



Asteroidea of the southern tip of South America, including Namuncurá Marine Protected Area at Burdwood Bank and Tierra del Fuego Province, Argentina

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Abstract

In benthic communities, echinoderms are dominant in terms of abundance and diversity, and Asteroidea play an important role in the structure of communities. In the present study, Asteroidea were sampled in the recently created Namuncurá Marine Protected Area (N MPA) at Burdwood Bank (which has an average of 50–200 m depth and is delimited by abrupt slopes), the surrounding shelf break and Tierra del Fuego Province, Argentina, at 24 stations at different depths and seabeds on board the oceanographic vessel ARA “Puerto Deseado.” A total of 32 Asteroidea species were identified. The bathymetric ranges were extended for two of them, and the geographic distribution was updated for seven of them, this being their first record in the N MPA. The N MPA showed higher asteroid richness than Tierra del Fuego Province and the surrounding shelf break. Moreover, this area presented species shared with Antarctica, which enhances the importance of the Malvinas Current (formed mainly by the contribution of Antarctic waters) in the larval dispersal of some species. On the other hand, a high percentage of the species found at the N MPA presented direct development with brooding females. The N MPA represents an important biodiversity hotspot. Thus, to contribute to the formulation of precise conservation strategies and enhance its protection, it is crucial to promote and continue the efforts to know more about the ecosystems at these latitudes.

Keywords Asteroidea · Richness · Marine Protected Area · SW Atlantic Ocean

Introduction

The Burdwood Bank (BB) is a submerged plateau located about 150 km east from Isla de los Estados (Tierra del Fuego Province, Argentina) and 200 km south from Malvinas/Falklands Islands, centered at 54°19'S, 59°23'W (Schejter et al. 2016). Its seabed consists of accumulations of sand, gravel and shells and is located between 50 and 200 m depth. It is delimited by abrupt slopes, with a depth exceeding 3000 m. It has an area of about 34,000 km² circumscribed by the 200-m isobath, extending 370 km in an east–west direction and between 50 and 100 km in a north–south direction (Piola and Gordon 1989). To the north, the BB borders with a deep oceanic channel that separates it from the Malvinas/

Falklands Islands, whereas, to the south, it borders part of the continental slope. It is an intermediate area between South America and Antarctica and is part of the islands and shelf that constitute the Scotia Arc (Schejter et al. 2016). Due to its location, the BB plays an important role as a circumpolar ocean flow barrier because it is surrounded by the cold Malvinas Current, with an anticyclonic circulation pattern that mixes the waters and generates upwelling and nutrient uplift to the surface (Falabella 2017). This develops into abundant production of phytoplankton, which in turn enables the development of a rich biodiversity in its waters and bottoms (Falabella 2017). Despite its geographic distance, depths and oceanographic conditions, the Scotia Arc links Patagonia to the Antarctic Peninsula, playing a connecting role for many marine species (Arntz 2005; Schejter et al. 2016). When the ancient supercontinent of Gondwana disintegrated and the fragments drifted apart to form continents, Antarctica became very isolated over the geographic South Pole (Barnes 2005). Thus, the Patagonia–Scotia Arc–Antarctic Peninsula has become a crucial region of the globe for biologic and climatologic research (Barnes 2005).

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In 2013, through the enactment of law no. 26875, Argentina established the BB as its first oceanic protected area: the Namuncurá Marine Protected Area (N MPA). Falabella (2017) compiled general and historic information on the oceanography, biodiversity and fisheries exploitation in the BB. This compilation was used to provide the necessary baseline knowledge for the establishment of the N MPA and its division into three subareas (the “core”, “buffer” and “transition” subareas), according to the required protection level. The “core” or central subarea contains a representative fraction of the benthic marine biodiversity, and thus no activities other than control and monitoring are allowed since this subarea requires strict protection because of the vulnerable characteristics presented by the ecosystem components. In the “buffer” subarea (the area surrounding the core), activities such as scientific research, explorations dealing with natural resources and biodiversity and management of sustainable resources are allowed after previous authorization. Finally, in the external “transition” subarea, productive and extractive activities are allowed as long as they are considered within the Management Plan of the N MPA (Schejter et al. 2016). The shelf break and nearby areas have no protection regulations.

Some studies suggest that proper maintenance and management of marine protected areas can serve as a powerful tool to ameliorate the negative results caused by climate change. Roberts et al. (2017) have recently indicated that the widespread establishment of marine protected areas can help slow climate change, alleviate some of its expected hardships (e.g., reduced food security, sea-level rise, etc.), reduce biodiversity loss, help safeguard critical ecologic processes underpinning the planetary life-support system and improve the outlook for recovery after greenhouse gas emissions have been brought under control. Marine reserves not only limit direct anthropogenic stressors, thus enabling species to recover their abundance, biomass, diversity, age structure and reproductive output and enabling habitats to recover complexity (Roberts et al. 2017), but also offer a refuge to vulnerable species.

