A First Approach to Assess the Impact of Bottom Trawling Over Vulnerable Marine Ecosystems on the High Seas of the Southwest Atlantic

J. Portela, J. Cristobo, P. Ríos, J. Acosta, S. Parra,
J.L. del Río, E. Tel, V. Polonio, A. Muñoz,
T. Patrocinio, R. Vilela, M. Barba and P. Marín

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1. Introduction

The Southwest Atlantic (SW Atlantic), corresponding to FAO Statistical Area 41, includes a total continental shelf area of approximately 1.96 million km^2 of which a large portion lies off the Argentine coast (the Patagonian Shelf) and extends beyond Exclusive Economic Zones (EEZs) in the region [1-3]. This area is therefore integrated in the Southeast South American Shelf Large Marine Ecosystem (SSASLME) [4,5]. Currently, this region is the only worldwide significant area for high seas (HS) fisheries not covered by any Regional Fisheries Management Organisation (RFMO) [3].

The Patagonian Shelf (PS) hosts some of the most important fisheries in the world, targeting cephalopods (*Illex argentinus* [Castellanos, 1960] and *Doryteuthis gahi* [D'Orbigny, 1835]), and hakes (*Merluccius hubbsi* [Marini, 1933] *Merluccius australis* [Hutton, 1872]) [3,6-14]. Most of the exploited demersal stocks on the HS are straddling stocks, including Argentine shortfin squid (*I. argentinus*), Argentine hake (*M. hubbsi*) and southern blue whiting (*Micromesistius australis* [Norman, 1937]) [15].

Several authors [2,3,16-23] have studied the potential disturbance of the seabed by bottom otter trawls and the possible negative effects on the structure of benthic communities. In recent years, several resolutions of the United Nations General Assembly [24-28] on sustainable fisheries made a call to States and RFMOs to identify vulnerable marine ecosystems (VMEs)

and determine whether bottom fishing activities would cause a significant adverse impact on such ecosystems.

Sensitive species such as deep-water corals and deep-water sponges are found throughout the world oceans. Thus, the importance of habitat-structuring organisms is not restricted to shallow water, but also to shelf-break, hydrothermal vents, seamounts, and even the once considered constant and uniform deep-sea basins. Deep-water corals are vulnerable organisms occurring in the upper bathyal zones throughout the world and threatened by human activities, particularly fishing and oil exploration [29-31]. Fishing has a significant adverse impact (SAI) on deep-water coral communities in all oceans [32-35], particularly in the Northeast and Northwest Atlantic [36-40], Northeast Pacific [41,42], and Southwest Pacific [43-46]. In the SW Atlantic, the HS are one of the areas where deep-sea science has, to date, not been very active.

Protection of VMEs is a significant element of the management framework for bottom fisheries in high seas areas of the world ocean and its identification for selecting suitable protection areas is a challenge that conventional fisheries science cannot alone solve satisfactorily. Instead, it requires a multidisciplinary approach [21,22,47]. From the point of view of management of bottom fisheries and the governance of high seas areas, the situation in the PS poses an added problem as there is no any RFMO in force [2]. In its 2014 report [48], the Global Ocean Commission (GOC) recognises that continued scientific research is necessary to assess the cumulative impacts of human activities on the high seas so that informed decisions can be made about reversing the degradation of the global ocean.

Submarine canyons are unique habitats in terms of complexity, instability, material processing, and hydrodynamics. They may support diverse assemblages of larger epibenthos [49]. Inside canyons, abundance and diversity of the macrofauna depend, to some extent, on the physical disturbance regime and on the rate and quantity of organic matter deposited. In the study area, canyons and submarine mounts were shown to be hot spots of benthic biodiversity of species and ecosystems.

Benthos refers to the community of organisms which live on, in, or near the seabed, also known as the benthic zone. Megabenthos or macrobenthos comprises the more visible, benthic organisms exceeding 1 mm in size and large enough to be determined on photographs [50,51]. Megabenthos is a key issue of environmental studies, as it represents a major fraction of the deep-sea benthic biomass and plays a key role in deep-sea ecosystems [52]. Tracey et al. (2007) in [53] reported linear and radial annual growth rates of 20 mm and 0.2 mm, respectively, for some genera of the ISIDIDAE Family (Lamouroux, 1812), which is presumably evidence of the high vulnerability of these taxa to direct or indirect mechanical impact produced by the sediment removal, re-suspension, etc. caused by bottom fishing activities.

Some of these organisms form complex 3D structures protruding from the seabed, allowing for the settlement of sessile species needing consolidated substrata to settle and develop (sponges, other cnidarians), and providing shelter and food for a wide range of vagile fauna (crustaceans, echinoderms, molluscs, and some fish).

2. Materials and methods

In accordance with the aforementioned UNGA resolutions [24-28] and the FAO deepwater guidelines [54], the Spanish Institute of Oceanography (Instituto Español de Oceanografía [IEO]) conducted from October 2007 to April 2010 a series of 13 multidisciplinary research cruises on the HS of the SW Atlantic, to identify VMEs and to assess the potential interactions with fishing activities. This paper presents the results of the five first cruises, consistently with UNGA resolutions (paragraphs 80 and 83 to 87 of resolution 61/105 (2007) and paragraphs 117 and 119 to 127 of resolution 64/72 (2010) in [27,28], which support making publicly available information on interactions between bottom fisheries and VMEs in the HS.

The use of spatial management tools to preserve the marine biodiversity of species inhabiting the HS has been broadly discussed in recent years [55]. To make such spatial management possible, our immediate objectives are: assessing specific biodiversity (mainly describing new species to science); describing the different habitats, ecosystems and deep-sea geomorphological features identified; and analysing their interactions and relationships to protect the full range of potentially different habitats.

The explored area during the five cruises conducted between October 2007 and April 2008 (Table 1) was located on the southern part of the HS of the SW Atlantic, to the east of the Argentinian EEZ 200 miles limit and between 44° 40'S and 47° 51'S up to the 1500 m depth contour (Figure 1). The rest of the study area (up to 42°S) was surveyed during the eight following cruises (October 2008-April 2010), but the analysis of the information concerning VMEs collected during those last cruises, is still ongoing.

