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Long-term trends in the abundance and breeding performance in Adélie penguins: the Argentine Ecosystem Monitoring Program

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Abstract In this work, we report long-term trends in the abundance and breeding performance of Adélie penguins (*Pygoscelis adeliae*) nesting in three Antarctic colonies (i.e., at Martin Point, South Orkneys Islands; Stranger Point/Cabo Funes, South Shetland Islands; and Esperanza/Hope Bay in the Antarctic Peninsula) from 1995/96 to 2022/23. Using yearly count data of breeding groups selected, we observed a decline in the number of breeding pairs and chicks in crèche at all colonies studied. However, the magnitude of change was higher at Stranger Point than that in the remaining colonies. Moreover, the index of breeding success, which was calculated as the ratio of chicks in crèche to breeding pairs, exhibited no apparent trend throughout the study period. However, it displayed greater variability at Martin Point compared to the other two colonies under investigation. Although the number of chicks in crèche of Adélie penguins showed a declining pattern, the average breeding performance was similar to that reported in gentoo penguin colonies, specifically, those undergoing a population increase (even in sympatric colonies facing similar local conditions). Consequently, it is plausible to assume a reduction of the over-winter survival as a likely cause of the declining trend observed, at least in the Stranger Point and Esperanza colonies. However, we cannot rule out local effects during the breeding season affecting the Adélie population of Martin Point.

Keywords **long-term monitoring, Adélie penguin, breeding pairs, chicks crèched, breeding success, population trends**

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1 Introduction

The western Antarctic Peninsula and the Scotia Arc are subject to significant environmental changes. In the last decades, an increase in air and sea surface temperature has been reported, conducting anomalies in the atmospheric and oceanic circulation and a consequent spatio-temporal winter sea-ice loss (Kerr et al., 2018 and references therein). This led to the retreat of glaciers, ice-shelf collapse (Cook et al.,

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2016), ocean acidification (Sabine et al., 2004), changes in the wind regime (Ducklow et al., 2013), and an increase in the frequency of years with more snow accumulation (Thomas et al., 2008).

Environmental variability impacts the Antarctic ecosystem, affecting ecosystem processes with marked variability at the regional level (e.g., Bestley et al., 2020). These changes alter the concentration and composition of the primary producers (Ferreira et al., 2020; Schofield et al., 2017), which has cascading effect on the food web. Likewise, some authors reported fluctuations in the abundance, distribution, and recruitment of planktonic species, such as Antarctic krill (*Euphausia superba*, hereinafter referred to as krill) (Atkinson et al., 2019; Johnston et al., 2022), which showed bottom-up impacts with consequences for their predators, such as Pygoscelid penguins (e.g., Forcada and Trathan, 2009; Trathan and Hill, 2016; Trivelpiece et al., 2011). Therefore, environmental variability can impact ecosystem health through changes in the demography, phenology, distribution, foraging behavior, and diet of predators or by disruptions in interactions between species (e.g., Cimino et al., 2016; Forcada and Trathan, 2009; Ropert-Coudert et al., 2019; Trivelpiece et al., 2011).

Added to the impact of environmental variability on the krill population (sea ice-dependent species), the krill is also the target of commercial exploitation operating mainly in the waters of the northern Antarctic Peninsula and adjacent islands (Hinke et al., 2017a; Krüger, 2019). However, due to the increase in ice-free waters (as a consequence of the reduction in the extent of winter sea-ice) and the improvement in fishing gear and the operational capacity of fishing vessels, the spatial distribution of the krill fishery has expanded to the south-west of the Antarctic Peninsula (Krüger, 2019; Krüger et al., 2021).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was created in response to the increasing krill fisheries to avoid over-exploitation and maintain ecological relationships (Hill et al., 2016). The objective of CCAMLR is to conserve Antarctic marine living resources, and for this, it has a precautionary and ecosystem-based approach to the management of the fishery (i.e., it does not exclude the resource exploitation if they are carried out sustainably). In this sense, the Commission proposed – based on the best scientific information available – a series of conservation measures to regulate resource exploitation in the waters south of the Antarctic Convergence, considering species of economic interest as well as those species that depend on them. The CCAMLR sets precautionary catch limits on the krill fishery, which are under constant review.

