



Effects of a large-scale and offshore marine protected area on the demersal fish assemblage in the Southwest Atlantic

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There are few extensive and offshore located marine protected areas (MPAs) in the world oceans and their performance is still being debated. We evaluated the effects of a large-scale offshore MPA located on the Southwest Atlantic Patagonian Shelf (43°S 63°W) on the demersal fish assemblage. Compliance of the Patagonian MPA was assessed by analysing eight years of satellite vessel monitoring system (VMS; 2000–2008) data, which showed compliance and fishing effort concentrated near the protection boundaries. MPA effects were studied by employing a five year database collected by a scientific research vessel in protected and fishing locations, before and after the MPA establishment. We assessed 152 scientific trawling stations using multivariate analysis of fish assemblage structure, fish abundance (discriminating target and non-target species), and mean size and proportion of juveniles of the target species (Argentine hake, *Merluccius hubbsi*). The identified MPA effects were a trend towards increasing abundance of the demersal fish assemblage, the target and non-target fish species, and hake juvenile size, and a higher proportion of juveniles aged 2+ inside the MPA. These positive trends support the case for offshore, large-scale MPAs.

Keywords: abundance, closed area, fish size, fishing effort.

Introduction

The decline of marine resources is of global concern and very restrictive rebuilding measures, such as large-scale fishery closures, are being implemented (Worm *et al.*, 2009). The establishment of marine protected areas (MPAs) seems to be one of the potential solutions to this ecological crisis (e.g. Roberts, 2012). There is global interest in the use of protected areas as a management measure (e.g. Hilborn *et al.*, 2004; Worm *et al.*, 2009), and their performance needs to be assessed. However, MPAs alone are not enough to reduce fishing pressure, as there is a trade-off between recovery in the MPA and decline in the areas to which the fishing effort is displaced (Greenstreet *et al.*, 2009). Many studies have debated the effectiveness and limitations of MPAs for conserving and managing marine resources (e.g. Jones, 2007; Lester *et al.*, 2009).

Most MPAs are relatively small in size, and they are mainly located in tropical near-shore habitats (e.g. Halpern, 2003). Only a few large-scale MPAs have been established in offshore areas

(i.e. continental shelves, oceanic environments; see Murawski *et al.*, 2000; Blyth-Skyrme *et al.*, 2006; Game *et al.*, 2009). In particular, MPAs are scarce in the South Atlantic coasts of America, and although there are fishery management areas, there is a lack of comprehensive studies of the existing MPAs.

The Southwest Atlantic includes the Patagonian Shelf Large Marine Ecosystem (PSLME; Sherman, 2005), which is one of the most productive areas in the ocean world and the largest shelf area in the southern hemisphere (e.g. Acha *et al.*, 2004). There are several important fishery resources in the PSLME. Argentine hake (*Merluccius hubbsi*) sustains one of the most important fisheries over most of the Argentinean Patagonian Shelf. The Argentine hake stocks were overexploited by the mid-1990s (Aubone, 2004) and by the end of 1997 an extensive year-round fishing closure, the Patagonian closed area (PCA), was established in the PSLME to protect Argentine hake juveniles and spawners (Argentinean “Secretaría de Agricultura, Ganadería, Pesca y Alimentación”; SAGyP Res. No. 930/97; Figure 1). In terms of

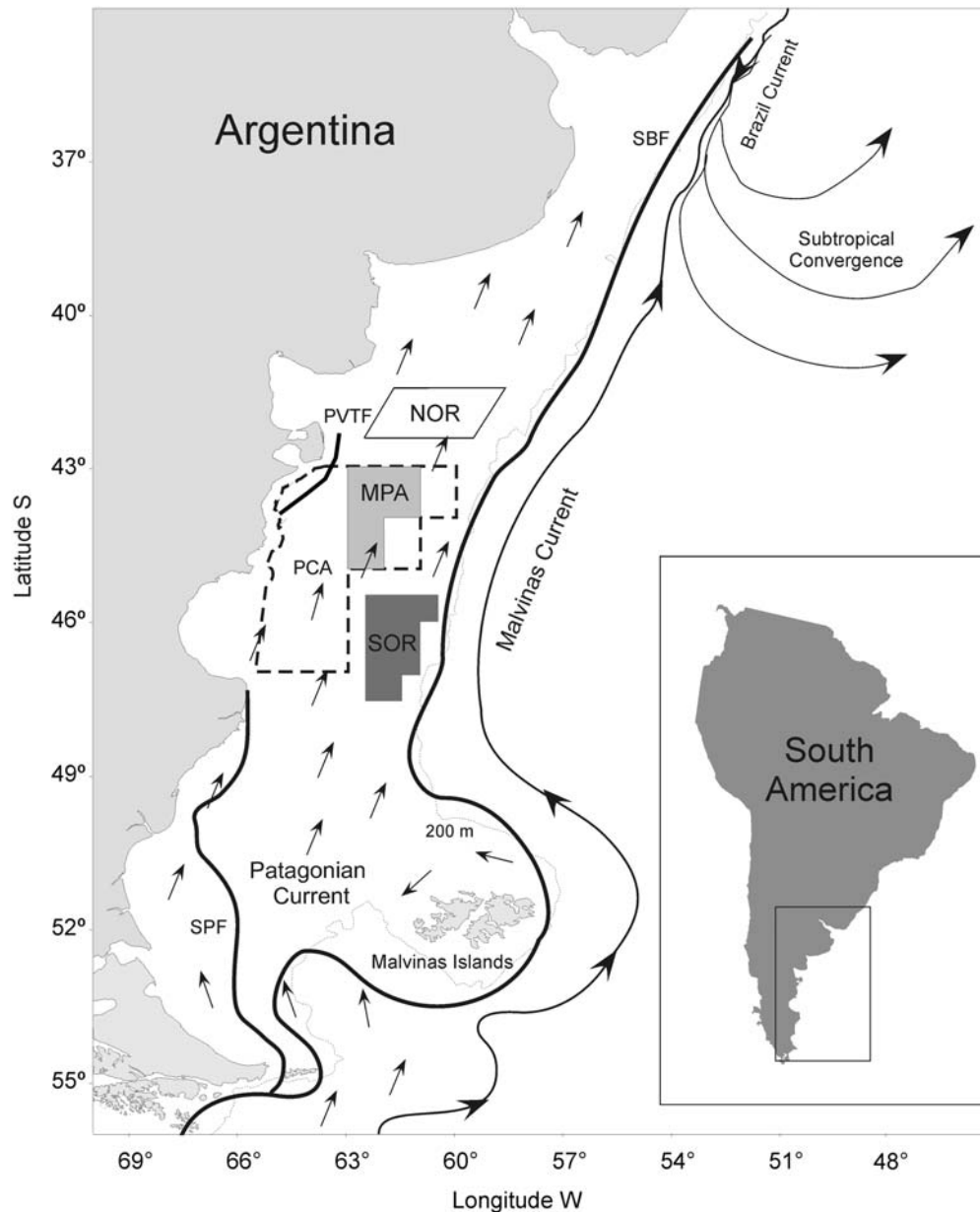


Figure 1. Study area in the Patagonian Shelf Large Marine Ecosystem. The Patagonian closed area (PCA; dotted line) established at the end of 1997 and the three zones analysed are shown: MPA (marine protected area; light grey background), NOR (northern fishing area outside the reserve boundaries; white background), and SOR (southern fishing area outside the reserve limits; dark grey background). Black arrows represent mean water circulation on the Argentine Continental Shelf, and black lines the main frontal systems (SBF = Shelf break front, PVTF = Península Valdés tidal front, SPF = Southern Patagonian front) in a schematic way (adapted from [Matano et al., 2010](#)).

fishery conservation, these year-round closures are considered analogous to MPAs ([Fisher and Frank, 2002](#)). The Patagonian MPA is quite large (119 000 km²) representing about 12% of the Argentine Continental Shelf (see [Figure 1](#)). Since this is one of the few large-scale offshore MPAs, we assessed its effects on the demersal fish assemblage. We are aware that sufficient spatial and temporal replication of a large-scale MPA is challenging and not always feasible but, nevertheless, some useful patterns for understanding MPA effects may emerge. Increases in fishing pressures usually drive population abundance and length distribution to decrease ([Rochet et al., 2010](#)). Fishing promotes age truncation, as

larger, older fish are removed, even at moderate levels of exploitation ([Berkeley et al., 2004](#)). MPAs are not only effective for increasing abundance, but they also induce changes in fish assemblage structure ([García-Charton et al., 2008](#)). As the Patagonian Shelf is an intensively fished region ([FAO, 2009](#)) positive effects of the MPA on the demersal fish assemblage can be expected.

