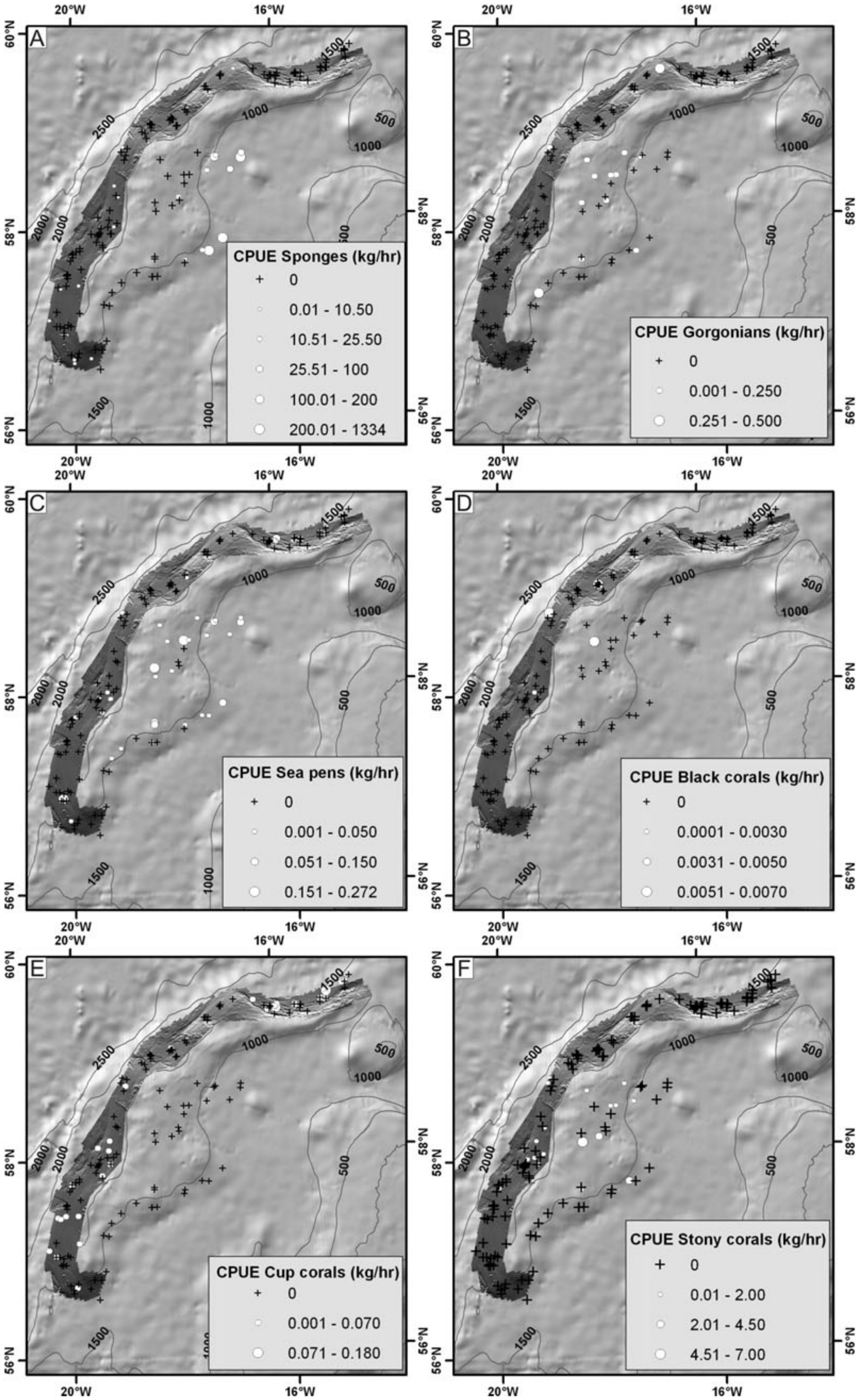

Fig. 6. Maps of the study area showing the distribution and abundance of vulnerable marine ecosystem indicator taxa ((A) sponges; (B) gorgonians; (C) sea pens; (D) black corals; (E) cup corals; (F) stony corals). The size of the symbols (white dots) represents the catch per unit effort (kg/hr), on a haul by haul basis (symbols are associated with the start position of the trawl hauls). Note that the scale of the symbols is not the same in the maps. Values = 0 are represented as +.