Cruise name	Start	End	Total days
Patagonia 11/07	28/10/2007	20/11/2007	24
Patagonia 12/07	24/11/2007	21/12/2007	28
Patagonia 01/08	08/01/2008	30/01/2008	23
Patagonia 02/08	30/01/2008	11/03/2008	41
Atlantis 2008	12/03/2008	15/04/2008	40

Table 1. Cruises carried out by R/V "Miguel Oliver".

In the right image of Figure 1 a non coloured area in the shelf can be roughly appreciated around 45°30'S and between 60°00'W-60°40'W, for which it was not possible to collect multibeam bathymetry data (no data) due to bad sea state conditions. The exploration of this area was carried out during one of the cruises conducted in 2009. Nevertheless, this type of data is not relevant for the present study, for which several trawl and CTD stations allowed the collection of pertinent information. The blue lines in the left image of Figure 1 corresponding to the 600, 1000 and 1500 m depth contours.

Key concepts for definition of VMEs were applied according to the FAO International Guidelines for the Management of Deep-Sea Fisheries in the High Seas [54]. These guidelines classify marine ecosystems as vulnerable based on several criteria: (1) uniqueness or rarity; (2) functional significance of the habitat; (3) fragility; (4) life-history traits of component species that make recovery difficult; and (5) structural complexity.
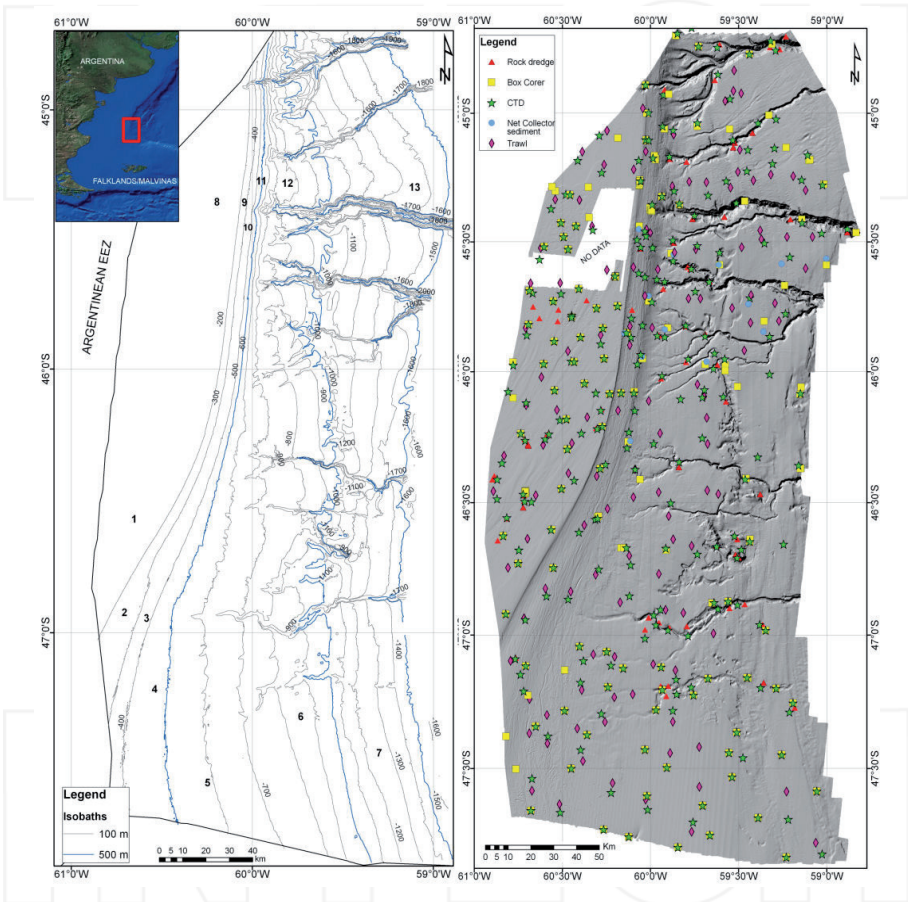

Figure 1. Study area and positioning of the stations carried out during the research cruises onboard the R/V "Miguel Oliver".

For an adequate identification of VMEs, the two approaches in operation since 2008 by the NAFO Scientific Committee and the NAFO Working Group on Ecosystem Approach to

Fisheries Management (WGEAFM) were applied in this study [56,57]: (1) the examination of cumulative catch data by ranking the biomass of VME taxa in each trawl from lowest to highest and then plotting the increase in cumulative biomass with each additional trawl; and (2) the use of Geographical Information System (GIS) to map the density of vulnerable species and groups' by-catch [58].

The study area included part of the outer shelf and upper and middle slope of the PS and was divided into thirteen depth strata in order to obtain a higher resolution in the description of vulnerable organisms. The research cruises involved five scientific disciplines: cartography, geology, benthos, fisheries, and hydrography.

This study used data from three main sources: i) Information from the five research cruises (geological, echosounder and oceanographic data; benthos and fish samples; fishery catch data [cpue]); ii) Data from commercial fishing activity collected by onboard scientific observers from 1989 to 2007 (fishery footprint); and iii) Commercial information on historical landings and effort data (provided by the Spanish fishing sector), as well as catch data for the main commercial species during the period 2000-2007 (logbooks filled in by captains of the fishing vessels, and provided by the Spanish General Secretariat for Fisheries [SGP]).

Geophysical and geological data were collected following internationally accepted standards and protocols for habitat mapping [20,59]. Full sea floor coverage using swath bathymetry provided a very high resolution of sea floor morphology. The backscatter data from multibeam echosounder together with high resolution seismic reflection profiles made available valuable data on the seabed sediments types. These data provided the geomorphological and acoustic basis to design a ground-truth planning strategy allowing for precise habitat mapping. Navigation during the surveys was via differential GPS Simrad GN33 using satellite corrections integrated into an inertial-aided Seapath 200 system. Swath-bathymetric data were acquired using a hull-mounted Kongsberg-Simrad EM 302 multibeam echosounder (288 individual beams, angular coverage up to 150°) operating at a frequency of 30 kHz. To correct the multibeam bathymetry, we carried out systematic casts of direct sound velocity profiles on the water column with an Applied Microsystems SV Plus equipment. Data processing included the removal of anomalies and the necessary sound velocity corrections using the Kongsberg–Simrad swath bathymetric software package NEPTUNE. Valid data were gridded at 50×50 m cell size resolution on a SUN workstation. The seismic parametric system Topas 18 produced very high resolution seismic profiles along all ship tracks. Sub-bottom penetration varied, according to the lithology, between 150 and 250 m. Morphometrical data were obtained using ArcGis (ESRI) and Fledermaus software (Interactive Visualization Systems [IVS]) to provide final 3D images of the seafloor morphology.