We first assessed the compliance of fishing vessels by analysing eight years (2000–2008, 2002 not available) of fishing events (as a proxy for fishing effort) from VMS data. Then, we evaluated the performance of the Patagonian MPA as a fisheries management measure, assessing MPA effects on:

- (i) structure and abundance of the demersal fish assemblage, discriminating target and non-target species. We expected changes in fish assemblage structure due to protection and positive effects of the MPA on fish assemblage abundance; as reported for other regions (Babcock *et al.*, 2010), target species should respond more strongly than non-target species to protection;
- (ii) size of the target species (the Argentine hake), and the proportion of juveniles inside the MPA. We predicted larger fish within the protected area as MPAs protect larger/older individuals from fishing pressure (e.g. García-Charton *et al.*, 2008). Moreover, given that the PCA was implemented to protect juvenile hakes by closing their nursery grounds to fishing, we expected a higher proportion of juveniles inside the PCA.

Methods

Study site

The study site extends from 41°S to 48°S, covering much of the Argentine Continental Shelf, which is included in the Patagonian Shelf Large Marine Ecosystem (Figure 1). The Argentine Continental Shelf varies in width but is regular in topographical features. It is relatively narrow and shallow to the north (38°S) and becomes broader and deeper to the south (51°S; Matano *et al.*, 2010). Argentine Shelf waters are of sub-Antarctic origin and show a north-eastward mean flow (Palma *et al.*, 2008). In the study area three major, highly productive frontal systems occur: the Shelf Break Front, the Península Valdés Tidal Front, and the Southern Patagonian Front (Acha *et al.*, 2004).

The PCA is located in the central portion of the Argentine Continental Shelf, between 43°S and 47°S, covering almost 119 000 km² in 1998 (approximately 12% of the Argentine Continental Shelf; Figure 1). Although large parts of the area always remain closed to fishing, its shape and extent varied from year to year following the recommendations by the National Institute for Fisheries Research and Development (INIDEP, Argentina) to protect Argentine hake juveniles and spawning adults (Figure 2). Depth ranges between 50 m near the coast and down to 100 m at its offshore boundary. Fishing by trawlers was permanently banned inside the PCA since its legal establishment in December 1997 and, to date, only vessels fishing red shrimp (*Pleoticus muelleri*) are allowed to operate within certain peripheral regions inside the western edge of the PCA (Figure 2). Therefore, for our purposes, we selected a sub-area (hereafter the Marine Protected Area; MPA) that was never opened to any type of fishing (ca. 28 000 km²) to compare with adjacent non-protected zones. The study area was divided into three zones to assess spatial and temporal trends: (i) the MPA, and two unprotected areas: (ii) a fishing area north of the MPA boundaries (NOR), and (iii) a fishing area south of the MPA limits (SOR; Figure 1). The three areas for comparison were equivalent in size and depth range, and located in the same biogeographical region (Angelescu and Prenske, 1987). To avoid border effects, zones were separated at least by 0.5° latitude and/or 0.5° longitude.

Data source

Compliance in the Patagonian MPA

Since 1997 the Argentine administration adopted a satellite vessel monitoring system (VMS) to achieve a comprehensive control over the fleet and to preserve areas closed to fishing on the

Continental Shelf. Between 1997 and 2003, 66% of the fishing fleet (ca. 400 fishing vessels) was equipped with GPS and monitored at a low daily rate (i.e. 1–15 times a day) up to 2003. Since 2004, all fishing vessels are required to have GPS and the VMS records vessel position and speed every hour; making it impossible for fishing vessels to get into the MPA without being noticed. The VMS is the only enforcement mechanism to control the fleets. The complete VMS database from 2000 to 2008 was used to estimate a proxy for fishing effort inside each analysed zone.

All records from vessels performing bottom trawling for demersal fish were treated together (jigging vessels specializing in shortfin squid were discarded). Data were filtered to include only records with vessel speeds between 2 and 5 knots (3.7 to 9.3 km h⁻¹), which are typical trawling speeds. To test the hypothesis that fishing effort inside the MPA was lower than outside, we analysed VMS records from 2000 ($n = 71\,041$), 2001 ($n = 63\,464$), 2003 ($n = 78\,988$), 2004 ($n = 871\,224$), 2005 ($n = 1\,095\,985$), 2006 ($n = 1\,899\,706$), 2007 ($n = 1\,150\,012$) and 2008 ($n = 1\,159\,728$); 2002 records were not available due to financial constraints during Argentina's economic crisis. All fishing operations recorded in the Argentine Shelf were considered as 100% of fishing effort for each year, and the percentage contribution of each zone (NOR, MPA, SOR and remaining Shelf) was then calculated. We also investigated the spatial pattern of annual fishing effort on the Patagonian Shelf and MPA surroundings. ArcGIS (version 9.3; Environmental Systems Research Institute, Redlands, CA, USA) was used for data management and analysis; VMS positions were converted into a continuous raster using the kernel density estimation function (Spatial Analyst, ArcMap 9.3). Output cell size was 18.5 km (ca. 10'). Six density classes were defined based on Jenks' natural breaks classification method (Jenks, 1967), which determines the best arrangement of values into different classes. This method seeks to reduce the variance within classes and maximizes the variance between classes. The resulting density plots express fishing events per 10' latitude × 10' longitude square, and are uncorrected for differences in acquisition (ping) rate and number of equipped vessels.

Demersal fish assemblage

For demersal fish comparisons we utilized a database of fishery research cruises from the National Institute of Fisheries Research and Development (INIDEP, Argentina). We analysed five cruises focused on demersal fish assessment that covered most of the Patagonian Shelf before (1996) and after (2000, 2001, 2003 and 2005) the creation of the Patagonian MPA (Supplementary Table S1). Given the lack of research cruises covering the study area, no information was available after 2005. Data were collected during the cold season (July to October) by the Argentinean trawler RV "Dr E. Holmberg". Sampling stations were located following a random sampling scheme and distributed inside and outside the MPA, obtaining large spatial coverage using a bottom trawl (5 m vertical and 30 m horizontal opening, codend mesh size 2.4 cm). Trawls were performed at 4 knots (7.4 km h⁻¹) for 30 minutes. To enable comparison between trawling stations, only the 152 hauls whose swept area ranged between 0.07 and 0.09 km² were selected for the analyses; as this range is so narrow we analysed absolute catch weights (t) instead of CPUE. Total catch was sampled at each station and all fish species (identified on board to the lowest taxonomic level) were included in the demersal assemblage analyses. For Argentine hake (MPA target

