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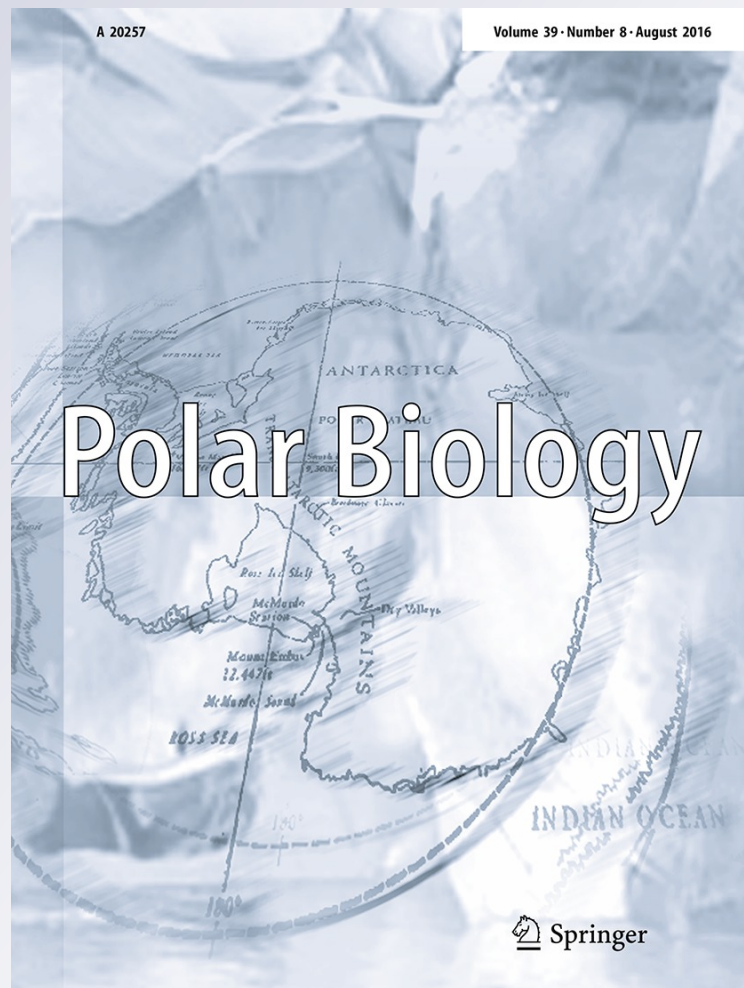
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Linking population trends of Antarctic shag (*Phalacrocorax bransfieldensis*) and fish at Nelson Island, South Shetland Islands (Antarctica)

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Abstract This study aims to provide consistent information to explain the steady declining trend in the number of breeding pairs of Antarctic shag *Phalacrocorax bransfieldensis* in two colonies on Nelson Island, South Shetland Islands, southern Atlantic sector of Antarctica, which was observed during the 1990s up to the mid 2000s over an overall monitoring period of over two decades. It addresses correspondence between long-term population trends of inshore demersal fish and inshore-feeding Antarctic shags of this area, where an intensive commercial fishery for shag prey once operated. The analysis also includes comparable information on diet (by examination of regurgitated pellets), foraging patterns, and breeding output of shags from the Danco Coast, western Antarctic Peninsula, an area where no commercial finfish fishery has ever existed. Integral study of these parameters there showed that, in Antarctic shags, low breeding success and high foraging effort might imply low recruitment and high adult mortality, respectively, with both factors adversely affecting

the population trends of this bird. In line with these premises, the declining trend observed in shag colonies on the South Shetland Islands appears to have been influenced by the concomitant decrease in abundance of two of their main prey, the nototheniids *Notothenia rossii* and *Gobionotothen gibberifrons*, due to intensive industrial fishing in the area in the late 1970s. In comparison, no such pattern occurred for the Danco Coast colonies.