Samples of benthic fauna analysed in this study were collected with the Lofoten bottom trawl gear itself. Benthic fauna samples were sorted on board and preserved (70% ethanol or 4% buffered formaldehyde-seawater solution) for further identification analysis. Even if the bottom-trawl by-catch collected information did not allow for a detailed habitat mapping of VMEs, it provided a valuable indication of VME presence/absence that can be used to propose conservation measures, such as candidate areas for bottom fishery closures [23].

Sediment samples were collected using net collectors attached to the Lofoten fishing gear (Atlantis 2008 cruise) and with an USNEL type box-corer (BC) (maximum breakthrough of 60 cm; effective sampling area of 0.25 m^2 [50×50 cm]). A few samples were taken using a Bouma type box-corer (effective sampling area of 0.0175 m^2 [10×17.5 cm]). Both gears are designed to take undisturbed samples from the top of the seabed, and are suitable for almost every type of sediment. Sediment temperature and redox profiles (Eh) were immediately performed for the box-corer sample after each station. In the laboratory, the granulometrical analysis of the sediment was carried out by dry sorting the coarse fraction (>62 μm) and the sedimentation of the fine fraction (<62 μm). The organic matter content was assessed after calcinating (at 500°C for 24 h) and drying the sediment sample.

The hydrographical conditions in the studied area during the Atlantis 2008 cruise were characterised by means of a Seabird-25 CTD probe (SBE-25), equipped with oximeter, fluorometer and PAR detector. The survey schedule was optimized by systematically deploying the CTD at fishing stations below 500 m, but not always at greater depths. At each cast, the CTD was deployed to 5 m depth and stabilised for approximately 3 min. Once stable, the CTD was brought back to the surface and started profiling at a constant speed of 1 m·s^{-1}. The SBE-25 worked in auto-contained mode at a frequency of 8 scans·s^{-1} and the downloaded data were converted into physical units and pre-processed by using the SeaBird software (SeaSave/SBE DataProcesing-win32) with standard calibration values. Quality control and post-processing was performed with MATLAB.

Atlantis 2008 stratified bottom trawl survey enabled the assessing of the biomass and bathymetric distribution of the main commercial and most abundant fishery stocks by means of the swept area method. The survey used a stratified random design with strata boundaries definedby latitude and depth ranges, depth strata 1-7 located south of parallel 45°S and depth strata 8-13 sited north of the referred parallel (Table 2). Scheduled fishing stations (hauls of 30 min) were performed using a Lofoten bottom trawl net fitted with a rockhopper mix train with bobbins and rubber separators, suitable for deep-water fishing over irregular bottoms. Mean trawl speed was of 3.2 knots and trawl direction followed the bathymetric profile in the upper slope, but was variable in the outer shelf and middle slope.

Data recorded by scientific onboard observers from 1989 to 2007 between latitude 42°S and 48°S were used for mapping only the Spanish fishery footprint, since fishing data of other fleets were unavailable to us. The IEO observers' program placed one observer per selected vessel to cover 12% to 15% of the whole fleet. Table 3 summarize the activities (number of hauls year^{-1}) of the IEO observers on the HS of the SW Atlantic, were Divisions 42 and 46 correspond to the areas roughly around parallels 42°S and 46°S.

Data used for each fishing haul corresponded to the middle tow position, since it offers more relevant information than the initial or final positions. All middle tow positions were imported into ArcGIS 9.3 mapping software to plot all trawl tows as straight lines between the reported start and end positions. They were then exported to a grid of 5'×10' min blocks, and any block including at least two tows was retained for mapping the bottom trawl footprint.

Strata	Depth range (m)	Surface (mn²⁾)	No. of grids (~5 mn²)	No. of scheduled hauls	No. of hauls made	
					Valid	Null
1	<200	1148	219	12	12	
2	201-300	272	51	3	4	
3	301-400	381	71	4	3	
4	401-500	518	119	7	7	
5	501-700	1513	318	18	18	
6	701-1000	1952	349	20	20	3
7	1001-1500	2007	435	24	2	5
8	<200	1394	254	14	15	
9	201-300	111	24	2	2	
10	301-400	121	21	2	2	
11	401-500	78	26	2	2	
12	501-1000	933	170	10	12	
13	1001-1500	2507	515	29	26	5
Total		12933	2571	147	125	13

Table 2. Scheme of hauls by depth stratum, and main characteristics (ATLANTIS 2008 cruise).

Year	Division 46	Division 42	Total
1989	756	734	1490
1990	411	222	633
1991	152	28	180
1992	561	9	570
1993	515	0	515
1994	469	0	469
1995	186	0	186
1996	310	21	331
1997	811	35	846
1998	709	0	709
1999	384	4	388
2000	590	44	634
2001	673	111	784
2002	452	142	594
2003	191	0	191
2004	472	0	472
2005	561	1	562
2006	477	0	477
2007	333	0	333
Total	9013	1351	10,364

Table 3. Number of hauls/year and division recorded by scientific observers.

Proper identification of the areas where VMEs are present followed the methodology used by the NAFO in its Regulatory Area [60]. Threshold catches, defined as catch levels of significant concentrations of invertebrates to be considered as possible VME areas, were assessed by analysing the cumulative biomass frequencies. Cumulative catch curve method was chosen to calculate the threshold catch. The cumulative frequency was plotted for all capture sets where taxa, considered as vulnerable by the International Guidelines for the Management of Fisheries [54] and by the Convention for the Protection of the marine Environment of the North-East Atlantic (OSPAR), were identified. The threshold selection for each taxon was made on the basis of minimum/maximum catch, density and morphological characteristics. Once a location of significant concentrations of vulnerable organisms was defined (key location), a 2 nm radius buffer zone around it was drawn to provide a safe margin of error on site.

The Random Forest algorithm for classification (RF) was used to predict the potential distribution of vulnerable benthic species by rating environmental conditions on the basis of previous observations.