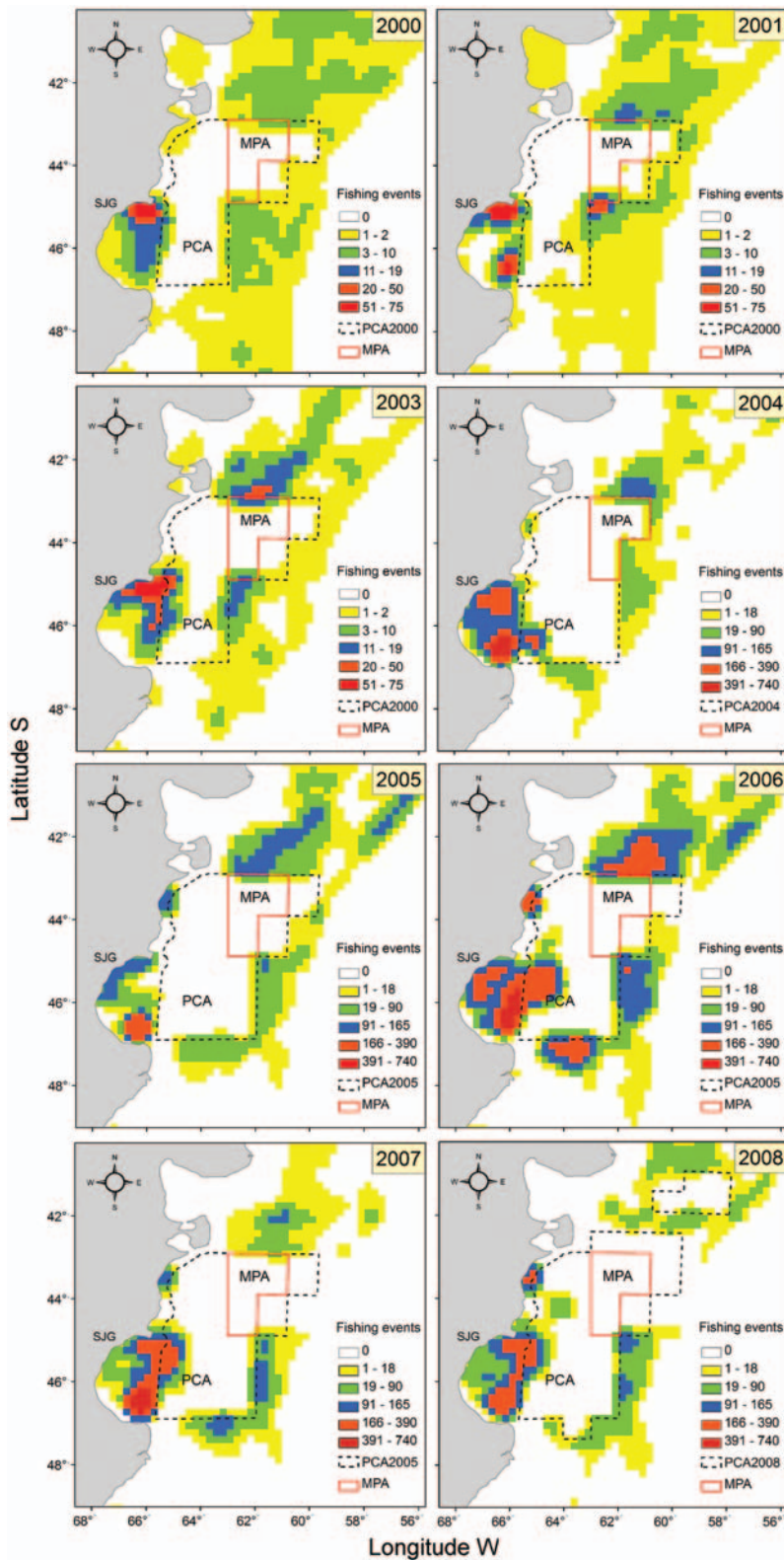


Figure 2. Spatial pattern of the fishing effort per year (2000–2008) on the Patagonian Shelf and MPA surroundings. Data were obtained from vessels using VMS (Vessel Monitoring System); acquisition frequency 1–2 a day up to 2003 and every hour from 2004. Kernel density plots express fishing events per $10'$ latitude \times $10'$ longitude squares (uncorrected for acquisition frequency), note that are two color scales: 2000–2003 and 2004–2008 (see the text). PCA = Patagonian Closed Area, MPA = Marine Protected Area, SJG = San Jorge Gulf.

species), sex and total length (L_T , accurate to 1 cm) of each individual were recorded for all hauls. Demersal hauls were ascribed to the three zones (NOR, MPA or SOR; Supplementary Table S1).

Data analysis

MPA effects on demersal fish assemblage structure and abundance

Since ecological data are mainly multivariate, we used the permutational multivariate analysis of variance (PERMANOVA) to evaluate spatial and inter-annual variations in the demersal fish assemblage structure and in fish abundance. This routine analyses multivariate or univariate data coming from complex and unbalanced designs (Anderson *et al.*, 2008). The two main factors were area and year.

To perform PERMANOVAs, PRIMER 6 software was used (Clarke and Gorley, 2006). To test the multivariate null hypothesis of no differences in assemblage structure among groups (Area and Year), Bray–Curtis abundance similarity matrices, on fourth root transformed data, were constructed to reduce the influence of the most abundant species (Clarke and Warwick, 2001). Two similarity matrices were constructed, at the whole fish assemblage level and for the non-target fish species, i.e. excluding Argentine hake. The Argentine hake is by far the most abundant species, representing more than 70% of catches, so it could mask possible patterns of the non-target and less abundant fish species.

Similarity matrices were used to explore fish assemblage structure with non-metric multidimensional scaling (MDS) ordination, where a stress value below 0.20 gives an adequate representation of the 2D MDS (Clarke and Warwick, 2001).

Fish species most responsible for the multivariate pattern were identified using a similarity percentages (SIMPER) analysis on fish abundance data. This method compares average abundances and examines the contribution of each species to similarities within a given group, or dissimilarities between groups (Clarke and Warwick, 2001).

To evaluate the null hypothesis of no difference in fish abundance among groups (Area and Year), abundances of all fish, Argentine hake, and of non-target fish species were calculated for each haul (expressed in tonnes, t) and tested with PERMANOVAs.

All permutation tests relied on 4999 permutations of residuals under a reduced model to obtain p -values. This permutation method is the more appropriate because it provides the best statistical power and the most accurate Type I error (Anderson *et al.*, 2008). When significant at the 0.05 level, the Area \times Year interactions were compared through *a posteriori* pair-wise comparisons using 4999 random permutations to obtain p -values.

MPA effects on Argentine hake mean size and age-2 juveniles

To assess temporal changes in size of the target species in each area, mean total lengths (L_T , in cm) of Argentine hake were compared using ANOVA, evaluating the null hypothesis of no difference between years in each area. Pair-wise *post hoc* tests for unequal sample size were used when statistical differences in one-way ANOVAs were detected (Zar, 1999). Argentine hakes were categorized as juveniles ($L_T < 35$ cm) and adults ($L_T > 35$ cm) following Simonazzi (2003). The total length of 68 448 Argentine hakes were analysed; the number of hakes is summarized in Supplementary Table S2.

To evaluate temporal changes, age-2 hake were selected as they are well represented in catches. Age estimation of hake was based

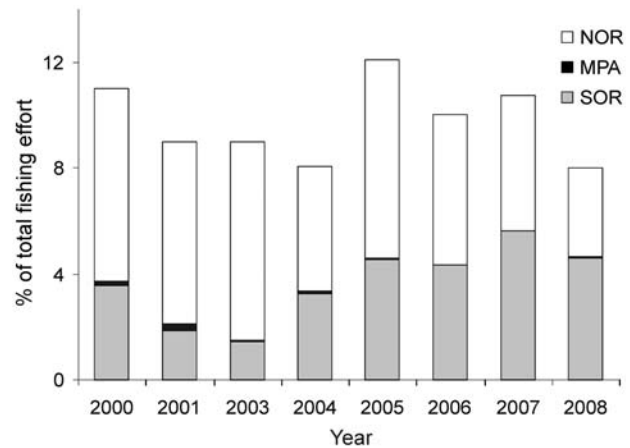


Figure 3. Annual percentage of the total fishing effort in the Argentine Shelf in the three zones analysed (NOR, MPA and SOR). Abbreviations as in Figure 1.

on otolith ring counting. For the study period, the total length of age-2 hake ranged between 28 and 44 cm (M. Renzi, Ageing Lab, INIDEP, pers. comm.). The abundance of age-2 hake inside the MPA was expressed in proportion to age-2 individuals in the entire survey area in each cruise. To test for differences among years, pair-wise comparisons with 1996 (designated as “control”) were carried out (Zar, 1999).

Results

Compliance in the Patagonian MPA

From 2000 to 2008 (except 2002), fishing effort (E) inside the MPA was negligible when compared with adjacent non-protected areas (NOR, SOR and remaining Shelf; Figure 3). Overall, the percentage of E within the MPA was lower than 0.09%, with the highest value registered in 2001 (0.26%) and the lowest in 2007 (0.01%). Inside NOR, the mean fishing effort was 6% while in SOR it was 3.7%. The rest of the Argentine Shelf contributed with 90% of the total effort. Given that the size of the Patagonian MPA and the fishing grounds were very similar, the low percentage of tracks within the protected area reflected true compliance.