Keywords Antarctic shag · Inshore fish · Notothenioids · Population trends · South Shetland Islands

Introduction

In Antarctica, the only flying bird species that feed chiefly on demersal coastal fish are the Antarctic shag *Phalacrocorax bransfieldensis*, which inhabits the Antarctic Peninsula and the South Shetland Islands, and the South Georgia shag *P. georgianus*, which inhabits the South Orkney Islands and the sub-Antarctic South Sandwich Islands, South Georgia, and Shag Rocks (Orta 1992). The diving ability of these shags (maximum diving depth and time: 120 m and 5.35 min, respectively) is similar to the diving abilities of the small Antarctic penguins (*Pygoscelis* spp.) (summarized in Casaux and Barrera-Oro 2006).

Analysis of pellets (=regurgitated casts) has been extensively used for shags and cormorants, and is an adequate method to estimate their diet qualitatively and quantitatively, reflecting differences in fish availability between years, seasons, and areas (Ainley and Boekelheide 1990; Casaux and Barrera-Oro 1993; Ainley et al. 1995). Caveats in applying this methodology have been identified (Barrett et al. 2007) with errors that can be minimized by means of adequate techniques (Casaux 2003). The diet of

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the Antarctic shag *P. bransfieldensis* in colonies on the South Shetland Islands agrees qualitatively and in relative numbers with the composition of fish regularly caught by bottom trammel/gill nets in the same area (Casaux and Barrera-Oro 1993). Notably, among the fish species caught inshore, only *Notothenia rossii* and *Gobionotothen gibberifrons* were absent or scarcely represented in the pellets (Barrera-Oro et al. 2000). For the South Shetland Islands this was not unexpected, since both fish species have decreased markedly in trammel-net catches over the last three decades due to commercial exploitation at the end of the 1970s (Barrera-Oro et al. 2000; Marschoff et al. 2012).

A steady declining trend in the number of breeding pairs of Antarctic and South Georgia shags has been reported for several colonies in the southern Scotia Arc region (Casaux and Barrera-Oro 1996; Naveen et al. 2000; Woehler et al. 2001; see summary in Ainley and Blight 2009). This demographic phenomenon in the South Shetland Islands was studied in detail at two colonies located at Duthoit Point and Harmony Point, Nelson Island, and Casaux and Barrera-Oro (2006) proposed that it was related to the low contribution of the two nototheniids targeted by the commercial fishery.

As a further test of this premise, the current study provides an analysis of the population trends of the two colonies of *P. bransfieldensis* on Nelson Island, monitored for a total period of 23 years. For comparison, the diet, foraging patterns, and breeding output of shags breeding at colonies on the Danco Coast, western Antarctic Peninsula, are also provided; the Danco Coast was not part of the commercial fishery.

Materials and methods

The data of fish sampled in the South Shetland Islands were taken from the study of Marschoff et al. (2012). Samples were collected in Potter Cove, King George Island/Isla 25 de Mayo, close to the Carlini Scientific Station (62°14'S and 58°40'W) from 1983 to 2010 (Fig. 1). Data from around 18,500 specimens caught in trammel nets belonging to the species *N. rossii*, *G. gibberifrons*, and *Notothenia coriiceps* were processed. Since sampling did not utilize a consistent amount of effort between years, catches per haul of *N. rossii* and *G. gibberifrons* were represented along time as their values relative to the catches of *N. coriiceps* obtained in the same haul. Details of the sampling and data processing methods are described in Marschoff et al. (2012).

Monitoring of the number of Antarctic shag breeding pairs on Nelson Island, South Shetland Islands, was carried out in summer in colonies at Duthoit Point (62°18'S, 58°47'W) in 1990, 1992–2004, and 2008, and at Harmony

Point (62°18'S, 59°11'W) in 1988–1989, 1995–1996, 2000–2005, and 2009–2010 (Fig. 1). The feeding ecology of the Antarctic shag in this area and the sampling procedures are described in Casaux and Barrera-Oro (2006).