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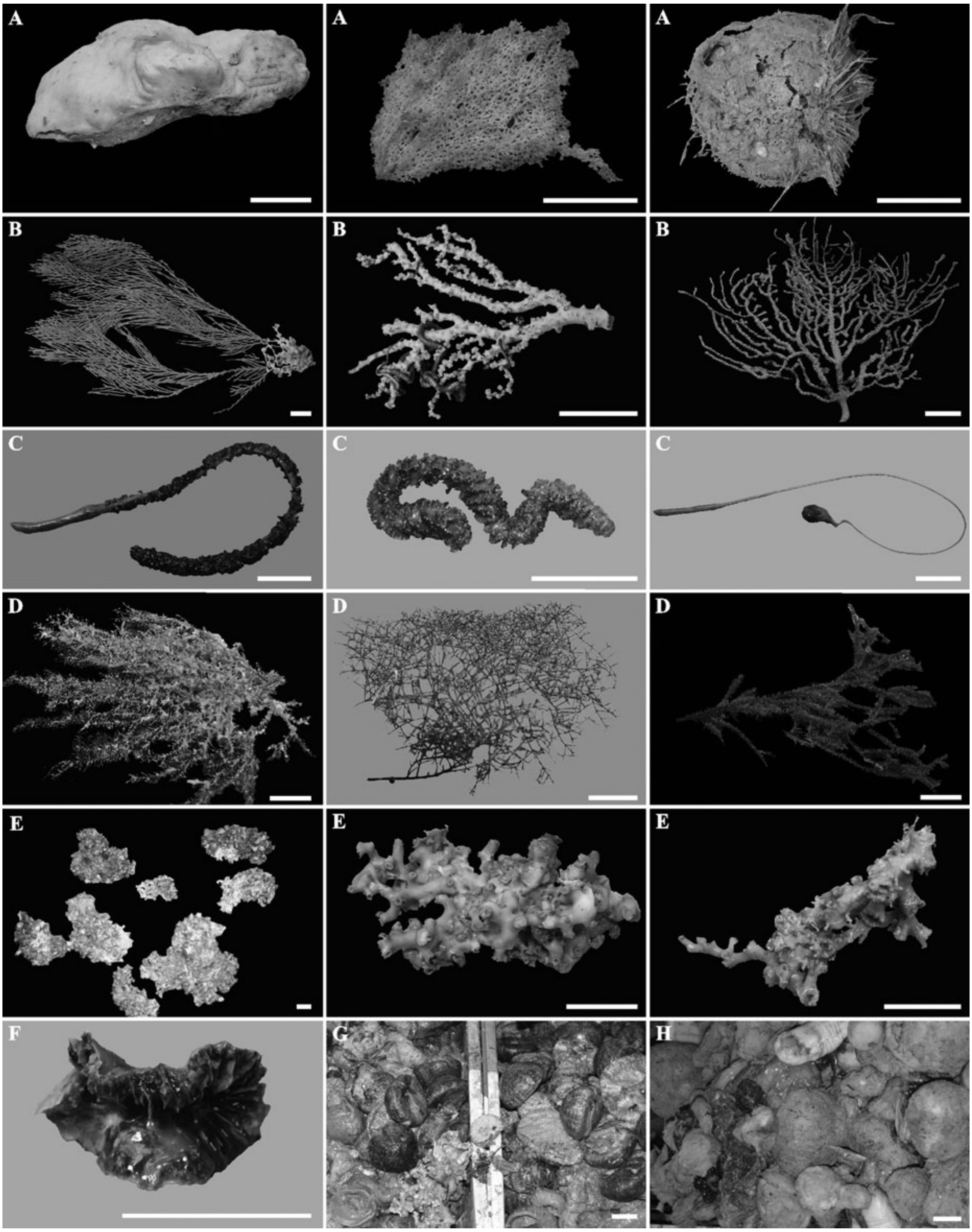

Fig. 7. Photographs showing some examples of vulnerable marine ecosystem indicator species captured with trawls in the study area. ((A) large sponges; (B) gorgonians; (C) sea pens; (D) black corals; (E) stony corals; (F) cup corals). Examples of large by-catches of sea urchins (G) and large by-catches of sponges (H) are also presented.