Furthermore, the CCAMLR has implemented a CCAMLR Ecosystem Monitoring Program (CEMP), which involves monitoring the land-based krill-dependent predators (such as penguins), the target species, the extraction strategies, and the environmental parameters. The aims of the CEMP are: (1) to detect and record significant changes in critical components of the ecosystem, serving as a basis for the conservation of Antarctic marine living resources; and (2) to distinguish between changes due to harvesting of commercial species from those changes that are the product of environmental variability, both physical and biological.

Among the indicator species used by the CEMP to monitor changes in the status of the ecosystem, there are the three Pygoscelid penguin species: ice-loving Adélie penguins (*Pygoscelis adeliae*), ice-tolerant chinstrap penguins (*P. antarctica*), and ice-avoiding gentoo penguins (*P. papua*). The Adélie penguin has the strongest ties to sea ice since it overwinters and molts on the ice (Ainley, 2002). These penguins are bioindicators of the ecological health of the ecosystem and environmental variability since they are sensitive to changes in the availability of their prey and vulnerable to human activity and degradation or alteration of the marine and terrestrial habitat (Boersma, 2008; Roupert-Coudert et al., 2019). However, their biological responses will depend on the life strategies of each species, their sensitivity and intrinsic plasticity, and the regional and local conditions that they must face at each stage of their life cycle (e.g., Borowicz et al., 2018; Casanovas et al., 2015; Cimino et al., 2016, 2019; Forcada et al., 2006; Fraser et al., 2013; Roupert-Coudert et al., 2019; Talis et al., 2023). Therefore, it is important to evaluate the impact of environmental alterations and anthropic activities on penguins in different sites simultaneously.

Since 1995, the "Ecosystem Monitoring – CCAMLR" project has been developed by the Instituto Antártico Argentino, Dirección Nacional del Antártico (under the Ministerio de Relaciones Exteriores y Culto). Thus, this project has a long-term database of breeding and trophic parameters for all three Pygoscelid penguin species in different Antarctic localities (i.e., south of 60°S), which is essential to assess their population trends and ecological responses (Roupert-Coudert et al., 2019; Taig-Johnston et al., 2017).

The Argentine CEMP first monitored three colonies (Figure 1): (1) Martin Point on Laurie Island (South Orkneys Islands); (2) Stranger Point/Cabo Funes on 25 de Mayo/King George Island (South Shetland Islands); and (3) Esperanza/Hope Bay at the tip of the Antarctic Peninsula. More recently, we began to study the penguin populations breeding at Cierva Cove (Danco Coast) and Paradise Bay, both on the west coast of the Antarctic Peninsula, and those located on Seymour (Marambio) Island, in the east of the Antarctic Peninsula. Thereby, we can have a comprehensive panorama to compare populations facing different local conditions, identify patterns of changes, and evaluate the underlying ecological processes.

Currently, the Ecosystem Monitoring program of the Instituto Antártico Argentino is working on:

(1) The updating of the population sizes of the different colonies to contribute to the estimation of the total number of penguins in the Antarctic Peninsula and islands of the