The information on the Antarctic shag from the Danco Coast, west Antarctic Peninsula, was collected from the 20 December 1997 to 20 February 1998 breeding season at three colonies: Primavera Island (PI, 64°09'S, 60°59'W, 9 breeding pairs), Midas Island (MI, 64°10'S, 61°05'W, 23 breeding pairs), and Py Point (PP, 64°13'S, 61°00'W, 22 breeding pairs) (Fig. 1). The distance between the two farthest colonies (Primavera Island and Py Point) is 9.2 km. Diet was determined by analysis of 465 pellets (PI, 151 pellets; MI, 165 pellets; PP, 149 pellets) using the methods described in Casaux et al. (2002). Detailed information on the methodology used for the study of foraging effort, brood size, and breeding success at the three shag colonies is described in Casaux (2013).

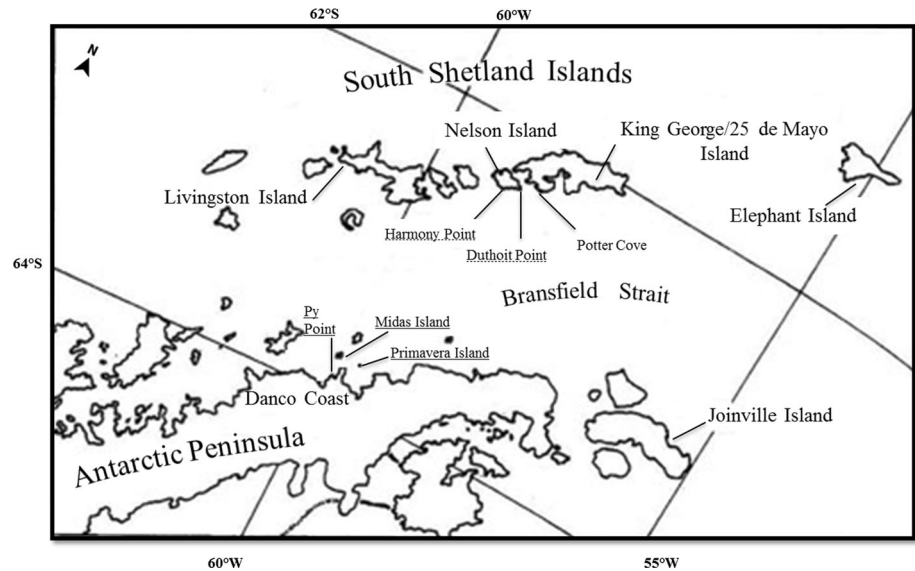
Results and discussion

Regular sampling of coastal fish populations can reveal changes in species prevalence within offshore marine ecosystems, owing to ontogenetic movement of size classes between these habitats (Casaux and Barrera-Oro 2002). Juvenile specimens of *N. rossii* and *G. gibberifrons* inhabit littoral waters, but the reproductive portion of the stock occurs offshore. Major changes in the offshore reproductive stock will be reflected in the inshore populations through recruitment processes. Associated with these species, the black rockcod *Notothenia coriiceps* is a species that was not commercially fished but has ecological habits in the fjords exploited by shags similar to the exploited species. The three species are demersal nototheniids that spend at least part of their life cycle in inshore waters (<120 m deep) but move ontogenetically to offshore shelf waters at depths down to 200–550 m (Barrera-Oro 2002).

Earlier research during 1983–1990, comparing catches among the three nototheniid species, showed a sharp decline in the abundance of young *N. rossii* and *G. gibberifrons* but not of *N. coriiceps* at several inshore South Shetland sites (Barrera-Oro et al. 2000). These juvenile fish are the size suitable for shag predation. Subsequent sampling at Potter Cove, King George Island/Isla 25 de Mayo, up to 2010 indicated that the population of *N. rossii* showed signs of recovery but is still far off the levels registered before the commercial fishery, while that of *G. gibberifrons* remains very low (Barrera-Oro and Marschoff 2007; Marschoff et al. 2012; for location of sites see Fig. 1).