RF is a non-parametric statistical method for data analysis that makes no distributional assumptions about the predictor or response variables [61], showing high prediction accuracy classifying rocky benthic communities [62] and beating other methods commonly used for ecological prediction [61,63]; The algorithm calculate the suitability of a given habitat for a given species based on known affinities with habitat characteristics, stored as raster maps, and called independent ecogeographical variables (EGV). According to HSI values, a map of species' expected distribution is produced, a value ranging from 0 to 1 showing the probability that the habitat of a given location is suitable for the species occurrence [64]. Thus, for a particular location, high HSI values mean high chances of the species' occurrence. To perform this mapping, presence/absence data from different vulnerable benthic organisms found in the study area were used as dependent variables of the different EGV.

Gathering accurate sampling presence/absence data is a critical part of the study, since the absence of a species in a given location can be due to several reasons: the species is present but is not observed, the species is absent even though the habitat is suitable, or the species is absent because of the unsuitability of the habitat. Only the last reason is considered as a "true absence" [65,66]. As presence data were aggregated into one single group named "vulnerable organisms", the resulting HSI predicted the potential habitat of any of the considered vulnerable organisms in the HS of the SW Atlantic under study.

The RF method offers the possibility to calculate an accurate unbiased estimator, using Out-Of-Bag (OOB) observations as an internal validation data set [67], computed from the resulting confusion matrix [68]. Accuracy is the proportion of the total number of predictions that were correct and this accuracy indicator is offered to the user as a measure of the model's predictive performance. It is determined using the equation:

$$ACC_{OOB} = \frac{TS + TU}{N}$$

Where TS is the number of truly suitable locations, i.e. suitable locations correctly classified by the model; TU is the number of truly unsuitable locations, in other words unsuitable locations that have been correctly classified; and N is the total number of observations.

Data was analyzed using the R statistical software [69] and the "Random Forest" package [70] and predictions were exported to a shapefile format using the "maptools" package [71]. GIS visualization of results was performed using the ESRI ArcMap 10.0 software.

Selected environmental variables involved in the study included depth, slope, sea bottom temperature, substrate characteristics and topographic position (Table 4). The topographic position was sorted into six categories: shelf (1), outcrop areas on the shelf (2), high slope (3), low slope (4), abyssal flats (5), and canyons (6).

	Variable	Type of variable	Range (min- max)
Hydrography	Sea bottom temperature	Continuous	1.70ºC – 6.14ºC
Topography	Bathymetry	Continuous	110.1m – 1848.6m
	Slope	Continuous	0º – 14.792º
Substrate characteristics	Q50	Continuous	2 – 3.59
	Coarse sand fraction	Continuous	0.17% – 11.2%
	Fine sand fraction	Continuous	57.2% – 97.28%
	Mud fraction	Continuous	2.17% – 41.31%
Topographic position	Seabed morphology	Discrete	1 – 6

Table 4. Summary of the environmental variables used for the Habitat Suitability Index (HSI) modelling of vulnerable organisms.

CTD stations' sea bottom temperature data were interpolated for the whole area using the local polynomial interpolation function (LPI) implemented in the ArcGIS 10.0 software. Slope was derived from the bathymetry high resolution data, and after studying the semivariogram, substrate characteristics were interpolated from granulometrical measures for the whole area using a universal kriging interpolator (Unpublished).

All the explanatory data were extracted for the presence/absence data locations, subsequently exported and analysed with the R statistical software using the BIOMOD package [72]. Several presence/absence models were performed: Generalized Additive Models [73,74], Multivariate Adaptative Regression Splines [74,75], Generalized Boosting Models [74,76] and Random Forest model (RF) [67,74].

3. Results

3.1. Geomorphology

Geomorphological and geophysical data from the five research cruises revealed that the outer shelf was mantled by 15 m high sand ridges, and was 60 to 67 m deeper than the maximum 120 m lowering of sea-level during the last glacially induced regression. This difference in

depth indicates that the PS had experienced subsidence in the Holocene. These ridges are relict and were probably constructed during the post-glacial transgression by the north flowing Falkland (Malvinas) Current, since they are resting on shell layers of <35,000 to 11,000 years old [77].

The upper continental slope descends from the shelf break, located at depths from 200 to 750 m, and is scarred by iceberg plough marks whose orientation and morphology suggest that icebergs carried northwards by the Falkland (Malvinas) Current were probably responsible for this erosion during the last glaciations [78].

Scattered over the study area (south of 45°S) we found pockmarks, carbonate mounds formed by deep-water corals, northwards furrows, areas of smooth topography and sediment waves indicating that deposition on this part of the middle slope is controlled by bottom currents [79].

Seven submarine canyons were identified on the middle slope surveyed (Figure 2). Canyons 1 to 6 were cut by turbidity currents, whereas canyon 0 resulted from the combined effect of turbidity currents and coalescence of pockmarks (formed by the expulsion of thermogenic gas). These gas and fluid seepages contributed to the formation of canyons and to the partial detachment of blocks from the canyon walls. Thus, the thermogenic gas responsible for the formation of the identified pockmarks on the middle slope could be deep-seated, probably related to the Falkland Rift Basin, north of the Falkland (Malvinas) Islands [80,81].
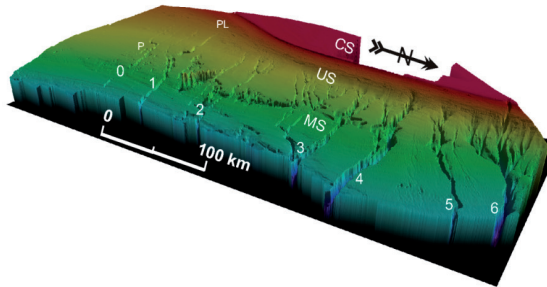

Figure 2. Colour shaded 3D bathymetric map of a segment of the Patagonian Argentinian margin compiled from multibeam backscatter data. Arabic numbers identify submarine canyons discussed in text. CS=Continental shelf; US=Upper continental slope; MS=Middle continental slope; P=Pockmark; PL=Iceberg plough marks.

The association of gas seepage with deep-water corals has been reported by [82] in pockmarks off Brazil. If such association also occurs on the Patagonian margin, those communities may be quite widespread in our study area.