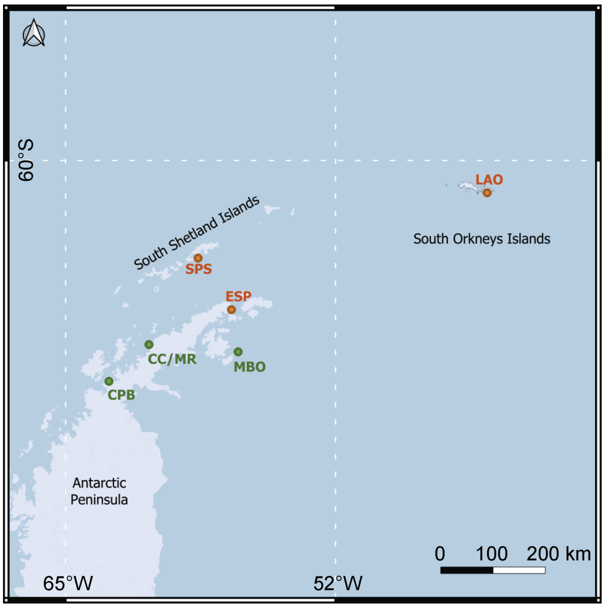

Figure 1 Studied colonies. In orange those monitored from 1995/96: (1) Martin Point, on Laurie Island (LAO); (2) Stranger Point, on 25 de Mayo/King George Island (SPS) and (3) Esperanza/Hope Bay (ESP). In green those more recently monitored: (4) Cierva Cove and Mar Rock (CC and MR, respectively); (5) Paradise Bay (CPB), both in the west of the Antarctic Peninsula, and (6) Seymour (Marambio) Island (MBO), in the east of the Antarctic Peninsula.

Scotia Arc (e.g., Talis et al., 2023). This, coupled with information on diet, will allow us to estimate krill consumption by these species (Santos et al., 2018).

(2) The recording of breeding parameters (such as the chronology and breeding success and the body conditions of the emancipated chicks) to evaluate the potential effect of environmental variability (Cimino et al., 2019; Hinke et al., 2007, 2012; Juáres et al., 2013).

(3) The determination of feeding areas during the breeding season to identify high-quality areas (Handley et al., 2021) and evaluation if there is an overlap between areas used by predators and those exploited by the fishery (e.g., Hinke et al., 2017a; Watters et al., 2020).

(4) The determination of overwinter zones, since the different strategies used by each species can be a determining factor of their population trends (e.g., Korczak-Abshire et al., 2021).

Changes in the population size and breeding success of penguins can be used as indicators of shifts in their ecosystem (CCAMLR, 2014). In the last decades, significant changes in population trends of Pygoscelid penguins have been reported in the western Antarctic Peninsula and adjacent islands. Several Adélie and chinstrap penguin populations have experienced a marked population decline (Cimino et al., 2019; Dunn et al., 2016; Fraser et al., 2013; Hinke et al., 2017b; Lynch et al., 2012; Santos et al., 2018; Talis et al., 2023; Trivelpiece et al., 2011; among others). In contrast, gentoo penguin colonies have remained stable or increased in breeding population size (e.g., Casanova et al., 2015; Dunn et al., 2016; Herman et al., 2020; Juáres et al., 2020; Lynch et al., 2012; Talis et al., 2023). Furthermore, even a southward expansion in its breeding range has been reported, which is consistent with documented population growth (Herman et al., 2020). Here, we update information on the abundance and breeding performance of Adélie penguins that nest in three Antarctic colonies (i.e., on South Orkneys Islands, South Shetland Islands, and Antarctic Peninsula), and assess the direction and magnitude of changes in the number of breeding pairs and chicks in crèche over a 28-year period (from 1995/96 to 2022/23).

2 Materials and methods

2.1 Study areas

Fieldwork was carried out on three Adélie penguin breeding colonies (Figure 1): (1) Martin Point (60°46′S, 44°42′W; Mossman Peninsula, Laurie Island, South Orkneys Islands); (2) Stranger Point/Cabo Funes (62°16′S, 58°37′W; Potter Peninsula, 25 de Mayo/King George Island, South Shetland Islands) and (3) Esperanza/Hope Bay (63°24′S, 57°01′W; Antarctic Peninsula).

Following Carlini et al. (2009), a breeding group was defined as an assemblage of individuals nesting as a geographically continuous unit within a colony. At Stranger Point, almost all breeding groups (i.e., all groups except for four of them. Please see Carlini et al., 2009) were annually surveyed, while 24 and 26 selected breeding groups were annually counted at Martin Point and Esperanza/Hope Bay (Santos et al., 2018), respectively.