The decline of inshore fish populations appears to have affected other components of the food web. As shags in

Fig. 1 The South Shetland Islands-Antarctic Peninsula region showing the main localities considered in this study: King George Island/Isla 25 de Mayo, Nelson Island, and the Danco Coast. Sites where shag colonies were affected and not affected by the commercial fishery are underlined with *dotted lines* and *full lines*, respectively



Antarctica feed heavily on inshore demersal fish, it might be expected that they will be affected by changes in prey availability in shallow waters. Not surprisingly, among the prey species caught with nets inshore at the South Shetlands, only *N. rossii* and *G. gibberifrons* have been absent or scarcely represented in shag's pellets (Table 1). The absence of otoliths from the two exploited species contrasts with the high occurrence of those from *N. coriiceps*. At the Danco Coast, western Antarctic Peninsula, high incidence of *G. gibberifrons* was observed both in the diet of shags and in trammel-net catches, reflecting higher availability of this fish in an area remote from the main historical fishing grounds of the South Shetland Islands (Elephant Island and north of Livingston/King George Islands) and the Antarctic Peninsula (Joinville-D'Urville Islands) (Casaux and Barrera-Oro 2006). The geographical distribution of *N. rossii* barely reaches the Danco Coast area (DeWitt et al. 1990), explaining its low frequency in the shag diet.

The numbers of Antarctic shag breeding pairs at the two colonies on Nelson Island show a declining trend over the sampling periods (Fig. 2). The Duthoit Point colony was monitored for almost 15 consecutive years (except in 1991) over a total period of 19 years. The time series at Harmony Point, due to logistic limitations, was not as long, about 10 years. At both colonies, the number of breeding pairs decreased from the late 1980s to 2004, then stabilized close to the lower values. The parallel decline in the abundance of the two exploited fish species in Potter Cove and that of the Antarctic shag *P. bransfieldensis* on Nelson Island, both nearby localities in the South Shetland Islands, is shown in Fig. 3.

To test the hypothesis expressed by Casaux and Barrera-Oro (1996), in the present study we considered comparable information on feeding ecology and breeding performance

of the Antarctic shag nesting on the Danco Coast, western Antarctic Peninsula, an area that remained outside of the main commercial fishing grounds. For this region, it was reported that the fish prey consumed at Py Point differed markedly from those consumed at three nearby colonies (Midas and Primavera Islands and Cape Herschel) (Casaux 2013). Interestingly, the diet of shags at Py Point was broadly similar to that observed for shags breeding on the South Shetland Islands (see Casaux et al. 1998 for review). Simultaneously with the diet study at the Danco Coast, information on foraging patterns and breeding output was also obtained at three of the Antarctic shag colonies sampled. This allowed comparison of the relationship between diet composition, foraging behavior, breeding performance, and population trends (Casaux 2013). Between colonies, there were marked differences in the size of the fish consumed, the smaller specimens being eaten by shags from Py Point. This was mainly influenced by the number of specimens of the smallest fish prey species, *Harpagifer antarcticus*, consumed at that colony. As mentioned, the composition of the diet of Antarctic shags from Py Point was similar to that observed at different localities on the South Shetland Islands. Compared with Midas Island and Primavera Island (where shags preyed intensively on *G. gibberifrons* and *N. coriiceps*), shags from Py Point displayed longer foraging trips and invested more time in foraging activities. Although at the beginning of the study the number of chicks per nest observed at the three colonies was similar, the breeding output at Py Point was markedly lower. The most likely explanation for the relatively higher foraging effort and lower breeding output observed at Py Point might be the differences in fish prey consumption between these shags and those from Midas Island and Primavera Island (Casaux 2013). It is possible that, because

Table 1 Fish represented in the diet of Antarctic shags breeding at different localities of the Danco Coast (1997–1998 summer season), Antarctic Peninsula, and South Shetland Islands (1995–1996 summer season)