Spatial patterns of fishing effort in the Patagonian Shelf and in MPA surroundings varied interannually, but in most the years a border effect is apparent (Figure 2). Note that due to the higher acquisition rate from 2004 more fishing events were recorded. Fishing effort concentrated particularly around the PCA during 2001, 2003 and 2006. Particularly, in 2001, 2003 and 2005, fishing effort was higher along the northern and eastern edges of the PCA. More fishing effort occurred in 2006 along the Patagonian Shelf than in other years, and the VMS data concentrated at the northern, eastern and southern boundaries of the PCA. In 2007 and 2008, fishing effort was higher on the eastern edge of the PCA. For all years, it is clear that there was more effort along the PCA boundaries than in distant areas. Highest values in the San Jorge Gulf corresponded to the red shrimp fishery.

Demersal fish assemblage

A total of 73 fish taxa were identified along the Patagonian Shelf during the cruises from 1996 to 2005. Supplementary Table S3 shows the fish occurrence in each area.

Table 1. Summary of the PERMANOVA main tests to assess differences in the structure of the whole fish assemblage and of the non-target fish species assemblage (excluding the MPA target species, the Argentine hake), between areas (MPA, NOR and SOR) and years (1996, 2000, 2001, 2003 and 2005).

Source of variation	df	MS	Pseudo-F	p-value
Fish assemblage				
Area	2	14 303.0	17.6	0.0002
Year	4	15 485.0	19.0	0.0002
Area x Year	8	2 158.2	2.7	0.0002
Residuals	137	814.2		
Non-target fish species				
Area	2	19 239.0	17.1	0.0002
Year	4	22 928.0	20.4	0.0002
Area x Year	8	3 338.9	3.0	0.0002
Residuals	137	1 122.2		

MPA effects on demersal fish assemblage structure and abundance

In the case of the structure of the whole demersal fish assemblage and that of the non-target fish species, PERMANOVAs showed a significant Area × Year interaction (Table 1). The MDS ordination was split by year given the complexity of showing the data (152 hauls) in a single MDS (Figure 4). The ordination of the non-target fish assemblage structure is not shown as it is almost equal to that of the whole fish assemblage.

A posteriori tests showed that in 1996, fish assemblage structure and that of the non-target fish species did not differ between MPA and NOR, but both differed from SOR. After 1996 fish assemblage structures were different for MPA, NOR and SOR.

The results of SIMPER analysis on the whole fish assemblage showed that the Argentine hake was the fish species that contributed most to dissimilarities among areas (Table 2), its average

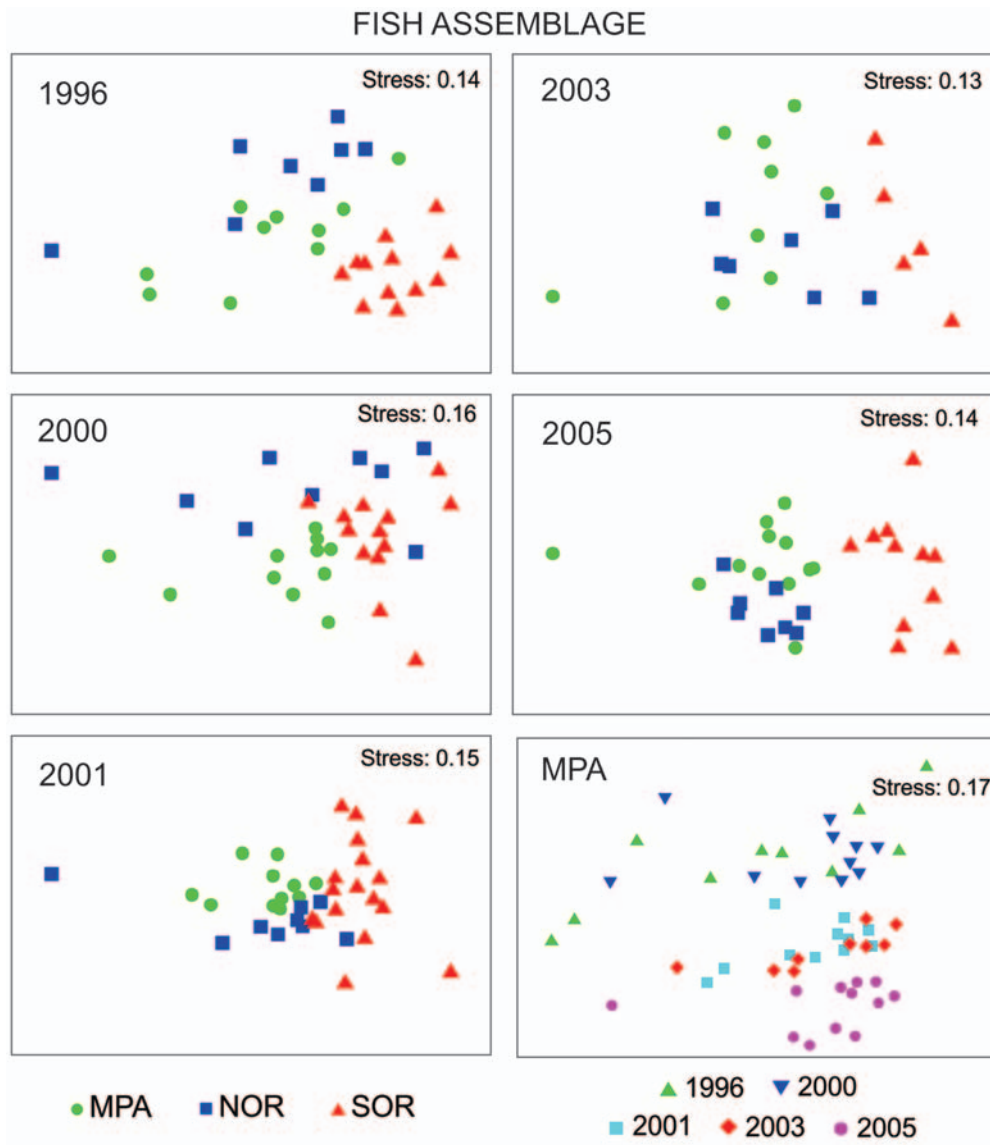


Figure 4. Non-metric multidimensional scaling (MDS) ordination on fish assemblage structure comparing the three areas (MPA, NOR and SOR) per year. At the lower right corner, the MDS on fish assemblage structure inside the MPA across five years is shown.

Table 2. SIMPER results showing the fish species that contributed most to the dissimilarity across areas (MPA, NOR and SOR) at the fish assemblage level and for the non-target fish species assemblage.

	% Dissimilarity		
	MPA-NOR	MPA-SOR	NOR-SOR
Fish assemblage			
<i>Merluccius hubbsi</i>	60	63	36
<i>Squalus acanthias</i>	5	–	–
<i>Macruronus magellanicus</i>	–	8	12
<i>Genypterus blacodes</i>	–	–	6
Non-target fish species			
<i>Squalus acanthias</i>	14	17	9
<i>Patagonotothen</i> sp.	10	10	8
<i>Patagonotothen ramsayi</i>	8	–	–
<i>Congiopodus peruvianus</i>	6	8	–
<i>Genypterus blacodes</i>	6	9	7
<i>Acanthistius brasiliensis</i>	5	6	–
<i>Macruronus magellanicus</i>	–	12	12
<i>Notothenia</i> sp.	–	9	6

‘–’ = dissimilarity <1%.

abundance in the MPA being 3-fold higher than in NOR, and 2-fold higher than in SOR. Other fish species contributed to dissimilarities among areas, but their percentage contributions were less than 10%. In the case of the non-target fish assemblage, eight species contributed to dissimilarities between areas, with *Squalus acanthias*, *Patagonotothen* sp. and *Macruronus magellanicus* making the highest contributions.