2.2 Abundance and breeding performance

During 28 breeding seasons (from 1995/96 to 2022/23), we counted annually in selected breeding groups: (1) the total number of breeding pairs (as the sum of the number of nests with eggs – identified by birds lying down in a nest – and pairs occupying an empty nest) approximately one week after the peak of egg-laying; and (2) the total number of chicks in crèche when at least two-thirds of the chicks had entered crèche. According to the standard protocols defined by the CEMP (CCAMLR, 2014), each breeding group was counted by eye for three times, and its mean value was calculated, and these were then summed.

We estimated the breeding population size from the sum of all breeding pairs and the productivity as the sum of all chicks in crèche. Furthermore, we assessed the direction and magnitude of abundance changes calculating the percentage annual change (P) in the number of breeding pairs and chicks reared to crèche.

$$P(\%) = (X_{s+1} / X_s - 1) \times 100\,, \tag{1}$$

where X_s is the population size or chicks in crèche in season s.

We also calculated the annual intrinsic rate of population changes as:

$$R=(\ln X_{s+1}-\ln X_s)^T, \quad (2)$$

where $\ln X_s$ is the natural logarithm of the population size or chicks in crèche in season s, and T is the time interval between each count.

Additionally, we calculated the index of breeding success (IBS) as total chicks in crèche/total breeding pairs (CCAMLR, 2014). This index was estimated for each season when both counts were available.

Line charts ("ggplot" function from the ggplot2 package; Wickham, 2016) and scatter plots ("plot" function from the R base package), with the corresponding linear regressions, were performed with R software v.4.2.3 (R Core Team, 2023) in RStudio software v.3.0.386 (Posit Team, 2023). Furthermore, we used the Spearman correlation coefficient to establish whether there was a relationship between the analyzed parameters ("cor.test" function). The significance level was assumed at α=0.05.

QGIS 3.30 was used to make the map. The topography map of the Antarctic Peninsula was sourced from the Antarctic Digital Database (https://www.scar.org/data-products/antarctic-digital-database/).

3 Results

3.1 Abundance

Overall, the total number of Adélie penguin breeding pairs on Stranger Point decreased by 89.8% between 1995/96 (5293 pairs) and 2022/23 (542 pairs) at an annual rate of −8.4% (Figure 2a) while the breeding population on Martin Point decreased by 65.9% at a rate of −4.0% per annum (from 3377 to 1153 pairs). Finally, the number of Adélie penguins on Esperanza/Hope Bay declined from 5096 to 3275 breeding pairs, which represents a decline of 35.7% (−1.6% per annum) throughout the study period. Despite the differences observed in inter-annual fluctuations and the rate of decrease, the number of breeding pairs was positively correlated between colonies, i.e. it had a similar variability over time (Figure 3).

Over the study period, the total number of chicks in crèche of Adélie penguins declined by 93.1% at Stranger Point (from 6169 to 427 chicks) at an annual rate of −9.9% (Figure 2b) while the number of chicks decreased by 67.6%