Echinoderms are a dominant group in many soft- and hard-bottom marine assemblages (Ellis and Rogers 2000; Lebrato et al. 2010) and thus play an important role in the structure of benthic communities (McClintock 1994). Sea stars (Asteroidea: Echinodermata) represent a diverse group of benthic invertebrates, with a long paleontologic history (Sutton et al. 2005; Stilwell and Long 2011; Jagt et al. 2014). They have successfully colonized all depths of the world’s oceans, including the Southern Ocean (De Broyer et al. 2014). They display numerous feeding strategies (omnivorous, deposit feeding, suspension feeding or carnivorous) (Jangoux 1982) and reproduction strategies (benthic embryos and larvae, benthic embryos with planktotrophic larvae, planktotrophic embryos and larvae, or even

brooding) (Bosch 1989; Bosch and Pearse 1990; Pearse et al. 1991; Cossi et al. 2015; Pérez et al. 2017). Many species that inhabit high southern latitudes present direct development with brooding females (Bosch and Slattery 1999). In general, brooding can take place on the female’s mouth, in a nidamental chamber (Fisher 1917, 1940; Bernasconi 1970) (a space between the true aboral surface and the supradorsal membrane supported by the tips of the pseudo-paxillar spines), on the dorsal surface under the paxillae (Lieberkind 1926), in the cardiac stomach (gastric brooding) (Lieberkind 1920) or even within the ovaries (intraovarian brooding) (Studer 1885; Thomson 1876; Byrne 1996, 2005).

The main objective of the present study was to study and characterize the Asteroidea fauna of the N MPA and to compare it with that of Tierra del Fuego Province. This comparison is relevant because these two areas are at the same latitude and have comparable bathymetry but are geographically isolated, with different physical conditions, such as salinity and temperature. We also compared the fauna of the N MPA with the surrounding shelf break to demonstrate the importance of adding its extension to the marine protected area. A second objective was to revise the numerous reproduction strategies of the Asteroidea fauna of the N MPA as an approach to understanding the importance of these strategies at high latitudes. The results are expected to make a valuable contribution to better understanding the general patterns of distribution, richness and reproduction strategies of the Asteroidea, a group of organisms that are among the most abundant in the oceans and, in most cases, turn out to be modelers and top predators of communities.

Materials and methods

The study area comprised the three subareas of the N MPA (core, buffer and transition), the BB shelf break and two areas of Tierra del Fuego Province (Atlantic Coast and Beagle Channel) (Fig. 1). In April 2016, samples were taken at 24 stations (different latitude/longitude combinations) at different depths (from 92 to 785 m) and different seabed types (rocky, sand, sludge and gravel) on board the oceanographic vessel ARA “Puerto Deseado” by using a bottom otter trawl and a Rauschert dredge to complement the study with the species that live buried in the sediment. In all cases, sampling was qualitative.

Samples were photographed and then preserved in formaldehyde 10% for their taxonomic identification to the lowest possible taxonomic level. Depth, surface temperature and salinity were measured at each station (Table 1).

Taxonomic determinations were performed based on Sladen (1889), Koehler (1913), Verrill (1914), Fisher (1940), Bernasconi (1970), Tablado (1982), Clark and Downey (1992), Starnanato and Jangoux (1993), Janosik and