	South Shetland Islands						Danco Coast					
	Harmony Point			Duthoit Point			Primavera I.			Midas I.		
	F%	N%	M%	F%	N%	M%	F%	N%	M%	F%	N%	M%
Nototheniidae												
<i>Gobionotothen gibberifrons</i> ^a	15.4	1.3	1.2	15.6	1.4	2.0	50.3	17.1	30.9	58.8	20.8	38.3
<i>Lepidonotothen larseni</i>	0.8	0.0	0.0	1.7	0.2	0.1	5.3	0.9	1.2	1.2	0.2	0.1
<i>Lepidonotothen nudifrons</i> ^a	25.6	7.6	6.3	42.8	16.5	9.0	60.3	19.3	8.8	60.6	18.3	6.2
<i>Notothenia coriiceps</i> ^a	76.7	13.1	65.9	72.8	10.2	62.0	49.7	8.8	33.0	58.2	15.9	39.5
<i>Notothenia rossii</i> ^a	1.9	0.2	1.2	2.9	0.2	2.0	0.7	0.1	1.7	–	–	–
<i>Pagothenia borchgrevinki</i>	–	–	–	–	–	–	2.0	0.3	0.2	4.2	0.4	0.3
<i>Trematomus bernacchii</i> ^a	2.6	0.3	0.2	4.0	0.3	0.3	27.2	4.5	5.7	21.2	4.4	3.9
<i>Trematomus newnesi</i> ^a	7.5	0.7	0.6	23.7	3.5	3.3	53.0	14.9	11.4	58.8	20.6	10.2
<i>Trematomus scotti</i>	–	–	–	–	–	–	3.3	0.2	0.3	0.6	0.1	0.1
Harpagiferidae												
<i>Harpagifer antarcticus</i> ^a	41.4	68.5	22.7	50.9	53.6	19.8	28.5	22.0	5.6	20.0	7.8	1.8
Bathydraconidae												
<i>Gymnodraco acuticeps</i>	0.4	0.0	0.1	–	–	–	–	–	–	–	–	–
<i>Parachaenichthys charcoti</i>	2.3	0.1	1.2	2.9	0.2	1.5	2.7	0.3	1.1	1.8	0.2	0.1
Channichthyidae												
<i>Chaenodraco wilsoni</i>	–	–	–	–	–	–	0.7	0.1	0.1	–	–	–
<i>Pseudochaenichthys georgianus</i>	0.4	0.0	0.2	–	–	–	–	–	–	–	–	–
Myctophidae												
<i>Electrona antarctica</i>	0.8	0.0	0.0	–	–	–	0.7	0.1	0.0	–	–	–
<i>Gymnoscopelus nicholsi</i>	0.8	0.0	0.1	–	–	–	–	–	–	–	–	–
<i>Protomyctophum normani</i>	–	–	–	–	–	–	–	–	–	–	–	–
Paralepididae												
<i>Notolepis coatsi</i>	0.4	0.0	0.0	–	–	–	–	–	–	0.6	0.1	0.0
Unidentified	44.0	8.0	–	53.8	14.0	–	60.9	11.4	–	52.1	11.3	–

^a Species most frequently caught inshore with nets: F%, frequency of occurrence; N%, importance by number; M%, importance by mass

Fig. 2 Population trends observed in Antarctic shag colonies at Harmony Point and Duthoit Point, Nelson Island, South Shetland Islands