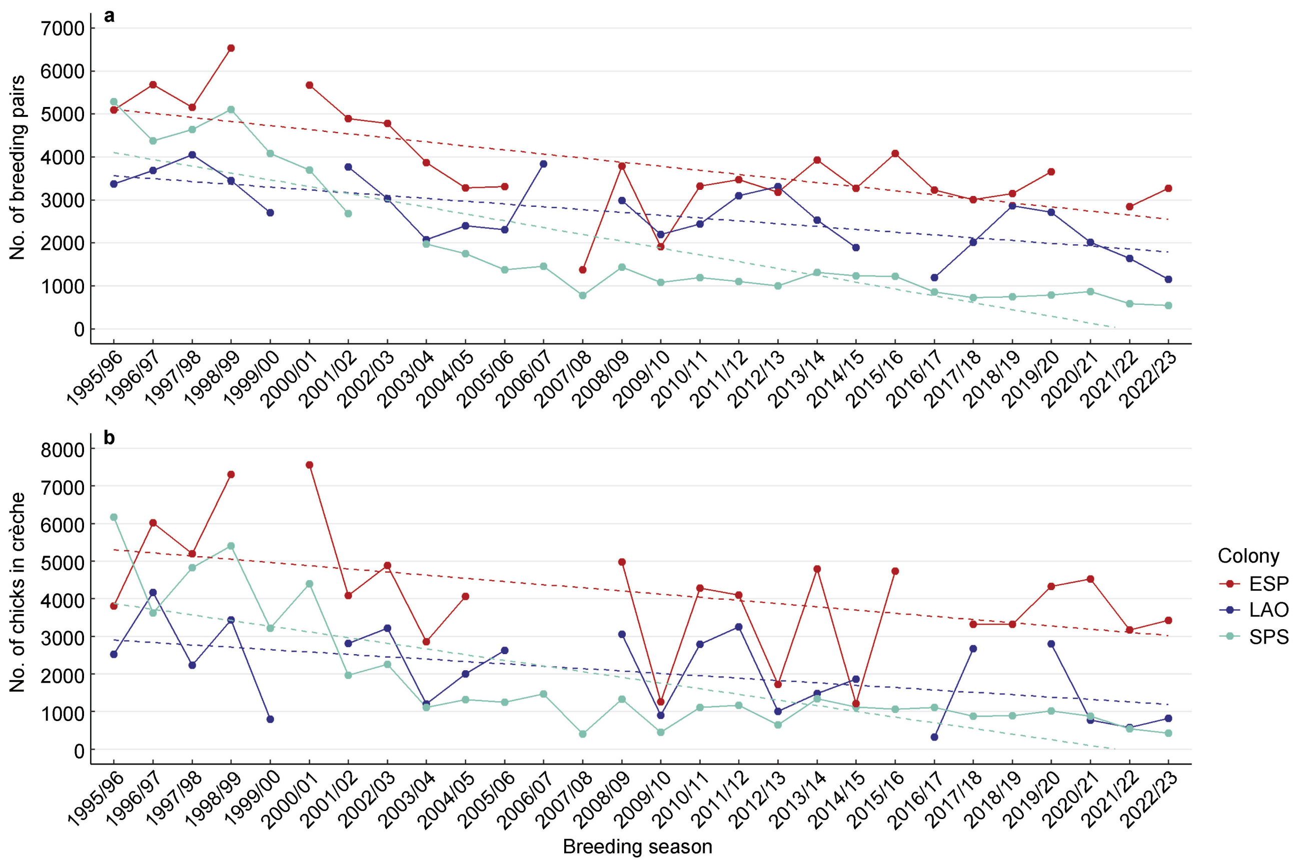

Figure 2 Inter-annual fluctuations in the total number of breeding pairs (**a**) and chicks in crèche (**b**) of Adélie penguins (*Pygoscelis adeliae*) at Martin Point (Laurie Island, South Orkneys Islands. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island, South Shetland Islands. SPS) and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23. Linear regressions of the abundance were plotted. Part of this data was previously published by Alfonso et al. (2022), Juáres et al. (2015), and Santos et al. (2018).

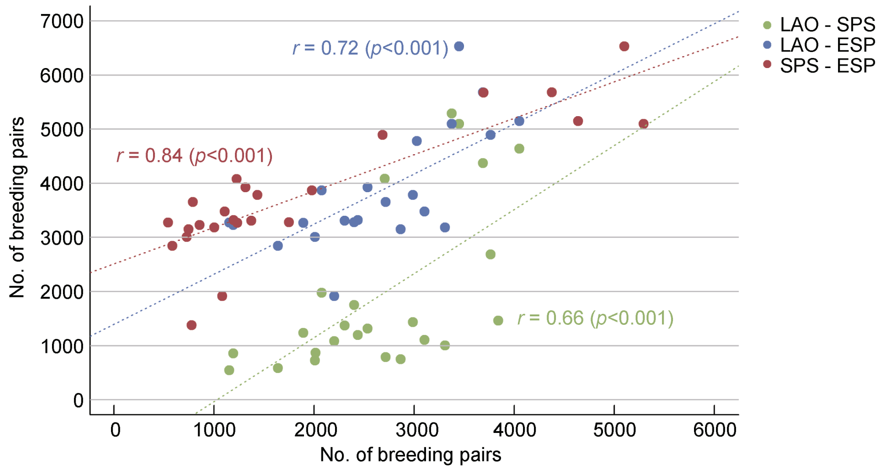

Figure 3 Spearman's correlations among the total number of breeding pairs recorded in Adélie penguins breeding at Martin Point (Laurie Island. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island. SPS), and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23.