composition of discarded fish (length range (LR) = 5.5–19.5, ML = 10.4 cm, N = 640) were similar to previous data (Lorance *et al.*, 2008). 92% of *Trachyrincus murrayi*, the most abundant non-commercial grenadier, were larger than 12 cm in length (LR = 8.5–20.5 cm, ML = 15.2 cm, N = 425)—their size at maturation (Lorance *et al.*, 2008). Discards rate of *Alepocephalus bairdii* was lower than that of *Coryphaenoides rupestris* (Figure 3) indicating that *Alepocephalus bairdii* is a target species (Bensch *et al.*, 2009) in its own right on the Hatton Bank. It is worth noting that this is infrequent in other deep-water trawl fisheries that operate to the west of the British Isles, where smoothheads are the main non-macrourid discards species (Connolly & Kelly, 1996; Allain & Kergoat, 1997; Allain *et al.*, 2003;

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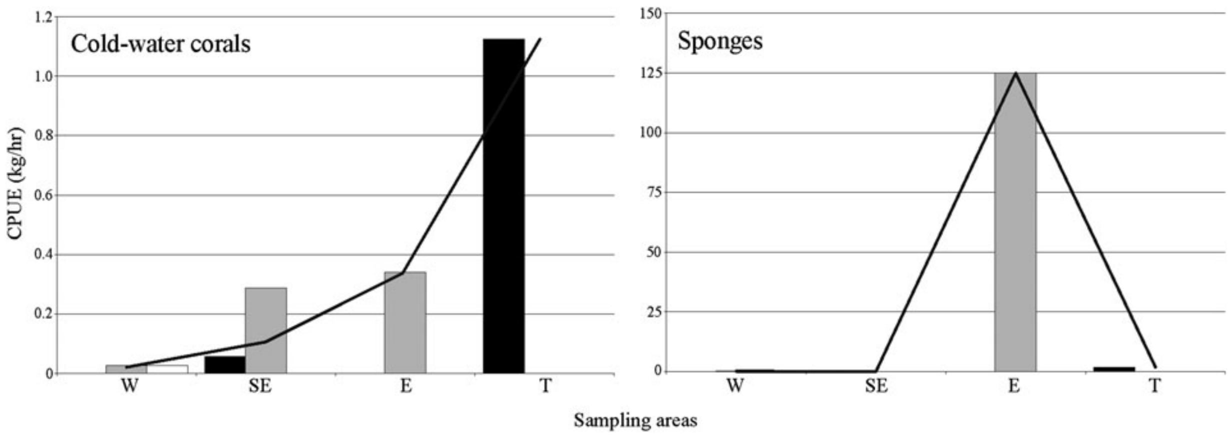

Fig. 8. Catch per unit effort (kg/hour) for total cold-water corals and total sponges, by depth (black bars, <1000 m; grey bars, 1000–1300 m; white bars, >1300 m, black line, total) and sampling areas (W, western slope; SE, south-eastern slope; E, eastern slope; T, top of the bank).