3.2. Benthic communities

Bathelia candida (Moseley, 1881) was found to be one of the main reef builder species in the study area, providing habitat for diverse associated fauna of sponges, crustaceans, echinoderms, molluscs, and other cnidarians. The benthic megafauna caught during the cruises

included invertebrates as well as Phyla Chordata and Hemichordata. Phyla Cnidaria and Porifera were dominant in terms of biomass (46% and 30%, respectively [Figure 3A]). The high abundance of Cnidaria is remarkable, since 33.7% of the biomass of this phylum corresponded to the Class Octocorallia, including significant groups such as gorgonians (sea fans), alcyona‐ceans (leather corals) and pennatulaceans (sea pens). In addition, the VMEs dominated by suspensivore and/or filter feeding organisms are habitats with high biodiversity and many resources.
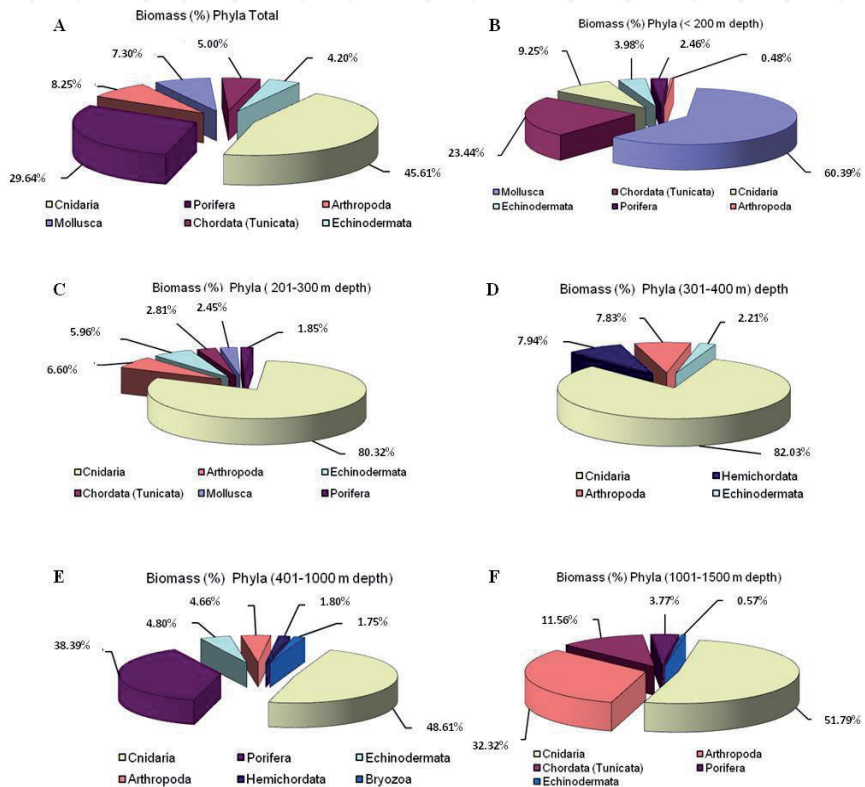
Figure 3. Biomass per Phyla in total strata (A) and by stratum < 200 (B), 201-300 (C), 301-400 (D), 401-1000 (E), 1001-1500 m depth (F).

A large part of the benthic samples contained erect sponges, octocorals, colonial scleractini‐ans, calcified antipatharians, and hydrozoans (Family STYLASTERIDAE), all of them slow-growing organisms considered as vulnerable by the UN and the OSPAR standards (see Table 7).

Bathymetric strata differences clearly arise by comparing the composition of the sampled benthic megafauna (Figures 3B-F):

Strata 1 and 8 (<200 m) showed a low catch of benthos (17,209 and 41,202 g. respectively), both in number and diversity. We observed a strong dominance of pectinid molluscs of the Genus *Zygochlamys* (Ihering, 1907) (60.39% of the biomass [Figure 3B]), mainly *Z. patagonica* (King & Broderip, 1832), followed by those of the Genus *Chlamys* (Röding, 1798). Vulnerable organisms were practically unrepresented in these shallower strata, probably due to the bottom trawling activities for years by bottom trawlers from international fleets.

Strata 2 and 9 (201-300 m) recorded the lowest catch in terms of biomass (2121 and 1576 g, respectively). In these strata, detritivorous and opportunistic species were predominant, and the presence of vulnerable organisms was negligible again. Compared to strata 1 and 8, we observed an increase of the benthic cnidarians' biomass values, dominated by gorgonians from Family PRIMNOIDAE (Milne Edwards, 1857) (Octocorallia; Gorgonacea) (80.32% in biomass, [Figure 3C]).

Strata 3 and 10 (301-400 m) were hardly sampled due to the reduced number of valid hauls (3 in stratum 3 and 2 in stratum 10). The low benthic biomass and the negligible presence of vulnerable organisms (Figure 3D) could be attributed to bottom fishing activities, as above-mentioned for strata 1 and 8.

Strata 4, 11, 5, 6, and 12 of intermediate depths (401-1000 m, [Figure 3E]) recorded high biomass and numbers of octocorals, sponges, colonial scleractinians (*Bathelia candida*), and large hydrocorals. Octocorals included colonies of various genera belonging to families PRIMNOI-DAE and ISIDIDAE. As aforementioned, the increase and proliferation of these species create complex 3D structures providing the ideal habitat for a wide range of organisms. In those strata, the large amount of filter feeders and suspensivore sessile organisms is an indication of the presence of unaltered, complex and structured ecosystems. In the future, ROV and other submersible camera systems could confirm these assumptions.

Strata 7 and 13 (1001-1500 m, [Figure 3F]) were the most difficult ones for trawling. Numerous tows failed to produce valid results. In these strata, the highest proportion of animals was of benthopelagic crustaceans, usually making diel migrations, even though they were normally present on the seafloor. Benthic cnidarians were dominated by octocorals of the Order PENNATULACEA (Verrill, 1865), with a wide bathymetric distribution, adapted to live on soft substrates.

3.3. Sediments

Sediment data obtained during Patagonia 1207, Patagonia 0108, and Atlantis 2008 cruises showed that fine sands were generally predominant throughout the study area, with low contents of organic matter and sediment sorting varying from poor to moderately good. In more detail, the bathymetric sedimentary classification would be as follows:

Depths <200 m: fine sand (mean diameter=210 µm) with low organic matter content (mean value=1.14 %), moderately sorted.