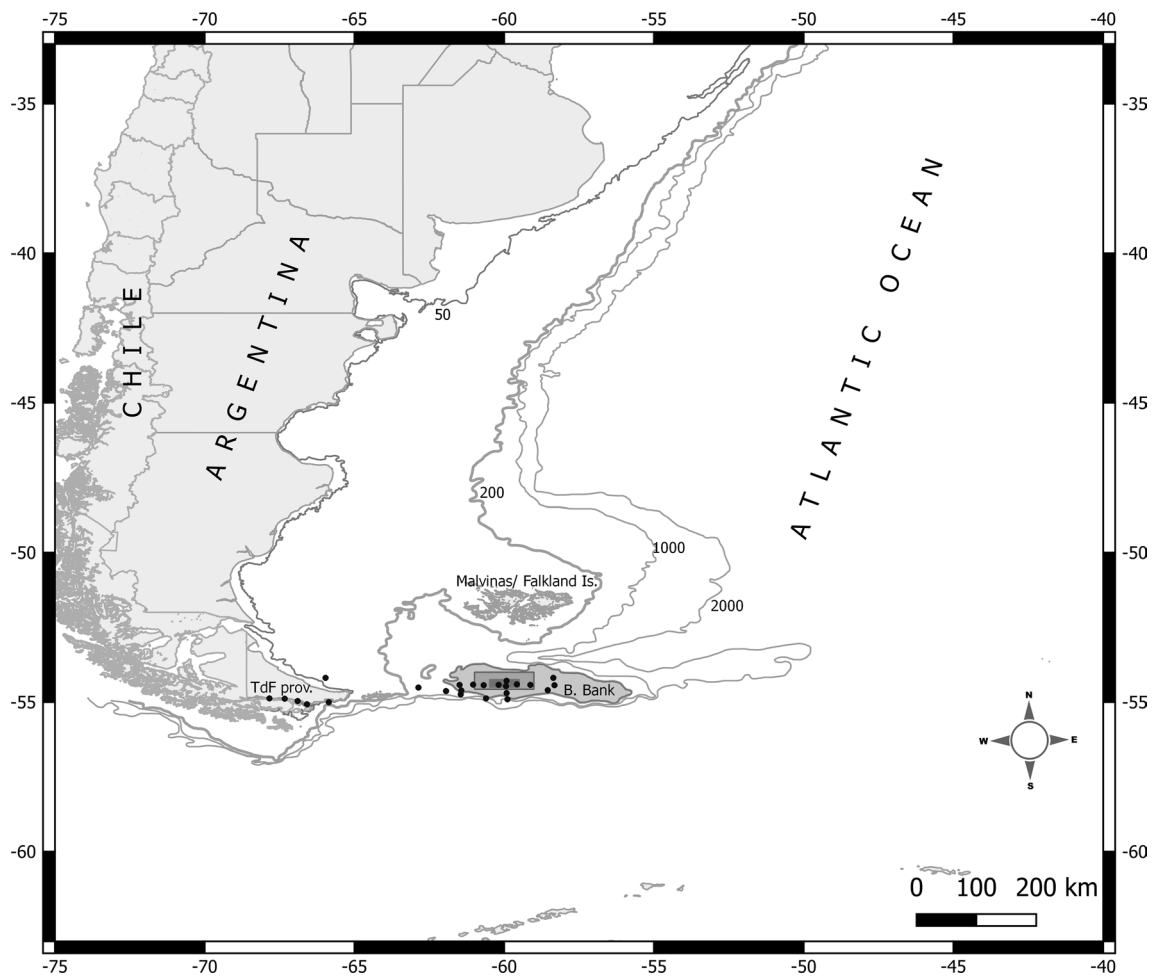


Fig. 1 Location of the stations visited during the research cruise (points), the Namuncurá Marine Protected Area (N MPA) at the Burdwood Bank (B. Bank) delimited by the 200-m isobaths, Tierra del Fuego Province (TdF prov), Malvinas/Falkland Islands and the

50-m, 200-m, 1000-m and 2000-m isobaths. N MPA color reference: dark gray = N MPA core area; middle gray = N MPA buffer area; light gray = NMPA transition area

Table 1 Sampling areas during the research cruise on board the oceanographic vessel ARA “Puerto Deseado”

Area	Depth (m)		Surf. temp. (°C)		Salinity	
	Min	Max	Min	Max	Min	Max
N MPA core (4)	65	125	6.705	7.342	34.015	34.034
N MPA buffer (3)	100	128	7.130	7.514	33.995	34.035
N MPA transition (6)	90	202	6.716	7.530	33.918	34.033
BB shelf break (5)	203	785	6.837	7.020	33.957	34.033
Tierra del Fuego Beagle Channel (4)	68	111	8.915	9.846	32.290	32.599
Tierra del Fuego Atlantic Coast (2)	70	70	9.140	9.140	32.902	32.902

Depth, surface temperature and salinity maxima and minima. The number of stations for each site is indicated between parentheses

Halanych (2010), Mah et al. (2014) and Arntz and Rauschert (2015). Then, taxonomy and distribution were matched against the Register of Antarctic Marine Species (Clarke and Johnston 2003; De Broyer et al. 2018), the World Register of Marine Species (Horton et al. 2018), De Broyer and Danis

(2010), OBIS (2017) and the World Asteroidea database (Mah 2017) to ensure that synonymies or misspellings were removed as well as to compare the known distribution to the one recorded in this study. Furthermore, the developmental mode for each Asteroidea species was revised based on

MacBride (1920), Lieberkind (1926), Fisher (1940), Hyman (1955), Bernasconi (1970), Bosch (1989), Bosch and Pearse (1990), Pearse et al. (1991) and Pearse and Bosch (1994).