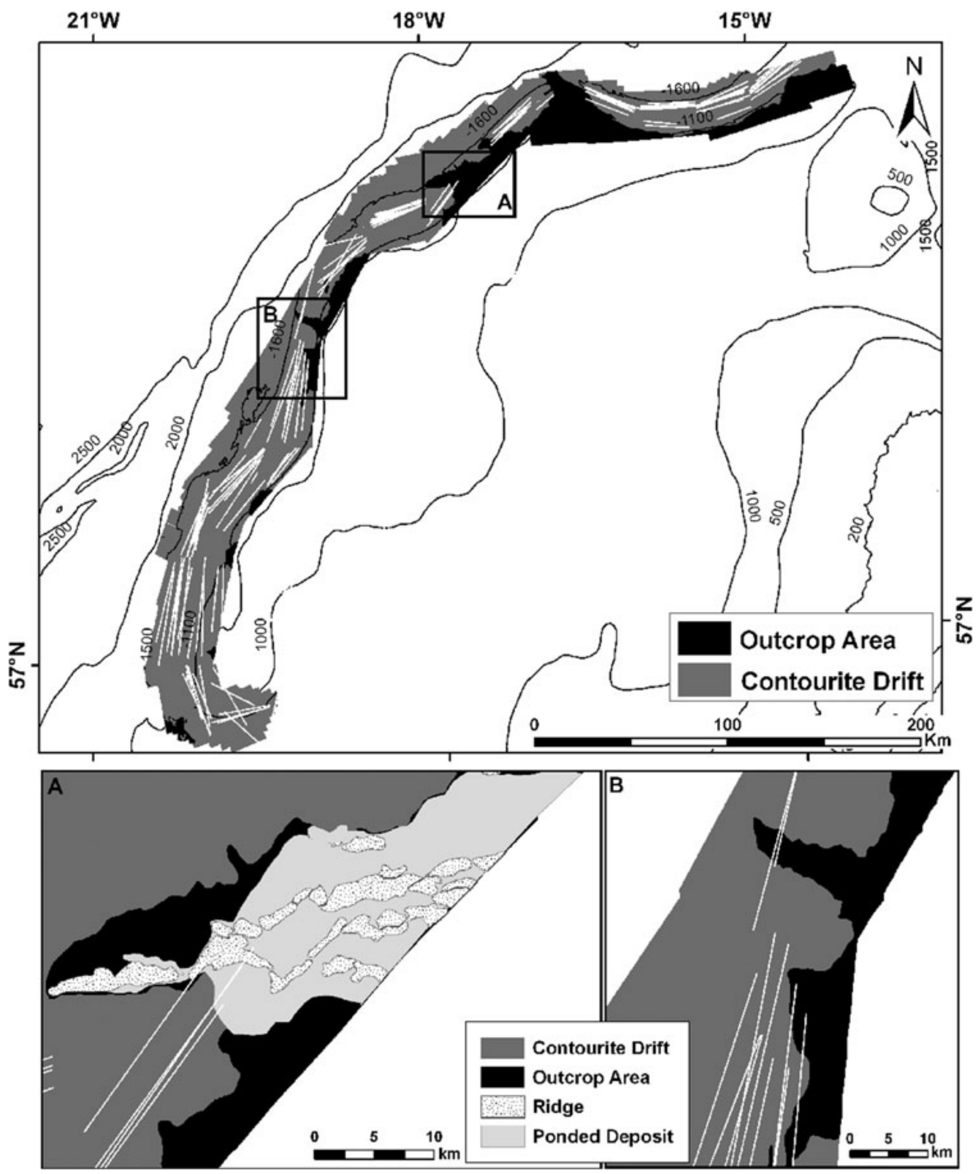

Fig. 9. Sketch showing the two main domains—outcrop area and contourite drift (part of the Hatton Drift)—identified in the main trawl fishing grounds prospected with multibeam echosounder (western slope of the Hatton Bank). The positions of the trawl hauls (based on start and end of trawl operations) are shown superimposed on the surveyed area. Details of the ridge areas (A) and central outcrop areas (B) are presented.

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Lorance *et al.*, 2008). With regard to *Centroselachus crepidater*, 73% of individuals measured (LR = 28–88 cm, ML = 74.0 cm, N = 334) were larger than 68 cm in length—their size at female maturation (Clarke *et al.*, 2001). No dense aggregations of *Molva dypterygia* or *Reinhardtius hippoglossoides* were found because the survey was undertaken outside their spawning seasons. Chimerids were clearly more abundant at the top of the bank. A large part of this area (~11,300 km^2) is currently closed (EC, 2009; NEAFC, 2011), suggesting that interactions between bottom fishing and chimerids have probably decreased over the past years.

Present results on discards cannot be directly extrapolated for the commercial fleet, because discards depend on several factors (gear used, mesh, market considerations, etc.). The discards ratio observed during this experimental survey was a consequence of trawl catch composition on the sedimentary grounds: catches were largely dominated by grenadiers although *Coryphaenoides rupestris* is the only currently marketable species. *Macrourus berglax* has commercial value but catches were negligible. Moreover, the trawl gear used in this survey appeared to be poorly selective: small individuals (that were discarded) and large ones (that were landed) were present in the catches. Most deep-water sharks captured were of low value and therefore just two shark species were landed. *Alepochephalus bairdii*, *Molva dypterygia*, *Aphanopus carbo* and *Reinhardtius hippoglossoides* were other species landed due to their commercial value. Chimerids were occasionally retained on-board. A group denominated 'others' was generally discarded (Table 2). It included a wide variety of teleost fish species of minor importance in terms of weight (Appendix 1). The current restrictive quotas for most of the above mentioned deep-sea species and the ban on shark fisheries (EC, 2010) suggest that the viability of the multispecies trawl fishery is now being questioned. Severe current catch restrictions mean that trawl fishing effort on the Hatton Bank will remain at a very low level.