Inside the MPA, the fish assemblage structure and that of the non-target fish species changed with years (P perm = 0.0002, in both cases), except between 2001 and 2003 (Figure 4; MDS of the non-target fish species assemblage inside the MPA is not shown as is almost equal to that of the whole assemblage). Again, at the fish assemblage level, the SIMPER analysis revealed that inside the MPA the Argentine hake contributed more than 70% to dissimilarities among years (Table 3), with the most remarkable differences occurring between 1996 and 2003 (average abundance 1.4-fold higher in 2003) and between 1996 and 2005 (average abundance 1.6-fold higher in 2005). Regarding the non-target assemblage inside the MPA, 10 fish species were most responsible for the differences between years. These species, except *Squalus acanthias*, were more abundant after protection, with *Genypterus blacodes*, *Macruronus magellanicus* and *Patagonotothen ramsayi* showing the most remarkable increases.

PERMANOVAs performed on the abundance of the fish assemblage, Argentine hake, and the non-target fish species showed a significant Area \times Year interaction (Table 4).

At the fish assemblage level, *a posteriori* comparisons showed that in 1996, 2000 and 2005, fish abundance within the MPA did not differ from that of NOR and SOR, although there were differences between areas in 2001 and 2003, with fish abundance being higher in the MPA (Figure 5). Inside the MPA, the mean abundance of fish increased across years, being 1.8-fold higher in 2005 than in 1996. In NOR and SOR, a different trend was observed; fish abundance decreased after 1996 but then increased in 2005 (in NOR 1.5-fold higher in 2005 than in 1996; in SOR 1.2-fold higher in 2005 than in 1996).

Given that Argentine hake represented, on average, 70% of the catch in each haul, the pattern observed at the assemblage level is

Table 3. SIMPER results showing the fish species that contributed most to the dissimilarity inside the MPA across years, comparing 1996 (year before protection) with years after protection, at the fish assemblage level and for the non-target fish species assemblage.

1996 vs.	% Dissimilarity			
	2000	2001	2003	2005
Fish assemblage				
<i>Merluccius hubbsi</i>	71	77	79	73
<i>Squalus acanthias</i>	6	6	–	–
<i>Congiopodus peruvianus</i>	5	–	–	–
<i>Acanthistius brasiliensis</i>	–	5	–	–
<i>Patagonotothen</i> sp.	–	–	–	12
Non-target fish species				
<i>Congiopodus peruvianus</i>	22	8	8	8
<i>Squalus acanthias</i>	19	28	23	12
<i>Raja flavirostris</i>	12	–	–	–
<i>Genypterus blacodes</i>	8	11	6	–
<i>Acanthistius brasiliensis</i>	8	17	10	–
<i>Stromateus brasiliensis</i>	5	–	–	–
<i>Xystreuris rasile</i>	5	–	8	–
<i>Dipturus chilensis</i>	–	8	–	12
<i>Macruronus magellanicus</i>	–	–	10	–
<i>Patagonotothen ramsayi</i>	–	–	7	40

‘–’ = dissimilarity <1%.

Table 4. Summary of the PERMANOVA main tests to assess differences in the abundance of the fish assemblage, Argentine hake and non-target fish species between areas (MPA, NOR and SOR) and years (1996, 2000, 2001, 2003 and 2005).

Source of variation	df	MS	Pseudo-F	p-value
Fish assemblage				
Area	2	5 082.9	5.7	0.0002
Year	4	5 088.1	5.7	0.0002
Area \times Year	8	2 939.4	3.3	0.0002
Residuals	137	885.7		
Argentine hake				
Area	2	9 600.8	8.2	0.0002
Year	4	6 238.1	5.3	0.0002
Area \times Year	8	3 400.6	2.9	0.0002
Residuals	137	1 168.3		
Non-target fish species				
Area	2	10 123.0	9.7	0.0002
Year	4	7 605.5	7.3	0.0002
Area \times Year	8	3 225.9	3.1	0.0002
Residuals	137	1 037.4		

similar to that of Argentine hake, the MPA target species (Figure 5). In 1996, Argentine hake abundance did not differ between areas, however, after protection (since 2000 up to 2005) the protected area always showed higher abundance of hake in comparison with the fishing zones (NOR and SOR). Inside the MPA, Argentine hake abundance increased with years, being 1.6-fold higher in 2005 than in 1996. In NOR and SOR, the abundance of Argentine hake decreased after 1996 up to 2001 but then increased up to 2005. In NOR, the abundance was 1.4-fold higher in 2005 than in 1996 but in SOR Argentine hake abundance was slightly lower in 2005 than in 1996.

In reference to non-target fish species, there were no clear trends as their abundance changed between areas and years, although inside the MPA these fluctuations were lower in

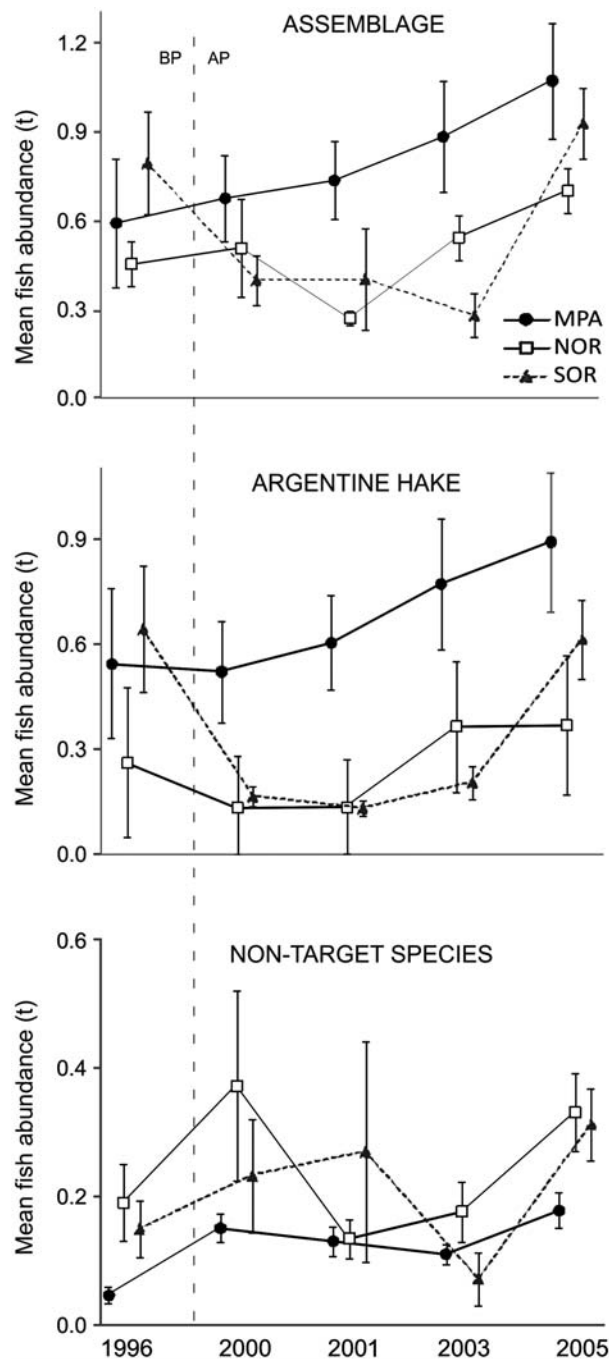


Figure 5. Abundance of the demersal fish assemblage, the Argentine hake (the MPA target species) and the non-target fish species (mean \pm s.e.) at each area (MPA, NOR and SOR) through years. Dotted line indicates before protection period (1996). BP = before protection, AP = after protection. Abbreviations as in Figure 1.

comparison with NOR and SOR (Figure 5). In 1996, mean abundance of non-target fish was lower in the MPA than in NOR and SOR, but in 2005 there were no differences between areas. In the three studied areas, a higher abundance of non-target species was registered in 2005 than in 1996, with the strongest trend in the MPA (3.8 fold higher; in NOR: 1.7 fold higher; in SOR: 2.1 fold higher).