Due to unequal sampling efforts and use of heterogeneous gears to collect the samples, we chose binary data (presence/absence) to construct the species similarity matrix. The Bray-Curtis index was used to build the data matrix, this index being equivalent to the Sørensen index for binary matrices (Clarke et al. 2006). A cluster analysis was performed to evaluate the faunal patterns in the different areas. Hierarchical clustering was obtained using the group linkage clustering technique to analyze the similarities in species compositions between areas displayed graphically in a dendrogram, using Infostat v2016 software.

Maps were made using QGIS 2.18.3 and Surfer v10.

Results

The study area presented different physical conditions (Table 1), such as a lower temperature and higher salinity in the N MPA than in Tierra del Fuego Province.

New data

A total of 32 Asteroidea species belonging to 25 genera and 14 families were identified at the three subareas of the N MPA, the BB shelf break and Tierra del Fuego Province (Table 2). Our data extended the bathymetric ranges of two species: *Cryptasterias turqueti* and *Peribolaster folliculatus*. *C. turqueti* is known to occur from 0 to 36 m depth (Bernasconi 1970), while here it was found from 76 to 183 m ($n=31$), whereas the deepest record of *P. folliculatus* in the metadata consulted is 332 m, and here it was found at 372 m depth ($n=24$). Our study also extended the geographic distribution of seven species, for which this is the first record in the N MPA: *Anasterias pedicellaris* ($n=34$), *Cosmasterias lurida* ($n=1$), *Diplodontias singularis* ($n=1$), *Henricia obesa* ($n=19$), *Notioceramus anomalus* ($n=4$), *Peribolaster folliculatus* ($n=1$) and *Solaster regularis* ($n=1$). A distribution map was made for each of these species to show the known geographic distribution and the new records (Fig. 2). The highest number of asteroid species was found at 50–200 m depth (Fig. 3).

Species richness

The N MPA showed the highest number of species, thus representing the area with the highest asteroid richness, with 26 species records in this study (48%) (Tables 2, 3), whereas Tierra del Fuego province presented 12 species belonging to

8 families. Within the N MPA, the richness among subareas was quite similar (Table 3).

Geographic relationships

The dendrogram obtained after the cluster analysis suggested three regional groups with similar faunal composition (Fig. 4). One of the clusters was formed by the three subareas of the NMPA, with a faunal similarity greater than 50%, whereas the other two clusters were those formed by the BB shelf break and Tierra del Fuego Province fauna on their own.

Reproduction strategies

Regarding the reproduction strategies, 50% of the species found at the N MPA presented direct development with brooding females (Table 2), whereas the other 50% were species with lecithotrophic and planktotrophic larvae (25% each). An example of brooding female was observed in *Diploteraster verrucosus*, which carried its embryos in a nidamental chamber (Fig. 5).

Discussion

This study provides new information that allows comparing the marine benthic biodiversity of the N MPA and Tierra del Fuego Province, which are two areas at the same latitude and with similar bathymetry, but with different physical conditions (Table 1). The lower mean salinity in Tierra del Fuego Province (Beagle Channel and Atlantic Coast) than in the N MPA is due to the influence of melting and freshwater outflows. In addition, the fauna of Tierra del Fuego is probably affected by the physical conditions caused by anthropogenic activities such as urban effluents (Gil et al. 2011; Malanga et al. 2004).

A total of 32 Asteroidea species belonging to 14 families were collected in the sampling area. In almost all the areas studied, the most represented family was the Asteroiidae, whereas in the Beagle Channel the family with the highest richness was the Odontasteridae (Table 2). Our study contributes to increasing the knowledge on the bathymetric and geographic distribution of Asteroidea in the study area. It represents the first record in the area of interest for 7 of the 26 Asteroidea species found in the N MPA (Table 2): *A. pedicellaris*, *C. lurida*, *D. singularis*, *H. obesa*, *N. anomalus*, *P. folliculatus* and *S. regularis* (Fig. 2). Besides, special mention must be made about the *Odontaster* sp. found in the N MPA (transition subarea), which is probably a new record of *O. pearsei* (Janosik and Halanych 2010), although more

Table 2 List of the Asteroidea species recorded at the three subareas (core, buffer and transition) of the N MPA