Effects on vulnerable marine ecosystems

The by-catch data did not provide any clear evidence of overlapping between trawling and dense sponge communities on the deep western slope or in the shallow parts of the bank. But the eastern slope of the Hatton Bank (E sampling area, from 57°30′N to 59°00′N) appears to be an important location for aggregations of structure-forming sponges within a narrow depth range (~1060–1250 m depth) similar to that found by other authors in adjacent areas (Rice *et al.*, 1990). Large-sized species characteristic of sponge-dominated biotopes (Barthel *et al.*, 1996; Klitgaard & Tendal, 2004) were recorded in most of the trawls conducted there: generally sponges were the dominating taxon, representing at least 60% of the biomass excluding fish (reaching >90% in three cases). The massive by-catches of sponges are called '*patatada*' by Spanish fishers, meaning 'lots of potatoes' (this refers to the amounts, the shape and colour of such sponges). Sponge by-catches from the same area had also been reported previously (Durán Muñoz *et al.*, 2011). The area is located outside the current closure boundaries (NEAFC, 2011) suggesting that sponges may be potentially threatened by bottom fisheries. Limited overlapping between trawling and cold-water corals was observed within the main trawler fishing grounds: most records were associated with accidental trawls over outcrop areas (Figure 9B) that were closed to fishing in 2009 (~4600 km^2) (NEAFC, 2010). Records of sea pens were observed throughout the study area but it is unclear whether these low by-catches indicate sea pen communities. Reef builders and coral garden components were quite abundant at the top of the Hatton Bank. Some sponges and dense aggregations of sea urchins were likewise recorded there. This confirms that the top of the bank is a key area for VMEs and biodiversity as was reported previously (Roberts *et al.*, 2008; Durán Muñoz *et al.*, 2009, 2011; Howell *et al.*, 2010). A large part of this area (~11,300 km^2) is currently closed to bottom fishing, suggesting that VMEs in this part of the bank are now adequately protected. Several records indicate that indicator species also present near the eastern closure boundary.

These results should be used with caution because the present study was mainly based on by-catch records and limited sampling effort. The survey suggests a low abundance of cold-water corals and sponge aggregations on the preferred bottom trawling fishing grounds. Such paucity may be a consequence of varying suitability of environmental conditions for such species or historical trawling activity (Murillo *et al.*, 2011). Environmental variables are factors that influence the distribution of VME indicator species (Barthel *et al.*, 1996; Mortensen *et al.*, 2001; Klitgaard & Tendal, 2004). Some such as seabed morphology (Sayago-Gil *et al.*, 2010), habitats and fisheries (Durán Muñoz *et al.*, 2009, 2011; Benn *et al.*, 2010) have been studied previously. The uneven surface of the outcrop (where trawling effort is low) is a suitable platform for most cold-water corals, and the gentler sedimentary deposits of the western (main trawling grounds) and eastern (less used grounds) slopes of the bank seem to be preferred by large sponges. Seabed characteristics (e.g. topography, substratum, etc.) and obviously fishing impact may have influenced the current distribution of these species. Food availability could probably be a key factor because they are filter feeders (Rice *et al.*, 1990; Barthel *et al.*, 1996). Dense aggregations of sponges were only found on the eastern flank of the Hatton Bank in a narrow depth range. This may indicate the presence of different water masses (Klitgaard & Tendal, 2004) along the western and eastern slopes. Further research into oceanographic parameters is needed to clarify the role played by bottom currents in the distribution of the Hatton Bank VME indicator species (e.g. food supply, temperature, salinity, etc.).

Bottom trawling produces impacts on VMEs when their distributions overlap with that of the trawl fishery spatial footprint. Many such impacts can be successfully avoided by closing areas to fishing, just as was done by the NEAFC and the EU. The present study supports the closure of the Hatton Bank (EC, 2009; NEAFC, 2010; EU, 2011) and also suggests some areas of VME indicator species near the eastern closure boundary, thus suggesting revision of closure boundary limits.