Depths from 201 to 400 m: fine sand (mean diameter ranging from 150 to 189 µm) with low organic matter content (mean value=1.06%), moderately well sorted.

Depths from 401 to 700 m: very fine sand (mean diameter from 110 to 120 μm) recording the highest organic matter content (mean value ranging from 2.23% to 2.35%) and also the highest percentage (up to 44.50%) of silt and clay (<62 μm). Sorting was poor to moderate.

Depths from 701 to 1500 m: fine sand sediments similar to those of the shallowest stratum (mean diameter 160 to 190 μm), with low organic matter contents (mean value ranging from 1.43% to 1.68%). Moderately sorted.

Depths >1501 m: the deepest stratum, located in the bottom of submarine channels and canyons, was characterised by the presence of heterogeneous sediments mainly composed of fine sand (mean diameter=200 μm), with low organic content (mean value=1.68%) and poor sorting. This stratum showed the highest percentage (up to 39.5%) of coarse particles (>500 μm).

3.4. Fishery footprint

The statistical analysis of the bottom trawl footprint plot generated with the georeferenced fishery data obtained by the IEO scientific observers (between 1989 and 2007, 9013 fishing operations) showed that most of the commercial hauls of the Spanish fishing fleet in the study area (99.85%) took place at depths below 300 m (Figure 4).
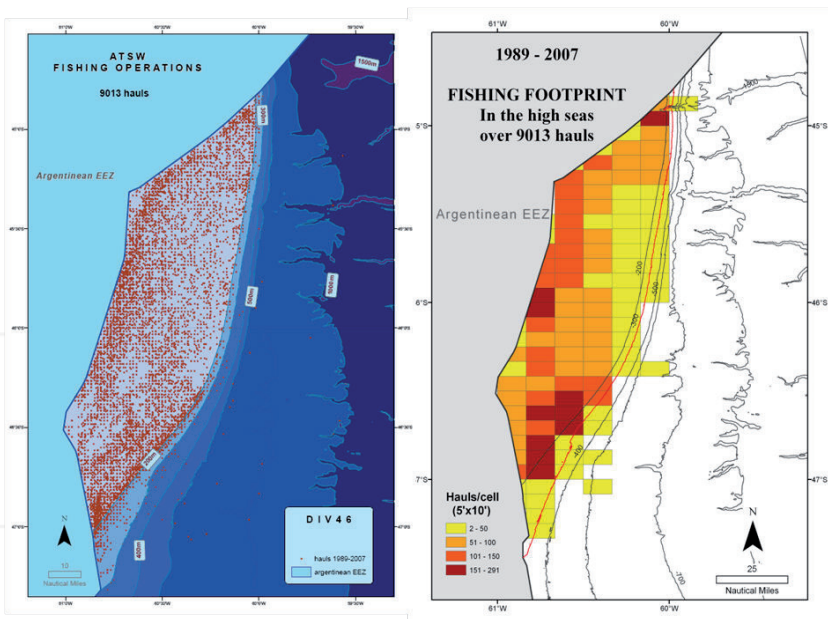
Figure 4. Location of commercial hauls and fishery footprint (5'×10') of the Spanish bottom trawl fleet on the HS of the SW Atlantic (1989-2007).

4. Multivariate analysis

4.1. Model selection

Predictive accuracy of the models was evaluated through multiple cross-validation proce-
dures, splitting the original data three times into two random subsets for calibration (80% data)
and evaluation (20% data). The mean area under the receiver operating characteristic (ROC)
curve (AUC) obtained from the three repetitions served to assess the predictive performance
index of the model. AUC ranks from 0.5 to 1, null accuracy or perfect accuracy of the model,
respectively [83]. Table 5 shows the best predictive performance score of the RF model, which
was subsequently chosen for vulnerable species modelling.

Model	Mean cross validation score
RF	0.876
GBM	0.825
MARS	0.804
GAM	0.778

Table 5. Validation of the predictive performance of the four candidate presence/absence models tested (RF: Random
Forest; GBM: Generalized Boosting Model; MARS: Multivariate Adaptative Regression Splines; GAM: Generalized
Additive Model).

4.2. Variable influence

The Mean Decrease Gini method, implemented in the BIOMOD package, was used to measure
the importance of the dependent variable. This exploration tool shows graphically the total
decrease in node impurities from splitting on the variable, averaged over all trees. Thus, for
classification, the node impurity is measured by the Gini index [72]. The higher the value in
the X axis, the higher importance the indicated variable will have on the classification of the
dependent variable. Figure 5 show that the topographic position is the main variable affecting
the distribution of vulnerable organisms in the HS of the PS, followed by the slope and the sea
bottom temperature. Comparatively, the sea floor granulometry has a negligible effect on the
distribution of the vulnerable organisms.