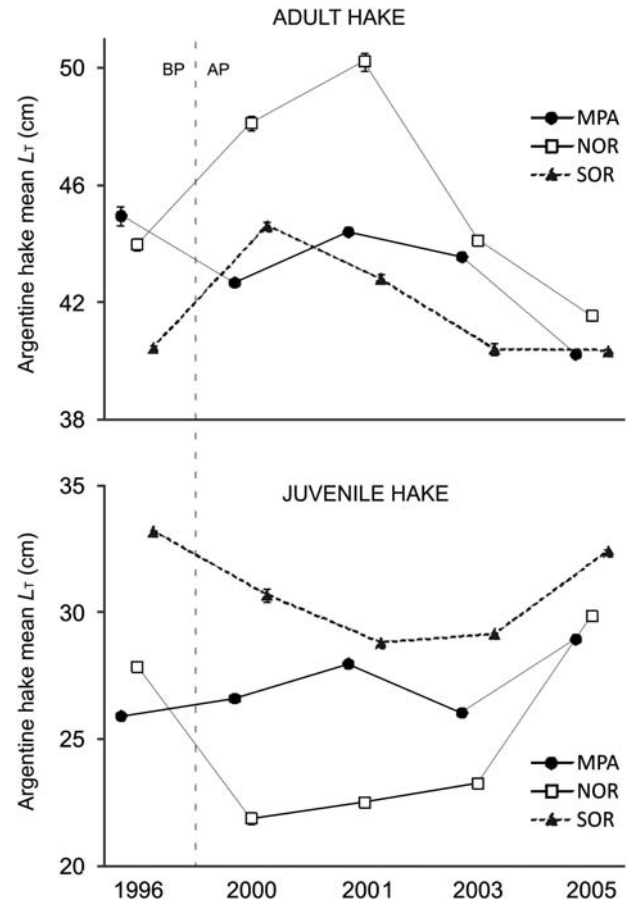


Figure 6. Total length (L_T , mean \pm s.e.) of adults and juveniles of Argentine hake for each area (MPA, NOR and SOR) through years. Dotted line indicates before protection period (1996). BP = before protection, AP = after protection. Abbreviations as in Figure 1.

MPA effects on Argentine hake mean size and age-2 juveniles

Mean total length (L_T) of Argentine hake adults differed among years in the protected area ($F_4 = 235$, $p < 0.001$) and in the two fished areas (NOR: $F_4 = 297$, $p < 0.001$; SOR: $F_4 = 262$, $p < 0.001$). Figure 6 show an overall decreasing trend in the L_T of hake in the three zones (MPA, NOR and SOR). *Post hoc* tests confirmed that at the MPA, mean L_T was higher in 1996 and 2001 than in 2000, 2003 and 2005. In 1996, Argentine hake adults were, on average, 4.7 cm larger than in 2005. Within the NOR area, mean L_T increased from 1996 to 2001 but then sharply decreased in 2003 and 2005. In 2005, adults were 2.5 cm smaller than in 1996. The trend observed in SOR was similar to that in NOR; the mean L_T of adult hakes increased from 1996 to 2000 and decreased up to 2003, however, no differences were detected between 1996 and 2005.

Juveniles of Argentine hake differed in their mean L_T among years in the three areas (MPA: $F_4 = 163$, $p < 0.001$; NOR: $F_4 = 486.5$, $p < 0.001$; SOR: $F_4 = 588$, $p < 0.001$) showing a different pattern from adults (Figure 6). Within the MPA, the mean L_T of juveniles increased from 1996 to 2001, decreased in 2003 and increased again in 2005. In 2005, inside the protected area, juveniles of Argentine hake were on average 3 cm larger (10%) than in 1996. As for adults, individuals in NOR and SOR showed a similar pattern. In NOR, juveniles decreased in size from 1996 to 2000 but then increased up to 2005,

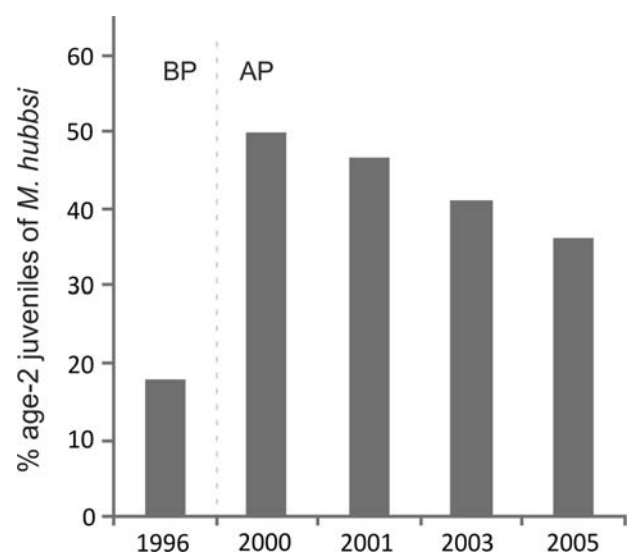


Figure 7. Percentage of age-2 juveniles of *Merluccius hubbsi* (Argentine hake) inside the MPA across years. Dotted line indicates before protection period (1996). BP = before protection, AP = after protection.

being on average 2 cm larger (7%) in comparison with 1996. In SOR, the mean L_T of juveniles decreased until 2001 and then increased until 2005, but in this area the size of juveniles in 2005 was slightly smaller (2.5%) than in 1996.

The proportion of age-2 juveniles of Argentine hake was, on average, 2.4-fold higher in 2000, 2001, 2003 and 2005 than in 1996 ($p < 0.01$; Figure 7). A decreasing trend in the proportion of age-2 juveniles of Argentine hake after 2000 appears in Figure 7. However, in 2005 the proportion of juveniles was still 2-fold higher than in 1996 (36% vs. 18%, respectively).

Discussion

We investigated the effects on demersal fishes of an offshore large-scale MPA, placed in the PSLME. Our results are in general agreement with the scarce contributions on the topic. MPA effects did not vary consistently through time but general trends show that the highest abundance of the fish assemblage, and that of the Argentine hake, occurs inside the MPA. An increasing trend in non-target fish species abundance and in hake juvenile size was also registered inside the protected area. Moreover, inside the MPA, the proportion of age-2 Argentine hake at least doubled compared with the proportion registered before protection.

Compliance in the Patagonian MPA

Analysis of hake landings showed that the region now occupied by the MPA was highly exploited before its implementation at the end of 1997; south of 41°S catches continuously increased from 300 000 t in 1987 to 600 000 t in 1997 (Irusta *et al.*, 2001). Our analysis of satellite monitoring data showed that fishing effort within the protected area was negligible, but the MPA was not completely intangible. Nevertheless, the results indicate that fishes may have benefited from the protection. This agrees with results from the Western Indian Ocean (McClanahan *et al.*, 2009) that showed positive fish responses to protection, even though closure regulations were not fully respected in some MPAs.

It is generally assumed that protection should enhance catch rates in non-protected areas through the net export of fish, and

“fishing the line” is nowadays a common tactic in which fishing effort is concentrated on the edge of a protected area (Kellner *et al.*, 2007). In that sense, the spatial analysis of VMS data showed that fishing pressure is higher near the boundaries of the PCA, which suggest better catches in their surroundings than in distant areas. Similarly, high concentrations of trawling effort were found around the boundaries of the large offshore Georges Bank MPAs (Murawski *et al.*, 2005); they were attributed to the apparent “spill-over” or seasonal movement of certain species out of the closed area. Although the high fishing effort around the PCA could be attributed to protection effects, it is important to note that before the PCA was implemented the Patagonian area was already one of the best fishing grounds of the Argentine Continental Shelf. Thus, it would be expected that after implementing protection measures, fishing effort displaced to the PCA boundaries, as occurred in closed areas off the northeast USA (Murawski *et al.*, 2005). Hence, a similar pattern of fishing effort concentration is expected due to “spill over” effects and/or because the area was an important fishing zone before protection. Finally, our results indicate that the boundaries of the PCA are preferred by fishers, since fishing activities concentrate around the protected area (presumably because they get better catches). This suggests that the MPA continues to be the area of greatest concentration of hake.