at Martin Point (from 2525 to 819 chicks, −4.2% per annum). In contrast, and despite the large inter-annual variations observed, the number of chicks crèched on Esperanza/Hope Bay only fluctuated by 10% between 1995/96 (3808 chicks) and 2022/23 (3428 chicks) at an annual rate of −0.4%. Just like the number of breeding pairs, the total number of chicks showed a significant positive correlation between colonies (Figure 4).

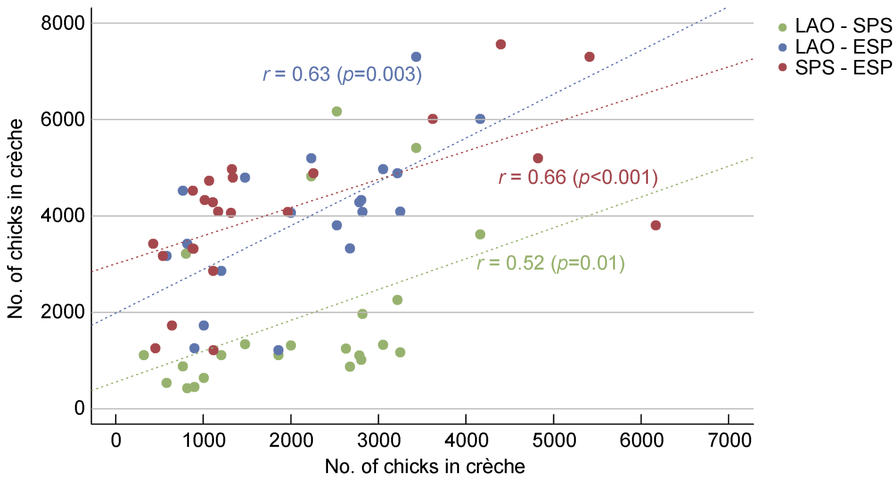

Figure 4 Spearman's correlations among the total number of chicks in crèche recorded in Adélie penguins breeding at Martin Point (Laurie Island. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island. SPS), and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23.

3.2 Index of breeding success

IBS values are shown in the Table 1. The mean IBS represents an average breeding performance of 38.4% (range=13.5%–66.5%), 46.4% (range=21.0%–64.9%), and 50.8% (range=18.6%–66.6%) for Martin Point, Stranger Point, and Esperanza/Hope Bay, respectively. IBS did not show a declining trend throughout the study period (Figure 5). Nevertheless, a higher temporal fluctuation of breeding performance was observed at Martin Point (Laurie Island. CV=42.9%, Figure 5 and Table 1). IBS was positively correlated between Esperanza and the other two colonies (i.e., LAO and SPS), but there was no significant correlation between Martin Point and Stranger Point (Figure 6).

4 Discussion

Pygoscelid penguins are excellent bioindicators of the state of ecosystem health (e.g., Boersma, 2008), used to assess the potential effects of environmental variability and resource exploitation on the populations (CCAMLR, 2014). In this sense, the long-term study of key parameters in the Pygoscelid penguin populations is essential to have reference data, identify population trends, and assess the potential ecological processes underlying such changes (Roupert-Coudert et al., 2019; Taig-Johnston et al., 2017).