In addition to this, it is possible to visualize how each environmental variable, independently
from any other, influences the response variable using partial dependence plots [73], which
graphically represents the relationships between each predictor variable and the predicted
occurrence probabilities of the vulnerable organisms obtained from the RF model. Figure 6
show that bathymetry has a positive effect between 500 and 1000 m depth. Regarding the
topographic position, the highest interactions with the presence of vulnerable organisms were
observed in canyons (6), followed by abyssal flats (5) and the slope (3 and 4). On the shelf, only
outcrop areas (2) were positively correlated with the dependent variable.
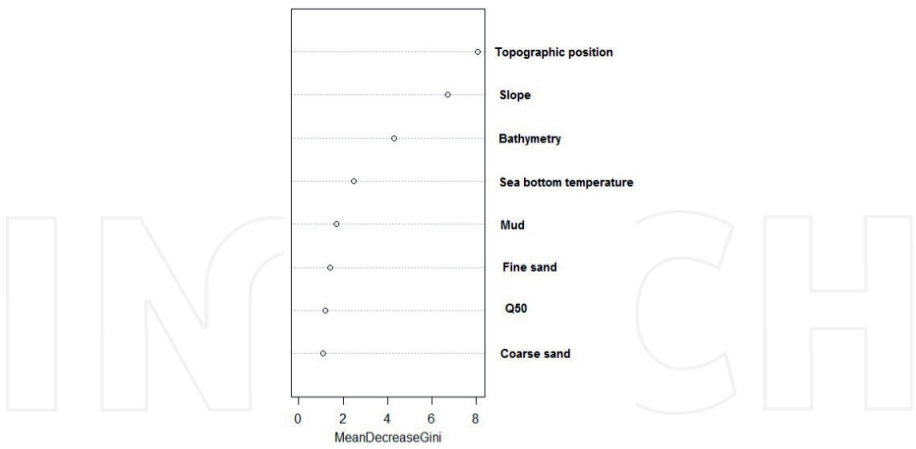
Figure 5. Mean Decrease Gini for each explanatory variable in the RF model. Higher values in the X axis indicate high-er influence of the environmental variable on the occurrence of benthic vulnerable organisms.
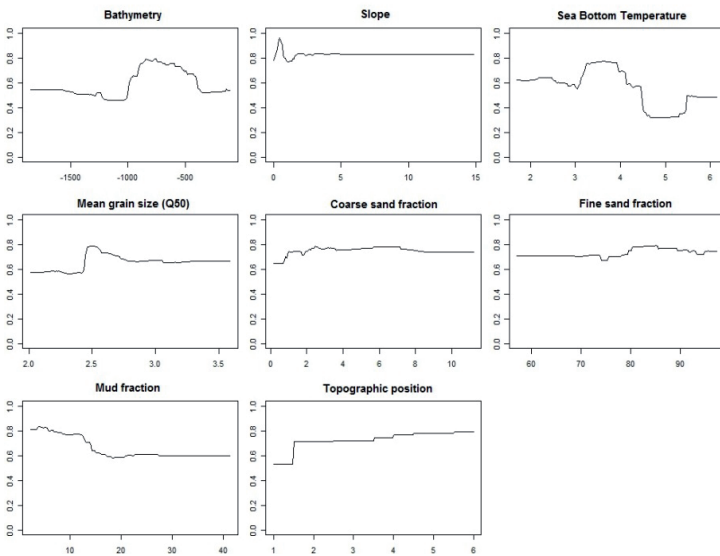
Figure 6. Partial dependence plots showing quantitative influence from each environmental variable on the occurrence of benthic vulnerable organisms predicted probability.

4.3. HSI mapping

Table 6 shows the presence data of benthic vulnerable organisms from the 169 sampled locations. Predicted values were plotted to produce a habitat suitability map showing survey sampling stations with presence/absence data and the vulnerable organisms' probability of occurrence (Figure 7).

Organism	Presence
Alcyonacea	15
Bathelia candida	23
Demospongiae	22
Gorgonacea	24
Hexactinellidae	14
Hydrozoa	41
Pennatulacea	7
Rhodalidae	9
Stylasteridae	25
Total VO	**76**

Table 6. Summary of the presence sampling data of vulnerable organisms (VO).
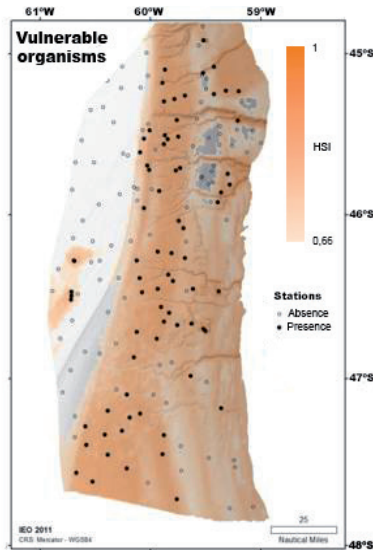

Figure 7. HSI map of benthic vulnerable organisms. Higher probability of occurrence is shown in darker tones. Survey sampling stations are overlapped, showing presence (black dot) or absence (circle) of such organisms.

5. Conclusions

Multibeam acoustic data showed that the upper slope and uppermost middle slope were scarred by iceberg plough marks. The middle slope surveyed was entrenched by seven submarine canyons [78]. Pockmarks and other seismic and morphologic evidence of gas/fluids seepage were pervasive throughout the entire survey area and more intense in the southern middle part [80]. Water coral communities associated with those pockmarks could be quite extensive in the study area.

The highest benthic biodiversity was found between 800 and 1500 m depth. Biodiversity was higher along the continental margin (per an equal number of individuals, and in terms of abundance) than biodiversity found along the continental shelf. Our results have confirmed the existence of close ecological relationships between Patagonian deep-sea fauna and Antarctic fauna of shallow waters. Benthic megafauna collected included invertebrates, chordates, and hemichordates. There was a clear dominance in biomass and diversity of the Phyla Porifera and Cnidaria. Most species of these groups are considered as vulnerable according to UN and OSPAR criteria: sponges, octocorals, colony scleractinians, anthipatarians, calcified hydrozoans (Family STYLASTERIDAE), and erect bryozoans (Table 7).

Shallow waters (<400 m) are the strata having sustained most of the fishing pressure for almost 50 years. Below 400 m we recorded the lowest biomass, abundance and diversity values, most likely due to this fishing pressure. In these strata we noted the presence of sparse organisms with erected growth, a high dominance of pectinid mollusks (*Zygochlamys patagonica*), and minor presence of species considered as indicators of VMEs.

Intermediate depths (401-1000 m) showed an important increase in number and biomass of vulnerable organisms, with outstanding numbers, densities and biomasses of octocorals, sponges, colony scleractinians (*Bathelia candida*) and big hydrocorals (*Errina* spp., *Cheiloporidion pulvinatum* [Cairns, 1983], *Sporadopora* sp., and *Stylaster densicaulis* [Moseley, 1879]). Also remarkable was the presence of sponges of the Family CLADORHIZIDAE (Dendy, 1922), a group of a great zoological importance because they are carnivorous and have developed a trophic adaptation to live in the ocean's depths.

In deeper strata (1001-1500 m) we found more anomuran crustaceans of the Family LITHO-DIDAE (Samouelle, 1819) (mainly *Paralomis formosa* [Henderson, 1888]). Amongst benthic cnidarians, the pennatulid octocorals (Order PENNATULACEA) were the most abundant.

The model accuracy is acceptable (0.876). Although the modelling' accuracy values were higher when considering each organism, this was an expected fact due to the different environmental preferences of the studied organisms. However, HSI mapping is a useful conservation management tool enabling an initial observation of how environmental conditions control the spatial distribution of vulnerable organisms in the study area. The research will proceed further when data from all 13 survey cruises undertaken in the area are analysed.