Family	Developmental mode	Namuncurá MPA			BB shelf break	Tierra del Fuego	
		Core	Buffer	Transition		Beagle Channel	Coast
Asteriidae		5	4	3	3	1	3
<i>Anasterias antarctica</i>	Brooder ^a	X	X			X	X
<i>Anasterias pedicellaris</i>	Unknown	X	X	X			
<i>Asterina fimbriata</i>	Brooder ^b				X		
<i>Cryptasterias brachiata</i>	Brooder ^c	X	X				X
<i>Diplasterias brandti</i>	Brooder ^c	X	X	X			
<i>Diplasterias brucei</i>	Brooder ^d				X		X
<i>Lysasterias</i> sp.		X		X			
<i>Tremaster mirabilis</i>	Brooder ^e				X		
Astropectinidae		1	1	2	1	0	0
<i>Bathybiaster loripes</i>	Broadcaster with lecithotrophic larvae ^d			X	X		
<i>Leptychaster</i> sp.		X	X	X			
Benthopentiniidae		0	0	0	1	0	0
<i>Cheiraster (Luidiaster) gerlachei</i>	Broadcaster with planktonic larvae ^f				X		
Ctenodiscidae		0	0	1	0	0	0
<i>Ctenodiscus australis</i>	Brooder ^g			X			
Echinasteridae		2	1	2	2	1	0
<i>Henricia obesa</i>	Unknown	X	X	X	X	X	
<i>Henricia studeri</i>	Unknown	X		X	X		
Ganeriidae		1	1	1	0	0	1
<i>Perknaster fuscus</i>	Broadcaster with lecithotrophic larvae ^d	X	X	X			X
Goniasteridae		2	2	3	1	1	0
<i>Ceramaster patagonicus</i>	Broadcaster with lecithotrophic larvae ^h	X	X	X		X	
<i>Hippasteria falklandica</i>	Unknown			X			
<i>Notioceramus anomalus</i>	Unknown	X	X	X	X		
Heliasteridae		0	0	0	0	1	0
<i>Labidiaster radiosus</i>	Unknown					X	
Korethrasteridae		0	0	1	1	0	0
<i>Peribolaster folliculatus</i>	Unknown			X	X		
Odontasteridae		3	1	3	1	2	0
<i>Acodontaster elongatus</i>	Broadcaster with planktonic larvae ^b	X		X	X		
<i>Diplodontias singularis</i>	Broadcaster with planktonic larvae ^b	X					
<i>Odontaster meridionalis</i>	Broadcaster with planktonic larvae ^d					X	
<i>Odontaster penicillatus</i>	Broadcaster with planktonic larvae ^b	X	X	X		X	
<i>Odontaster</i> sp.				X			
Poraniidae		1	1	1	1	0	0
<i>Glabraster antarctica</i>	Broadcaster with lecithotrophic larvae ^h	X	X	X	X		
Pterasteridae		2	3	4	3	1	2
<i>Diplopteraster verrucosus</i>	Brooder ⁱ	X	X	X	X		X
<i>Pteraster affinis</i>	Brooder ^j			X	X	X	X

Table 2 (continued)

Family	Developmental mode	Namuncurá MPA			BB shelf break	Tierra del Fuego	
		Core	Buffer	Transition		Beagle Channel	Coast
<i>Pteraster stellifer</i>	Brooder ^k		X	X	X		
Pteraster sp.		X	X	X			
Solasteridae		0	1	0	1	0	0
<i>Solaster regularis</i>	Unknown		X		X		
Stichasteridae		1	0	0	1	1	1
<i>Cosmasterias lurida</i>	Broadcaster with plankto-trophic larvae ^l	X			X	X	X

BB shelf break and two areas of Tierra del Fuego Province (Beagle channel and Atlantic Coast). The taxa richness per family is indicated

^aSalvat (1985)

^bBernasconi (1970)

^cHyman (1955)

^dPearse and Bosch (1994)

^eO'Loughlin and Waters (2004)

^fMacBride (1920)

^gLieberkind (1926)

^hBosch (1989)

ⁱFisher (1940)

^jMcClary and Mladenov (1990)

^kJanies (1995)

^lPastor-de-Ward et al. (2007)

studies are required to confirm this. Additionally, with the 27 Asteroidea species already known in the area (De Broyer and Danis 2010; OBIS 2017), there are 34 recorded species in the N MPA. As this increases the number of species identified at the N MPA by 26%, this study also enlarges the biodiversity known in the area. It is also possible to re-describe the bathymetric dispersal of *P. folliculatus* and *C. turqueti*, which were found at a greater depth than previously informed (Bernasconi 1970; OBIS 2017).

The richness percentage was higher in the N MPA than in Tierra del Fuego Province and similar in the three subareas (Table 3). This reinforces the importance of continuing and improving conservation and research efforts in the N MPA as it represents an important biodiversity hotspot to preserve its benthic marine biodiversity (Schejter et al. 2016). Since the results of the cluster analysis suggested that the BB shelf break is a cluster on its own (Fig. 4) and due to the presence of deep-sea species, we firmly believe that the BB shelf break should be incorporated into the N MPA.