MPA effects on demersal fish assemblage structure and abundance

At the community level, changes in assemblage structure are some of the expected ecological effects of MPAs (García-Charton *et al.*, 2008). In the study area, demersal fish assemblage structure changed with time, suggesting some effect of protection, the most remarkable changes being attributed to changes in Argentine hake abundance, the MPA target species. Regarding the non-target species responsible for the pattern observed, the information analysed did not allow us to discern the processes that could explain changes in their abundances. However, we detected changes in non-target fish assemblage structure after protection. In that sense, our findings agree with studies that propose that MPAs induce shifts in fish assemblage structure, as they protect large long-lived predators that are vulnerable to fishing (García-Charton *et al.*, 2008).

As expected, the abundance pattern of the fish assemblage showed higher average abundances in the MPA than in fished areas. This is mostly due to the fact that the Argentine hake is by far the most abundant species of this assemblage, significantly affecting its abundance pattern. Our results are in agreement with studies on Mediterranean MPAs, showing higher fish abundance within protected areas, not only for target species but for fish assemblages as a whole (e.g. García-Charton *et al.*, 2008).

The highest abundance of the Argentine hake was observed inside the protected area, suggesting positive effects of protection on this exploited target species. This is in agreement with results in multiple marine reserves in both tropical and temperate habitats (Babcock *et al.*, 2010) and in the Channel Islands reserves network in the Pacific Ocean (Hamilton *et al.*, 2010). Both studies reported that the most important target species showed a more evident response to protection than the rest. Protection affects individual species differently (Lester *et al.*, 2009), and non-target species show no overall response to it (Micheli *et al.*, 2004). However, our results showed that, although abundance of non-target species is at least one order of magnitude lower than that

of the Argentine hake, their abundance increased with time inside the MPA.

Thus, at the fish assemblage level, as for the target and non-target fish species, the increasing trend of abundance inside the MPA with years suggests a positive relationship with the Patagonian MPA implementation.

MPA effects on Argentine hake mean size and age-2 juveniles

Since fish mobility and home range size increase with body size and age (Grüss *et al.*, 2011), and considering part of the Argentine hake nursery ground is located inside the MPA, we predicted a stronger positive effect of the MPA on juveniles than on adults. In 1993 and 1994, in the area of the Patagonian MPA the mean total length of hake juveniles ($x = 25.6$, $s.e. = 0.18$; Author, unpublished data) was similar to that in 1996. As expected, the mean total lengths of juveniles increased (3 cm, 11%) inside the protected area after MPA implementation since protection may allow them to attain larger sizes, preventing the increase of early-maturing and small-sized individuals that negatively affects the reproductive output of the stock (Rochet, 2009). Although a decreasing trend of size at maturity of Argentine hake has been reported in the Patagonian Sea, given that from 1989–1994, length at first maturity was 34.7 cm for males and 36.2 cm for females (Ruiz and Fondacaro, 1997) and in 2001 decreased to 28.6 cm for males and 32.5 cm for females (Pájaro *et al.*, 2005), the mean total length of hake juveniles increased within the MPA. Moreover, the Argentine hake age-2 juvenile proportion increased inside the MPA after protection. Thus, the Patagonian MPA could be contributing to restoring the Argentine hake stock.

On the other hand, the size of adults varied between years, but on average, mean total lengths were smaller at the end of the study period. Analysis of adult hake sizes in the area of the MPA before its implementation (performed in 1993, 1994; author, unpublished data) showed a mean total length of 44.8 cm ($s.e. = 0.21$), similar to that reported for 1996. As a result of the high fishing pressure, a decreasing trend in mean total length has been reported in hake for all the Argentine Sea between 1986 and 1997 (Aubone *et al.*, 2004); and since 1997 older fish are less represented in catches (Renzi *et al.*, 2009). So our results could be explained by the general trend of hake size diminishing in the region as a consequence of the high fishing pressure outside the MPA, since fishing activities remove the largest and oldest fish (Berkeley *et al.*, 2004). In the case of species that exhibit a large home-range, such as the Argentine hake, closed areas may not be too effective as a primary protection tool for adults (e.g. Murawski *et al.*, 2000). This could be the situation in the Patagonian MPA regarding spatial patterns of fishing effort (Figure 3). Although MPAs are considered to be one management method that helps to protect older fish (Berkeley *et al.*, 2004), our results show that Argentine hake adults, regularly moving large distances, inside/outside the MPA, are smaller after eight years of protection. However, all evidence suggests that the Patagonian MPA, implemented to protect the nursery ground of Argentine hake, positively affects juveniles by limiting their exploitation, resulting in larger size and a higher proportion of them inside the MPA.

Global assessment of the Patagonian MPA

MPAs seem to be more effective for species with a limited home range and strong site fidelity (i.e. coral reef or benthic communities) than for migratory or far-ranging species (Blyth-Skyrme *et al.*,

2006; West *et al.*, 2009). The most abundant fish species inhabiting the Patagonian Shelf (*Merluccius hubbsi*, *Macruronus magellanicus*, *Micromesistius australis*, *Salilota australis*) are highly mobile and they migrate hundreds to thousands of kilometres to feed and/or reproduce (e.g. Podestá, 1990; Giussi *et al.*, 2002). Although all these migratory movements have much larger spatial scale than the Patagonian MPA, we found some positive effects.

The time framework for analysis is crucial for detecting positive effects of protected areas (Claudet *et al.*, 2008). Since fish population recovery is a cumulative process (Babcock *et al.*, 2010) decades could be needed to produce noticeable effects (Micheli *et al.*, 2004). The Patagonian MPA was implemented by the end of 1997 and, since we only evaluated it up to 2005, it could be possible that it was not long enough to show sound benefits.

Lack of time after MPA implementation, some degree of non-compliance with full protection, and the large home range of most of the Patagonian species, could reduce or prevent positive results being found for the protected area (e.g. Pelletier *et al.*, 2008). Despite these disadvantageous features of the Patagonian MPA, the increasing trend of abundance of the demersal fish assemblage, of abundance of the target and non-target fish species, of hake juvenile size, and the higher proportion of age-2 juveniles inside the protected area, provide promising results regarding the benefits of offshore, large-scale MPAs.

Supplementary data

Supplementary data are available at the *ICES Journal of Marine Science* online. This material describes the number of bottom trawling stations analysed, the number of Argentine hakes measured for each category and the occurrence of fish taxa at each zone of the Patagonian Shelf.

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References

- Acha, E. M., Mianzan, H., Guerrero, R., Favero, M., and Bava, J. 2004. Marine fronts at the continental shelves of austral South America. Physical and ecological processes. *Journal of Marine Systems*, 44: 83–105.
- Anderson, M. J., Gorley, R. N., and Clarke, K. R. 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK. 214 pp.
- Angelescu, V., and Prenske, L. B. 1987. Ecología trófica de la merluza común del Mar Argentino (*Merlucciidae*, *Merluccius hubbsi*). Parte