The main environmental conditions affecting presence of vulnerable organisms seems to be connected to the topographic position, slope and bathymetry. Sea bed granulometry appeared

Porifera Grant, 1836	*Chondrocladia* sp.
Class Hexactinellida Schmidt, 1870	*Euchelipluma* sp.
Rossella antarctica Carter, 1872	*Mycale* (*Oxymycale*) *acerata* Kirkpatrick, 1907
Class Demospongiae Sollas, 1885	*Mycale* (*Carmia*) *gaussiana* Hentschel, 1914
Tetilla leptoderma Sollas, 1886	*Isodictya kerguelenensis* Ridley & Dendy, 1886
Cynachyra sp	*Latrunculia* sp.
Geodia sp.	Axinellidae indet.
Polymastia sp.	*Haliclona* (*Haliclona*) sp.
Radiella sp.	*Haliclona* (*Gellius*) sp.
Tentorium sp.	Dictyoceratida indet.
Stylocordyla cf. *stipitata*	**Cnidaria Hatschek, 1888**
Timea sp.	**Class Hydrozoa Owen, 1843**
Lithistidindet.	*Errina* sp.
Iophon sp.	*Stylaster* cf. *densicaulis*
Clathria sp.	**Class Anthozoa Ehrenberg, 1831**
Raspailia sp.	*Alcyonium* sp.
Inflatella sp.	*Anthomastus* sp.
Pyloderma latrunculioides Ridley & Dendy, 1886	*Paragorgia* sp.
Desmacidon, sp.	*Primnoella* sp.
Hymedesmia (*Hymedesmia*) sp.	Isididae indet.
Hymedesmia (*Stylopus*) sp.	*Anthoptilum* sp.
Phorbas sp.	*Halipteris* sp.
Myxilla (*Myxilla*) *mollis* Ridley & Dendy, 1886	*Epizoanthus* sp.
Myxilla (*Burtonanchora*) *lissostyla* Burton, 1938	*Actinostola crassicornis* Hertwig, 1882
Tedania (*Tedaniopsis*) *charcoti* Topsent, 1907	*Bathelia candida* Moseley, 1881
Tedania (*Tedaniopsis*) *oxeata* Topsent, 1916	*Caryophyllia* sp.
Tedania (*Tedaniopsis*) *massa* Ridley & Dendy, 1886	*Desmophyllum* sp.
Tedania (*Trachytedania*) sp.	*Flabellum* sp.
Asbestopluma sp.	

Table 7. Cold-water corals and deep-water sponges concentrations: list of most common species collected in the campaigns of the Atlantis Project in 2007 and 2008.

to have a negligible effect on the presence of vulnerable organisms, contradicting published research results on this subject in other geographical areas, where substrate characteristics determine to a large extent the presence or absence of a particular benthic species [84-86].

Our study only calculated the general trends of the granulometrical parameters, while bathymetry, slope and topographic position were variables derived from high resolution data, strongly correlated with the response variable. Therefore, local conditions are the main factors ruling the potentiality of a habitat to host benthic vulnerable organisms in the HS of the PS.

The use of the Random Forest model offers both higher classification accuracy and determination of variable importance, and more stability where small perturbations of the data exist [76]. RF is a predictive classification and algorithm that does not make any distributional assumptions about the predictor or the response variables. It also handles situations in which the number of predictor variables exceeds the number of observations, offering a powerful non parametrical alternative for ecological modelling [64].

The vulnerable species groups, communities and habitats described here are mainly distributed beyond the 500 m depth contour. The presence of organisms considered as vulnerable is almost negligible in the fishing area. This fact is almost certainly due to bottom trawling operations of international fleets taking place in the study area for nearly 50 years. Also, the fishing grounds are far away from the geographical location of the main geomorphological features such as canyons, trenches, gas and fluid seepages observed in the middle slope, and identified as potential sites for VMEs.

The fishery footprint plot shows that the historical activity of the Spanish bottom trawler fleet has been located in the shallowest depth strata, at depths not generally exceeding 300 m. On this basis we think that the adverse impacts of current bottom fishing activities on VMEs are negligible or small. However, the displacement of the fishing fleet to target deep sea species at greater depths (were the existence of VMEs has been observed) could have a negative impact on those ecosystems. With this in mind and following the FAO deep-water guidelines, the potential threat of such a fishing strategy should be assessed.

Apart from Spanish fishing fleet, other bottom trawling fleets from different nations (former Soviet Union, Poland, GDR, Bulgaria, etc) have been operating intensively in the SW Atlantic (including our study area) from mid 60's until mid 80's, both over the continental shelf and slope [87-92]. Even if no data were made available to us for assessing the eventual negative impact of these fleets on VMEs, some experiences in other geographical areas such as the North Atlantic, Southwest and East Pacific, seamounts off Tasmania, and waters off New Zealand [31,45,92], have shown that high fishing pressure exerted by a large number of bottom trawlers over a long period of time could relevantly affect these VMEs. We therefore think that probably the almost 50 years of intensive bottom trawling in this SW Atlantic area by the abovementioned fleets could have contributed to the low presence of VMEs in the study area at depths lower than 500 m.

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Author details

J. Portela[1*], J. Cristobo[2], P. Ríos[2], J. Acosta[3], S. Parra[4], J.L. del Río[1], E. Tel[3], V. Polonio[2], A. Muñoz[5], T. Patrocinio[1], R. Vilela[1], M. Barba[1] and P. Marín[5]

*Address all correspondence to: julio.portela@vi.ieo.es

1 Spanish Institute of Oceanography (IEO), Vigo Oceanographic Center. Fisheries Dept. Vigo, Spain

2 Spanish Institute of Oceanography, Gijón Oceanographic Center. Benthos Dept. Gijón, Spain

3 Spanish Institute of Oceanography, Headquarters Madrid. Geology Dept. Madrid, Spain

4 Spanish Institute of Oceanography, A Coruña Oceanographic Center. Epibenthos Dept. A Coruña, Spain

5 Multidisciplinary Mapping Group (TRAGSATEC-SGP), Spanish General Secretariat for Fisheries (SGP). Cartography Dept. Madrid, Spain

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