The N MPA shares species not only with Tierra del Fuego Province, but also with Antarctica. This includes species such as *A. pedicellaris*, *Henricia studeri*, *P. folliculatus* (De

Broyer and Danis 2010; OBIS 2017), *Bathybiaster loripes*, *Acodontaster elongatus* (Bernasconi 1970) and *Pteraster stellifer* (Gutt et al. 2014). The Antarctic Circumpolar Current is dominant in controlling the distribution pattern of the Antarctic fauna (Kim and Thurber 2007; Moles et al. 2015). Although the Polar Front functions as a thermal and hydrographic barrier that hampers the dispersal of marine organisms from north to south, it simultaneously promotes the dispersal of marine organisms from west to east in Antarctica (Barker and Thomas 2004). The BB receives the inflow of the Malvinas Current, which is formed mainly by the contribution of the masses of the Antarctic Intermediate Water and the Upper Circumpolar Water (Falabella 2017). Thus, the Malvinas current transports cold, nutrient-rich sub-Antarctic waters, corresponding to the subpolar oceanographic system (Falabella 2017). Differences in the reproduction strategies might explain composition variations between sites (Raguá-Gil et al. 2004; Moreau et al. 2017) as most of the species shared between the N MPA and Antarctica present pelagic planktotrophic or lecithotrophic larvae (Table 2). The Malvinas current might thus be facilitating the spread of their larvae toward the BB plateau. The dispersal capacity