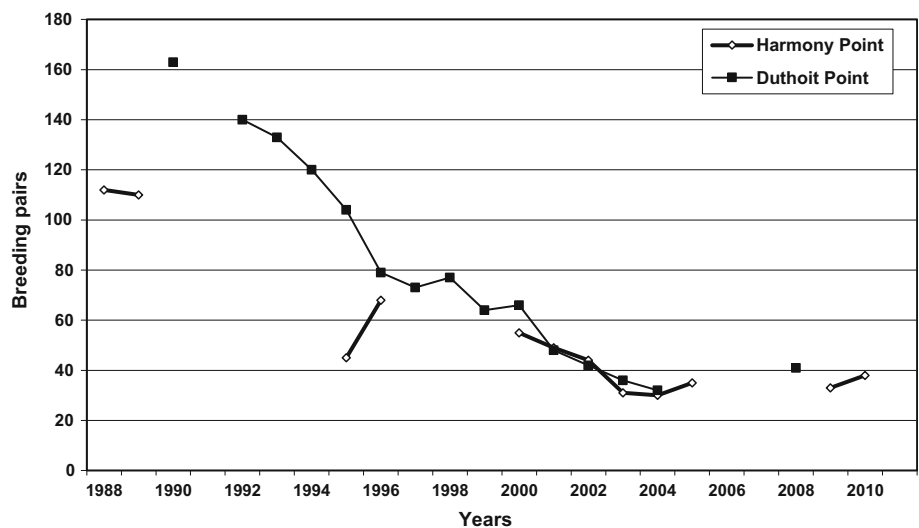
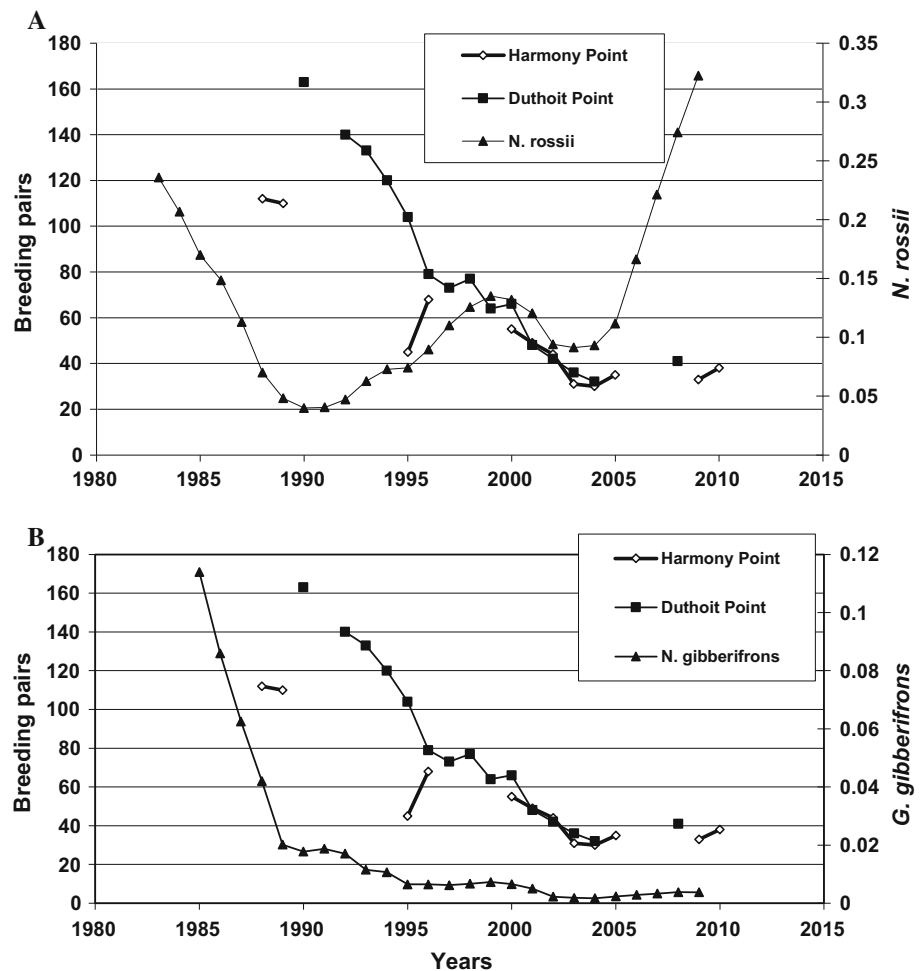