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Appendix 1. List of deep-sea fish captured with trawls in the Hatton Bank.

Family	Taxon (species or higher taxonomic level)
Myxinidae	*Myxine ios* Fernholm, 1981
Petromyzontidae	*Petromyzon marinus* Linnaeus, 1758
Triakidae	*Galeus melastomus* Rafinesque, 1810
Scyliorhinidae	*Apristurus* sp.
Somniosidae	*Centroselachus crepidater* (Bocage & Capello, 1864)
Dalatiidae	*Centroscyllium fabricii* (Reinhardt, 1825)
	Centroscymnus coelolepis Bocage & Capello, 1864
	Etmopterus sp.
	Scymnodon ringens Bocage & Capello, 1864
Centrophoridae	*Centrophorus squamosus* (Bonnaterre, 1788)
	Deania calcea (Lowe, 1839)
Rajidae	Rajidae indeterminate
	Rajella bathyphila (Holt & Byrne, 1908)
	Raja sp.
Chimaeridae	*Hydrolagus affinis* (Capello, 1868)
	Hydrolagus mirabilis (Collet, 1904)
Rhinochimaeridae	*Harriota raleighana* Goode & Bean, 1895
	Rhinochimaera atlantica Holt & Byrne, 1909
Halosauridae	Halosauridae indeterminate
Notacanthidae	*Notacanthus nasus* Bloch, 1788
Synaphobranchidae	*Synaphobranchus kaupi* Johnson, 1862
Nemichthyidae	*Nemichthys scolapaceus* Richardson, 1848
Serrivomeridae	*Serrivomer beani* Gill & Ryder, 1883
Nettastomatidae	*Venefica proboscidea* (Vaillant, 1888)
Alepocephalidae	*Alepocephalus bairdii* Goode & Bean, 1879
	Alepocephalus agassizii Goode & Bean, 1883
Platytroctidae [= Searsiidae]	Platytroctidae indeterminate
Gonostomatidae	Gonostomatidae indeterminate
Sternoptychidae	*Argyropelecus* sp.
Stomiidae	*Chaulodius sloani* Bloch & Schneider, 1801
	Borostomias sp.
	Stomias boa (Risso, 1810)
Ipnopidae	*Bathypterois dubius* Vaillant, 1888
Synodontidae	*Bathysaurus ferox* Günther, 1878
Paralepididae	*Paralepis (manisidium) atlantica* (Kroyer, 1868)
Myctophidae	Myctophidae indeterminate
Trachipteridae	*Trachypterus articus* (Brünnich, 1788).
Macrouridae	*Trachyrincus murrayi* Günther, 1887
	Trachyrincus trachyrincus (Risso, 1810)
	Coryphaenoides guenteri (Vaillant, 1888)
	Coryphaenoides rupestris Gunnerus, 1765
	Nezumia sp.
	Macrourus berglax Lacépède, 1801
	Gadomus longifilis (Goode & Bean, 1885)
Moridae	*Lepidion eques* (Günther, 1887)
	Antimora rostrata (Günther,1878)
	Halargyreus johnsonii Günther, 1862
Lotidae	*Gaidropsarus ensis* (Reinhardt, 1838)
	Molva dypterygia (Pennant, 1784)
	Brosme brosme (Ascanius, 1772)
Phycidae	*Phycis blennoides* (Brünnich, 1768)
Gadidae	*Micromesistius poutassou* (Risso, 1827)
Bythitidae	*Cataetix laticeps* Koefoed, 1927
Lophiidae	*Lophius piscatorius* Linnaeus, 1758
Ogcocephalidae	*Dibranchus atlanticus* Peters, 1876
Melanocetidae	Melanocetidae indeterminate
Himantolophidae	Himantolophidae indeterminate
Oneirodidae	Oneirodidae indeterminate
Ceratiidae	Ceratiidae indeterminate
Trachichthyidae	*Hoplostethus atlanticus* Collet, 1889
Diretmidae	*Diretmus argenteus* Johnson, 1864
Anoplogastridae	*Anoplogaster cornuta* (Cuvier & Valenciennes, 1833)
Oreosomatidae	*Neocytus helgae* (Holt & Byrne, 1908)

Continued

Appendix 1. Continued.