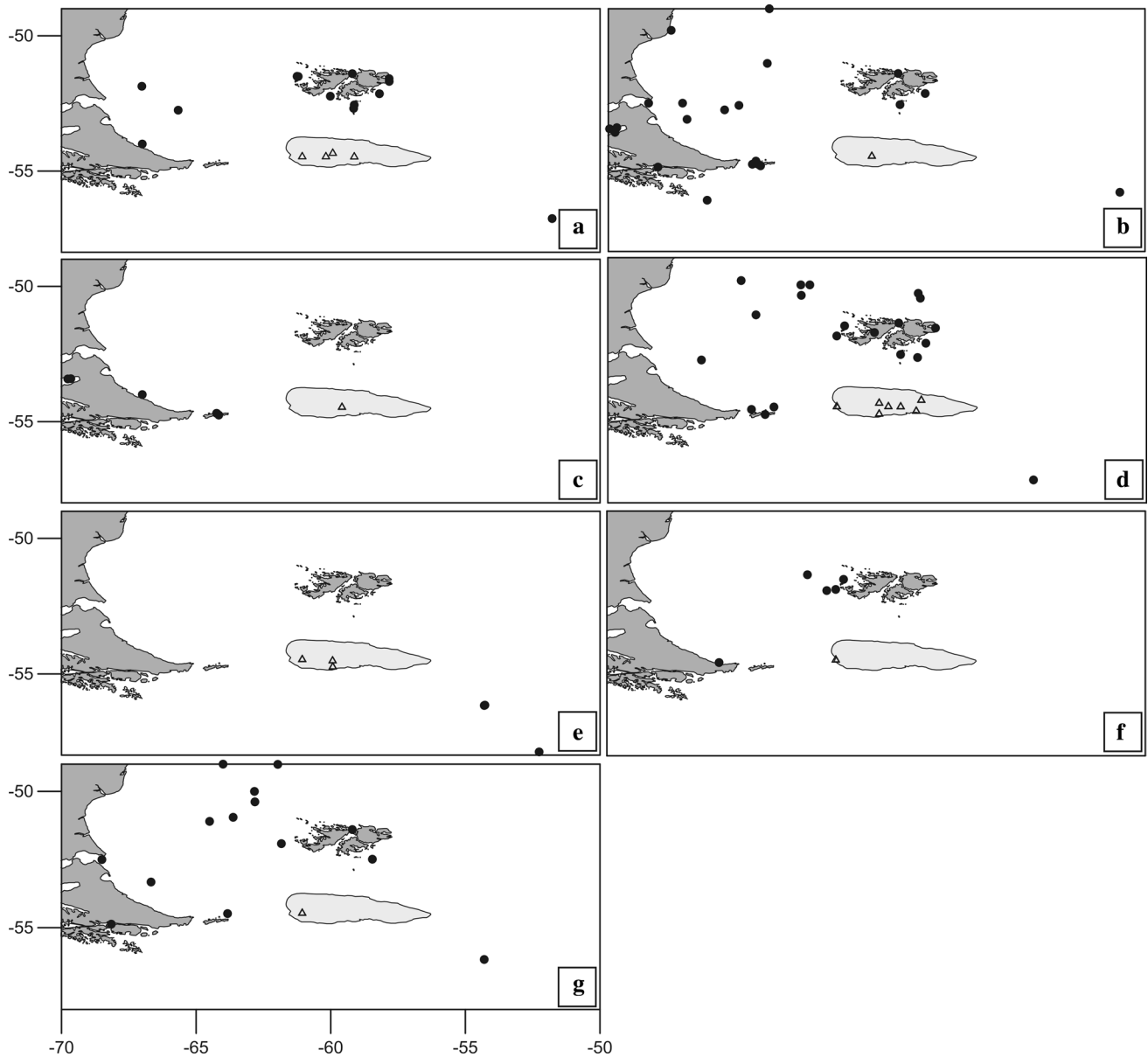


Fig. 2 Maps with the known geographic distribution (filled circle) taken from the literature (OBIS 2017) and new records (open triangle) in the N MPA for: **a** *Anasterias pedicellaris*; **b** *Cosmasterias*

lurida; **c** *Diplodontias singularis*; **d** *Henricia obesa*; **e** *Notioceramus anomalus*; **f** *Peribolaster folliculatus*; **g** *Solaster regularis*

of broadcasting species through the circumpolar current has been recently described by Moreau et al. (2017).

Regarding the other reproductive strategies, many (50%) of the species found at the N MPA presented direct development with brooding females (Tables 2, 3). *Anasterias antarctica* (Pearse and Bosch 1994), *C. turqueti* (Bernasconi 1970) and *Diplasterias brandti* (Bernasconi 1970) carry their embryos on the oral region over the mouth, *D. verrucosus* (Fisher 1940) (Fig. 5), *Pteraster affinis* and *P. stellifer*

(Hyman 1955) carry their offspring in nidamental chambers, and *Ctenodiscus australis* carries its embryos on the dorsal surface under the paxillae (Rivadeneira et al. 2017). The unusually numerous brooding species in the Southern Ocean may be the consequence of populations being repeatedly fragmented, with isolated units forming new species (Pearse et al. 2009). Non-pelagic development in the Southern Ocean may occur mainly in relatively few clades in which species proliferate (Pearse et al. 2009) rather than reflect an

Fig. 3 Species richness estimated for the samples collected at different depths from the N MPA, Burdwood Bank shelf break and Tierra del Fuego Province

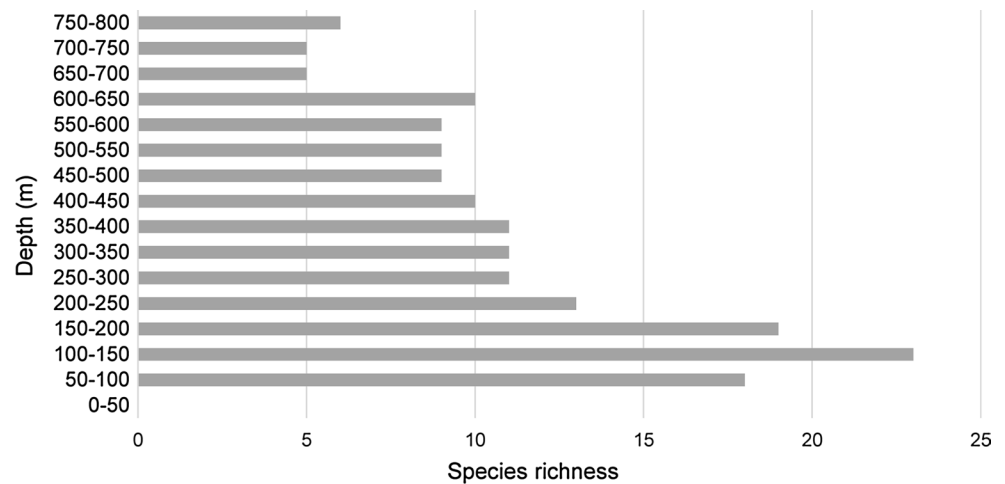


Table 3 Richness of Asteroid species collected from the N MPA, BB shelf break and Tierra del Fuego Province

Site	Asteroid species	Area in N MPA	Asteroid species
N MPA	26	Core	18
		Buffer	15
		Transition	21
BB shelf break	16		
Tierra del Fuego Province	12		