Fig. 3 Declining trends in inshore populations of two commercially exploited fish species and the simultaneous decrease in shag colonies, both at the South Shetland Islands. The curves of *Notothenia rossii* (a) and *Gobionotothen gibberifrons* (b) are reproduced from the study of Marschoff et al. (2012) in Potter Cove and are expressed in numbers relative to the abundance of the ecologically similar *Notothenia coriiceps*, because fish sampling did not utilize a consistent amount of effort between years



of the lower availability of *G. gibberifrons* around Py Point (see Casaux et al. 2003), the shags from this colony foraged more intensively on other demersal fish species, such as the smaller and more cryptic *H. antarcticus*, and this may have resulted in an increase of the time required to cover the energetic demands of the foraging trips. Owing to the proportional contribution to the diet by mass of the different fish species, to cover their own energy requirements and those of their chicks, each pair has to consume roughly 212 fish/day at Py Point, 160 fish/day at Midas Island, and 175 fish/day at Primavera Island (Casaux 2013). The distinct diet composition of the shags from Py Point, with a higher number of smaller prey, seems to be in line with the higher foraging effort, and consequently the lower breeding output, observed for this colony. Supporting this view are the facts that *H. antarcticus* lives sheltered under rocks, reducing access by shags, and that larger fish provide proportionately more energy than smaller ones (Hislop et al. 1991; see also Fritz et al. 2001); Cairns (1987), Burger and Piatt (1990), and Monaghan et al. (1994) reported that, in seabirds, use of time at sea is correlated

with prey availability, whereas Montevecchi (1993) indicated that prey availability influences foraging strategy, breeding output, and population parameters of their predators. In fact, these relationships are apparent and have been studied intensively among shags at the Farallon Islands, California, as well as in closely related cormorant species at the same location (Ainley and Boekelheide 1990; Elliott et al. 2015). In this sense, while analyzing the factors influencing the declining trend observed in Imperial shags *P. atriceps* at Nahuel Huapi Lake, Patagonia, Argentina, Casaux et al. (2010) observed that, due to low targeted fish availability, shags foraged on less profitable prey such as crustaceans, a pattern also seen at the Farallon Islands (Ainley and Boekelheide 1990). Foraging on crustaceans resulted in a comparatively lower rate of energy intake and, consequently, chick food provisioning, which negatively affected the shags' population trend.

In addition to the declining trend observed in shag colonies in the southern Scotia Arc (see "Introduction"), at Marion Island, sub-Antarctic Indian Ocean, a decrease in Crozet shag *P. marionensis* colony has been similarly

reported as being caused by altered availability of food, and especially a changed dominance in nototheniid prey in the diet (Crawford et al. 2003). Industrial fishing for demersal species has been intensive in these waters as well (Kock 1992). Furthermore, correlations between the populations of other high predators and fish biomass in predator foraging areas show that southern elephant seals *Mirounga leonina*, Antarctic fur seals *Arctocephalus gazella*, gentoo penguins *Pygoscelis papua*, and macaroni penguins *Eudyptes chrysolophus* all feed extensively on notothenioids (suborder Notothenioidei) (Barrera-Oro 2002; Ainley and Blight 2009). Monitoring of these seal and penguin populations where commercial fishing was concentrated showed their simultaneous decline during the periods of heavy fishing (Ainley and Blight 2009).

While the effects of climate change on marine ecosystems in the Antarctic Peninsula region have been substantial (e.g., Atkinson et al. 2004; Ducklow et al. 2007; Murphy et al. 2007), the consequences of major fish extraction by man are very important, too. In line with these premises and with results from the Danco Coast, the decrease at the South Shetland Islands of the inshore nototheniids *G. gibberifrons* and *N. rossii*, likely to have once been important fish prey of the Antarctic shag, would have influenced the declining trend in the number of breeding pairs at these colonies. These findings, obtained within the range of the Antarctic shag, also reflect the sensitivity of this bird's reproductive and behavioral parameters to significant changes in the availability of inshore fish.

The examples above show that substantive changes at one level of the food web can be traced to changes in other components, supporting the hypothesis of Ainley and Blight (2009) that the structure of the marine ecosystem of the western Antarctic Peninsula has been affected not just by climate change, weather, and sea ice, but equally by extractions of seals and whales as well as of fish in the 1970s and 1980s (see also Emslie and Patterson 2007). The consequences of these extractions were not at all unexpected. Inter alia, regarding whales and with respect to the ecological impact of fishing, Suarez (1927) already warned about the effects of intensive exploitation of marine species in the Antarctic.

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