Family	Taxon (species or higher taxonomic level)
Syngnathidae	*Enterulus aequoreus* (Linnaeus, 1758)
Sebastidae	*Sebastes* sp.
Psychrolutidae	*Cottunculus thompsoni* (Günther, 1882)
Epigonidae	*Epigonus telescopus* (Risso, 1810)
Zoarcidae	*Lycodes vahalii* Reinhardt, 1831
	Lycodonus flagellicauda (Jensen, 1902)
Anarhichadidae	*Anarhichas lupus* Linnaeus, 1758
	Anarhichas denticulatus Krøyer, 1845
Chiasmodontidae	*Chiasmodon niger* Johnson, 1864
Gempylidae	Gempylidae indeterminate
Trichiuridae	*Aphanopus carbo* Lowe, 1839
Centrolophidae	*Centrolophus niger* (Gmelin, 1789)
Pleuronectidae	*Reinhardtius hippoglossoides* (Walbaum, 1792)
	Glyptocephalus cynoglossus (Linnaeus, 1758)

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Appendix 2. Vulnerable marine ecosystems (VMEs) indicator taxa captured with bottom trawls in the Hatton Bank. Sampling area (SA), start and end positions of the haul (Lat, latitude; Long, longitude), average depth (m) and estimated catch in live weight (kg) are given (SG, sponges; GO, gorgonians; SP, sea pens; BC, black corals; CC, cup corals; SC, stony corals). Values <0.1 are noted as +.

SA	Start		End		Depth	VMEs indicator taxa					
	Lat (N)	Long (W)	Lat (N)	Long (W)		SG	GO	SP	BC	CC	SC
E	574110	175430	574730	173000	1122.5	65.6		0.2			
E	574600	172680	575340	170280	1247.5	1000.0	0.3	0.2			
E	574640	173430	573960	175960	1110.5	100.0		0.1			$13.9^{(D, L)}$
E	575330	171020	574720	172850	1153.5	800.0		0.3			
E	583470	165760	584600	164780	1149.5	106.4		0.2			
E	583490	172440	584670	171350	1068.0	105.3		0.1			$0.1^{(D)}$
E	584150	164440	583530	164860	1181.0	3000.0		0.2			
E	584280	171500	583150	172300	1064.0	404.0	0.1	0.5			
E	584370	171300	583130	172440	1060.0	130.7		0.2			
E	584400	164360	583410	165060	1158.0	283.5		0.1			
SE	572290	191820	571100	192980	1002.5		2.2	0.1			
SE	572840	190700	571920	192290	957.5			0.1			
SE	573180	183200	573460	185250	785.0			0.1			
SE	574220	182880	573150	182930	769.0		0.8	0.2			$0.4^{(L)}$
SE	574370	182870	573100	182970	782.5			0.4			
T	581100	182510	581240	180200	820.0			0.2			$25.7^{(D, L)}$
T	581400	180670	581400	183000	813.0			0.1			$8.5^{(D, L)}$
T	581620	182600	581610	180100	767.5		0.1	1.2			
T	581700	175800	583000	175100	777.5		0.4				
T	581950	175870	583000	175400	768.5	80.0					
T	583200	181050	584300	181480	606.0		0.1	+	+		
T	583240	175140	584560	173980	815.0		+	1.0			$0.2^{(L)}$
T	583250	174550	584710	173780	819.0		0.7	0.1			$1.2^{(L)}$
T	584200	181800	583020	181370	623.5		0.6	0.1			$7.7^{(L)}$
T	584550	173420	583100	174200	877.0		+	0.1			$0.8^{(D)}$
W	564030	200090	570000	201280	1167.5	0.7					
W	564260	200100	570000	200600	1114.0	1.5					
W	564300	194250	565950	195900	1066.0	0.4					
W	564380	195730	564810	193000	1151.0					+	
W	564510	200430	565990	201170	1154.0			0.1			
W	565760	200920	564480	200000	1116.0	8.0					
W	565770	201450	564080	200050	1212.5	1.0					
W	565850	201260	564480	200500	1153.5			1.0			
W	570280	202010	572730	201390	1349.0					+	
W	570650	202800	572860	201790	1466.0	6.4				0.1	
W	571060	195430	572770	195280	1054.5					+	
W	572560	201540	570360	202250	1404.5	1.7				+	
W	572630	201840	570000	202680	1443.5					0.4	
W	572700	200900	570720	201670	1294.0					0.1	
W	572720	195540	570920	195940	1058.5	0.1				+	
W	574420	200190	573000	200920	1337.5						$0.2^{(D)}$
W	574600	200270	573000	201180	1412.5					+	
W	574780	195790	575980	193020	1369.0			0.1			
W	575000	192710	580000	191180	1126.0			+			
W	575160	192750	580000	191330	1160.5					+	
W	575830	191810	574970	192930	1199.0			0.1		+	
W	575840	191730	574890	192980	1190.0			+			$0.1^{(D)}$
W	575900	193070	574310	200000	1328.5			0.1			
W	580160	192890	582290	191210	1386.5						$0.9^{(D, L)}$
W	580250	192100	582920	190810	1328.0			0.1	+		$0.1^{(L)}$
W	580270	191400	582640	190720	1260.5	0.2					
W	580450	191040	582430	190600	1251.5						$2.0^{(D, L)}$
W	580640	191950	583000	190980	1355.0					+	
W	580800	193200	580010	194090	1495.0					+	
W	581240	191810	582290	191190	1404.5					0.2	$2.8^{(D, L)}$
W	582060	190850	580450	191370	1258.0	25.1					$0.6^{(D)}$
W	582720	191240	580610	192660	1455.0	6.3					
W	584550	185800	585720	183230	1283.5					+	
W	584770	190310	583460	190970	1460.0						$0.5^{(D)}$
W	585040	190130	583020	191270	1497.0	0.8	0.4	0.1	0.1		$0.1^{(L)}$