In this study, we report the updated abundance and breeding performance of Adélie penguins nesting in three

Table 1 Index of breeding success (i.e., total chicks in crèche/total breeding pairs) of Adélie penguins at Martin Point (Laurie Island. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island. SPS), and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23

	Mean ± SD	Range	CV/%
Laurie Island (LAO)	0.77±0.33	0.27–1.33	42.9
Stranger Point (SPS)	0.93±0.23	0.42–1.30	24.8
Esperanza (ESP)	1.02±0.26	0.37–1.33	25.6

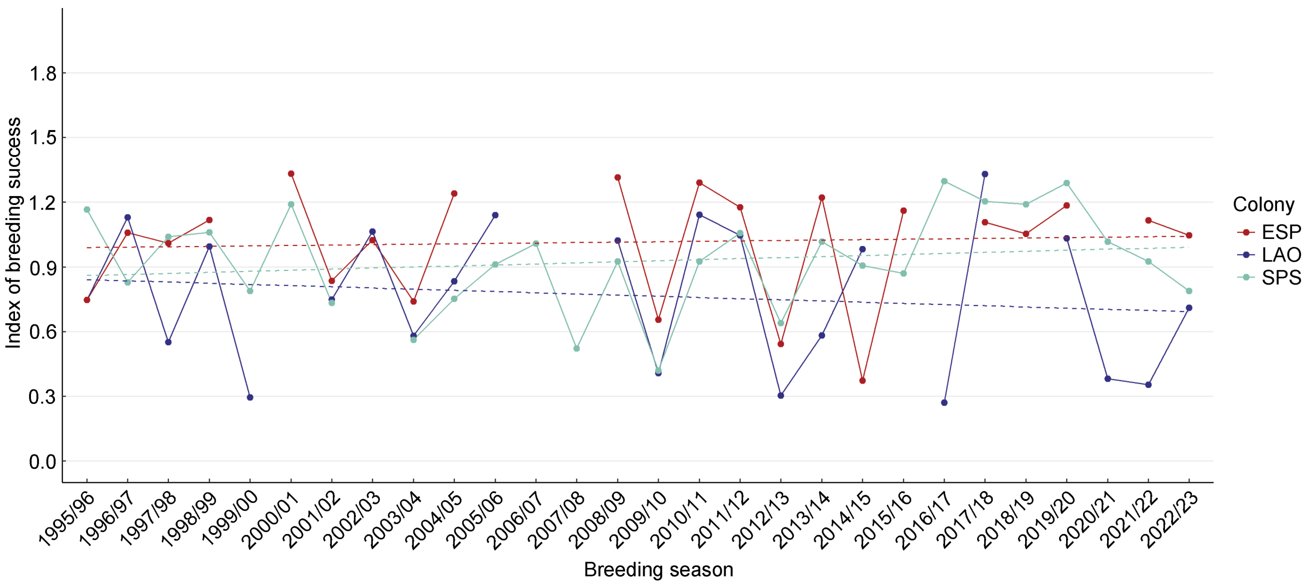

Figure 5 Inter-annual fluctuations in the index of breeding success of Adélie penguins (*Pygoscelis adeliae*) at Martin Point (Laurie Island, South Orkneys Islands. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island, South Shetland Islands. SPS) and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23. Linear regressions of the abundance were plotted. Part of this data was previously published by Juáres et al. (2015).