2. Dinámica de la alimentación analizada sobre la base de las condiciones ambientales, la estructura y las evaluaciones de los efectivos en su área de distribución. INIDEP, Contribución nº 561, 205 pp.
- Aubone, A. 2004. Loss of stability owing to a stable age structure skewed toward juveniles. *Ecological Modelling*, 175: 55–64.
- Aubone, A., Bezzi, S. I., Cañete, G. R., Castrucci, R., Dato, C. V., Irusta, G., Madirolas, A. O., *et al.* 2004. Hake (*Merluccius hubbsi*) resource assessment and management recommendations. The situation up to 1999. In *El Mar Argentino y sus Recursos Pesqueros*, 4, pp. 207–235. Ed. by E. E. Boschi. INIDEP, Mar del Plata. 359 pp.
- Babcock, R. C., Shears, N. T., Alcalá, A. C., Barrett, N. S., Edgar, G. J., Lafferty, K. D., McClanahan, T. R., *et al.* 2010. Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. *Proceedings of the National Academy of Sciences of the United States of America*, 107: 18256–18261.
- Berkeley, S. A., Hixon, M. A., Larson, R. J., and Love, M. S. 2004. Fisheries sustainability via protection of age structure and spatial distribution of fish populations. *Fisheries*, 29: 23–32.
- Blyth-Skyrme, R. E., Kaiser, M. J., Hiddink, J. G., Edwards-Jones, G., and Hart, P. J. B. 2006. Conservation benefits of temperate marine protected areas: variation among fish species. *Conservation Biology*, 20: 811–820.
- Clarke, K. R., and Gorley, R. N. 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth, UK. 190 pp.
- Clarke, K. R., and Warwick, R. M. 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation, 2nd edn. PRIMER-E, Plymouth, UK. 172 pp.
- Claudet, J., Osenberg, C. W., Benedetti-Cecchi, L., Domenici, P., García-Charton, J. A., Pérez-Ruzafa, A., Badalamenti, F., *et al.* 2008. Marine reserves: size and age do matter. *Ecology Letters*, 11: 481–489.
- FAO. 2009. The state of world fisheries and aquaculture 2008. Food and Agriculture Organization, Rome. 192 pp.
- Fisher, J. A. D., and Frank, K. T. 2002. Changes in finfish community structure associated with an offshore fishery closed area on the Scotian Shelf. *Marine Ecology Progress Series*, 240: 249–265.
- Game, E. T., Grantham, H. S., Hobday, A. J., Pressey, R. L., Lombard, A. T., Beckley, L. E., Gjerde, K., *et al.* 2009. Pelagic protected areas: the missing dimension in ocean conservation. *Trends in Ecology & Evolution*, 24: 360–369.
- García-Charton, J. A., Pérez-Ruzafa, A., Marcos, C., Claudet, J., Badalamenti, F., Benedetti-Cecchi, L., Falcón, J. M., *et al.* 2008. Effectiveness of European Atlanto-Mediterranean MPAs: Do they accomplish the expected effects on populations, communities and ecosystems? *Journal for Nature Conservation*, 16: 193–221.
- Giussi, A. R., Hansen, J. E., and Wöhler, O. C. 2002. Estimated total abundance and numbers-at-age of longtail hake (*Macruronus magellanicus*) in the Southwest Atlantic during the years 1987–2000. *Scientia Marina*, 66: 283–291.
- Greenstreet, S. P. R., Fraser, H. M., and Piet, G. J. 2009. Using MPAs to address regional-scale ecological objectives in the North Sea: modelling the effects of fishing effort displacement. *ICES Journal of Marine Science*, 66: 90–100.
- Grüss, A., Kaplan, D. M., Guénette, S., Roberts, C. M., and Botsford, L. W. 2011. Consequences of adult and juvenile movement for marine protected areas. *Biological Conservation*, 144: 692–702.
- Halpern, B. S. 2003. The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications*, 13: S117–S137.
- Hamilton, S. L., Caselle, J. E., Malone, D. P., and Carr, M. H. 2010. Incorporating biogeography into evaluations of the Channel Islands marine reserve network. *Proceedings of the National Academy of Sciences of the United States of America*, 107: 18 272–18 277.
- Hilborn, R., Stokes, K., Maguire, J.-J., Smith, T., Botsford, L. W., Mangel, M., Orensanz, J., *et al.* 2004. When can marine reserves improve fisheries management? *Ocean and Coastal Management*, 47: 197–205.
- Irusta, G., Bezzi, S. I., Simonazzi, M., and Castrucci, R. 2001. Los desembarques argentinos de merluza (*Merluccius hubbsi*) entre 1987 y 1997. INIDEP Informe Técnico 42, 24 pp. <http://hdl.handle.net/1834/2592> (last accessed 14 October 2012).
- Jenks, G. F. 1967. The data model concept in statistical mapping. *International Yearbook of Cartography*, 7: 186–190.
- Jones, P. J. S. 2007. Point-of-view: Arguments for conventional fisheries management and against no-take marine protected areas: only half of the story? *Reviews in Fish Biology and Fisheries*, 17: 31–43.
- Kellner, J. B., Tetreault, I., Gaines, S. D., and Nisbet, R. M. 2007. Fishing the line near marine reserves in single and multispecies fisheries. *Ecological Applications*, 17: 1039–1054.
- Lester, S. E., Halpern, B. S., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B. I., Gaines, S. D., Airamé, S., *et al.* 2009. Biological effects within no-take marine reserves: a global synthesis. *Marine Ecology Progress Series*, 384: 33–46.
- Matano, R. P., Palma, E. D., and Piola, A. R. 2010. The influence of the Brazil and Malvinas Currents on the Southwestern Atlantic Shelf circulation. *Ocean Science*, 6: 983–995.
- McClanahan, T. R., Graham, N. A. J., Wilson, S. K., Letourneur, Y., and Fisher, R. 2009. Effects of fisheries closure size, age, and history of compliance on coral reef fish communities in the western Indian Ocean. *Marine Ecology Progress Series*, 396: 99–109.
- Micheli, F., Halpern, B. S., Botsford, L. W., and Warner, R. R. 2004. Trajectories and correlates of community change in no-take marine reserves. *Ecological Applications*, 14: 1709–1723.
- Murawski, S. A., Brown, R., Lai, H. L., Rago, P. J., and Hendrickson, L. 2000. Large-scale closed areas as a fishery-management tool in temperate marine systems: The Georges Bank experience. *Bulletin of Marine Science*, 66: 775–798.
- Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., and Mountain, D. G. 2005. Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science*, 62: 1150–1167.
- Pájaro, M., Macchi, G. J., and Martos, P. 2005. Reproductive pattern of the Patagonian stock of Argentine hake (*Merluccius hubbsi*). *Fisheries Research*, 72: 97–108.
- Palma, E. D., Matano, R. P., and Piola, A. R. 2008. A numerical study of the Southwestern Atlantic Shelf circulation: Stratified ocean response to local and offshore forcing. *Journal of Geophysical Research*, 113: C11010.
- Pelletier, D., Claudet, J., Ferraris, J., Benedetti-Cecchi, L., and García-Charton, J. A. 2008. Models and indicators for assessing conservation and fisheries-related effects of marine protected areas. *Canadian Journal of Fisheries and Aquatic Sciences*, 65: 765–779.
- Podestá, G. P. 1990. Migratory pattern of Argentine hake *Merluccius hubbsi* and oceanic processes in the southwestern Atlantic Ocean. *Fishery Bulletin*, 88: 167–177.
- Renzi, M. A., Santos, B. A., and Abachian, V. 2009. Growth of hake (*Merluccius hubbsi*) in the Southwest Atlantic between 1993–2003 north and south of 41° S. INIDEP Informe Técnico 76, 33 pp. <http://hdl.handle.net/1834/3458> (last accessed 14 October 2012).
- Roberts, C. 2012. Marine ecology: reserves do have a key role in fisheries. *Current Biology*, 22: R444–R446.
- Rochet, M. 2009. Effects of fishing on the population. In *Fish Reproductive Biology: Implications for Assessment and Management*, pp. 172–204. Ed. by T. Jakobsen, M. J. Fogarty, B. A. Megrey, and E. Moksness. Blackwell Publishing Ltd, Oxford.
- Rochet, M.-J., Trenkel, V. M., Carpentier, A., Coppin, F., De Sola, L. G., Léauté, J.-P., Mahé, J.-C., *et al.* 2010. Do changes in environmental and fishing pressures impact marine communities? An empirical assessment. *Journal of Applied Ecology*, 47: 741–750.
- Ruiz, A. E., and Fondacaro, R. R. 1997. Diet of hake (*Merluccius hubbsi* Marini) in a spawning and nursery area within Patagonian shelf waters. *Fisheries Research*, 30: 157–160.

- Sherman, K. 2005. The large marine ecosystem approach for assessment and management of ocean coastal waters. *In* Sustaining Large Marine Ecosystems – The Human Dimension, pp. 3–16. Ed. by T. M. Hennessey, and J. G. Sutinen. Elsevier.
- Simonazzi, M. 2003. Relación largo-peso y largo-edad de primera madurez sexual de la merluza. INIDEP Informe Técnico 51, pp. 11–26. <http://hdl.handle.net/1834/2422> (last accessed 14 October 2012).
- West, C. D., Dytham, C., Righton, D., and Pitchford, J. W. 2009. Preventing overexploitation of migratory fish stocks: the efficacy of marine protected areas in a stochastic environment. *ICES Journal of Marine Science*, 66: 1919–1930.
- Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding global fisheries. *Science*, 325: 578–585.
- Zar, J. H. 1999. *Biostatistical Analysis*. Prentice Hall, New Jersey. 663 pp. plus appendices.

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