Continued

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Appendix 2. Continued.

SA	Start		End		Depth	VMEs indicator taxa					
	Lat (N)	Long (W)	Lat (N)	Long (W)		SG	GO	SP	BC	CC	SC
W	590360	182750	590740	180000	1460.5			0.1			
W	590390	182760	590800	180000	1472.0			0.1			
W	590620	180300	590210	183000	1435.0	0.2					
W	590650	180150	590160	183000	1430.0			0.1			
W	590670	180300	590430	182780	1470.0				+		
W	590770	180330	590210	183060	1476.5					0.1	
W	591000	174470	590020	175990	1188.5			+			
W	592530	171770	593250	170000	1400.5	0.3					
W	592780	160690	593320	163000	1435.0					+	
W	592860	160400	593540	162980	1534.0	0.9					
W	592890	152600	593300	150100	1503.5	10.2					
W	592890	155640	592890	153000	1515.5			0.1		0.9	
W	592890	152700	593310	150020	1513.5	2.0		0.4		0.4	
W	592900	153300	592910	155960	1518.5			0.1		0.1	
W	592910	160460	593660	162990	1526.0					0.1	
W	592920	155800	592920	153000	1523.0			+		0.1	
W	592940	155670	592960	153000	1540.0			0.2		0.4	
W	592940	153490	592970	160000	1540.5			0.3		0.3	
W	592960	160370	593640	163000	1524.0	7.9					
W	593000	153370	593000	160000	1556.5					0.2	
W	593070	155580	593010	153000	1566.0			0.3		0.3	
W	593120	145730	593880	143000	1402.5			0.1		0.1	
W	593140	150320	592870	153000	1486.0					0.1	
W	593180	150270	592820	152990	1486.5			0.1		0.1	
W	593220	150280	592900	153000	1510.5	3.7		0.1		0.1	
W	593420	162370	592930	160000	1508.0					+	
W	593430	145610	594300	143000	1487.5					+	
W	593500	164690	593100	165710	1266.5	2.4	1.0				
W	593600	145500	594500	143000	1526.0			0.1		0.4	
W	594020	143650	593250	145950	1465.0					+	
W	594100	143240	593130	145980	1434.0					+	
W	594150	143350	593180	145990	1452.0			0.1		0.1	
W(*)	583250	191040	583750	190890	1441.0						1.2(D)

Status of the stony corals captured (D, dead; L, live). Null haul (*).

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