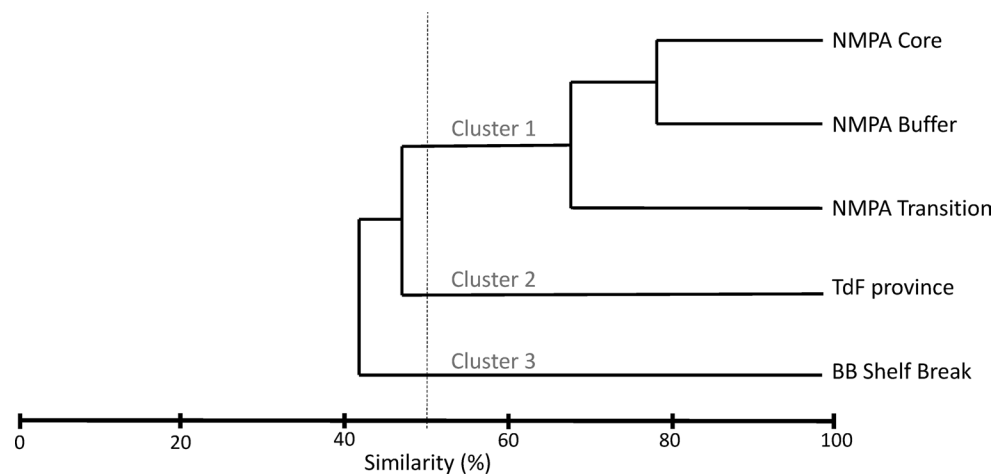
Comparison of the number of species within the N MPA (three sub-areas)

adaptation scattered among several clades to the peculiar conditions of polar seas, as it does elsewhere (Byrne et al. 2003). As postulated by Pearse et al. (2009), the occurrence of many species with non-pelagic development may be a

consequence of isolation after vicariant events that have led to their proliferation instead of specific adaptations to conditions in Antarctica.

Moreover, the lecithotrophic development eliminates the feeding stage and shortens the time larvae spend in the plankton. A lengthy period of development and energy utilization during brooding (Pearse et al. 1991) could deplete the reserves available to the juveniles. Depletion of adult somatic resources by limitations on feeding could also restrict the allocation of energy to reproductive tissues and delay future reproductive events (Bosch and Slatery 1999), also making these species more vulnerable to changing environmental conditions. This K-strategy means a tradeoff between the quantity and quality of offspring as brooding involves a high energetic cost and the production of large, slow-developing, nutrient-rich eggs, which often comes at the cost of reduced fecundity (Thatje 2018). As this work aims to highlight the importance of improving

Fig. 4 Hierarchical clustering (group average) of the Asteroidea fauna collected from all sampled areas by using the Bray-Curtis distance. A value of 50% of similarity was chosen as a threshold to group regions



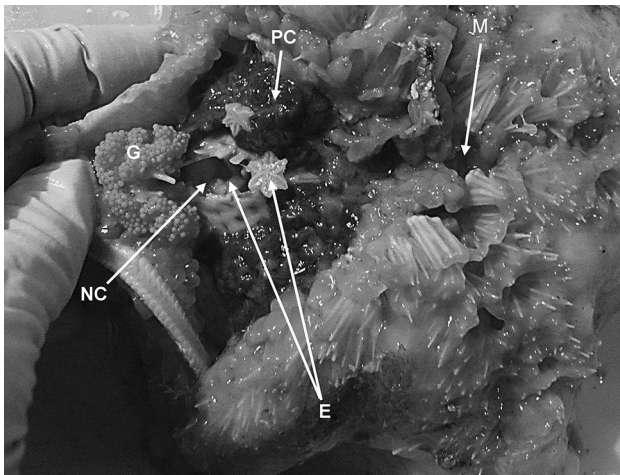


Fig. 5 Oral view of a female of *Diplopteraster verrucosus*. *E* embryo from the nidamental chamber, *G* gonad, *M* mouth, *NC* nidamental chamber, *PC* Pyloric caeca

the management of marine protected areas to preserve species richness and biodiversity, it is also important to focus on vulnerable species that require a greater effort of conservation.

By protecting predator populations, such as asteroid species, marine reserves can help prevent explosive prey growth and disease outbreaks (Packer et al. 2003; Planque et al. 2010). Moreover, as marine reserves support genetic diversity by increasing population sizes and broadening the selective environment, they promote adaptability and resilience and support populations outside reserve boundaries (Roberts et al. 2017).

We conclude that it is crucial to continue making efforts to increase the knowledge of ecosystems at these latitudes, in particular of the biologic and ecologic interactions that occur in them, to be able to formulate more accurate conservation strategies that enhance their protection.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national and/or institutional guidelines for the care and use of animals were followed.

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