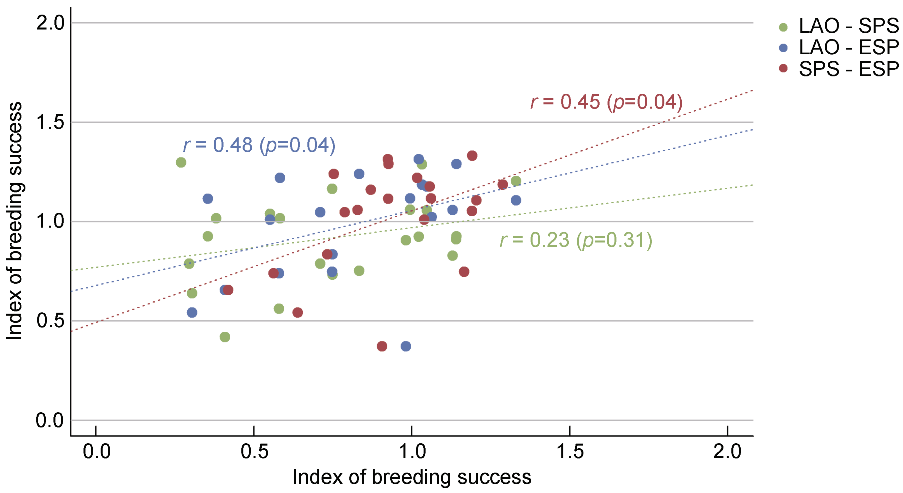

Figure 6 Spearman's correlations among the index of breeding success recorded in Adélie penguins breeding at Martin Point (Laurie Island. LAO), Stranger Point/Cabo Funes (25 de Mayo/King George Island. SPS), and Esperanza/Hope Bay (Antarctic Peninsula. ESP) from 1995/96 to 2022/23.

Antarctic colonies where Argentine CEMP holds a long-term monitoring program (Figure 1). From 1995/96 to 2022/23, the number of Adélie penguin breeding pairs has fallen at all colonies studied (although the number of breeding pairs observed at Stranger Point and Esperanza remained more stable or slowly declining since 2010/11 approximately) (Figure 2a). However, the magnitude of change was markedly higher at Stranger Point (25 de Mayo/King George Island) than in the remaining colonies, followed by Martin Point (Laurie Island) and Esperanza (tip of the Antarctic Peninsula). A similar trend was observed in productivity (Figure 2b), although the breeding performance was more variable at Martin Point than in the other colonies (Figure 5, Table 1). Furthermore, despite the differing rates of change, we observed strong positive correlations among the three monitored parameters (except for IBS between Martin Point and Stranger Point), which suggested that all three colonies faced similar effects (Figures 3, 4, and 6). Interestingly, the Adélie penguin colony that has experienced the strongest population decline (i.e., Stranger Point) showed an intermediate mean value and less variability in the breeding performance compared to the other two study colonies (Table 1). Moreover, this colony also showed the highest values of breeding performance in recent seasons (between 1.2 and 1.3 chicks/pairs from 2016/17 to 2019/20, Figure 5).

Long-term population trends in the Adélie penguin abundance recorded in our study were consistent with the general trend previously published for this species in the western Antarctic Peninsula and adjacent islands (Casanovas et al., 2015; Dunn et al., 2016; Forcada et al., 2006; Fraser et al., 2013; Hinke et al., 2017b; Talis et al., 2023; Trivelpiece et al., 2011; among others). Furthermore, IBS values recorded in our study fell within the range of breeding performance observed in other Adélie colonies (e.g., Dunn et al., 2016; Hinke et al., 2017b). Even these values were similar to those reported in gentoo penguin colonies that are undergoing a population increase (e.g., Dunn et al., 2016; Juáres et al., 2020). Specifically, at Stranger Point and Esperanza, Adélie and gentoo penguins breed sympatrically, and opposing population trends have been observed (Juáres et al., 2020; Libertelli et al., 2022; this study). A similar population trajectory has been reported for gentoo penguins at Signy Island (Dunn et al., 2016) in the South Orkney Islands (i.e., approximately 50 km west of Laurie Island, our study colony). It means that Adélie and gentoo penguins showed contrasting population trends at sites where they shared similar local conditions during the breeding season and where a similar mean breeding performance was observed. However, these species face different environmental conditions during the non-breeding period (Ainley, 2002; Korczak-Abshire et al., 2021).

Although the processes driving the population trends have not been fully elucidated, current hypotheses suggest that in general, environmental variability impacts the penguin populations through the loss or gain of critical habitat (both during the winter and during the breeding period), and by changes cascading in the structure and abundance of food webs. During winter, sea ice is essential for the survival of both the Adélie penguin and its main prey, krill. In general, the reproduction, survival, and recruitment of krill rely on sea ice conditions, which provide them with shelter, spawning habitat, and food (e.g., Flores et al., 2012). During the breeding stage (i.e., during austral spring and summer), extensive sea ice could reduce penguin access to the natal colony and productive prey ground, increasing foraging efforts (Casanovas et al., 2015; Dunn et al., 2016). Furthermore, as the krill dominate the diet of chick provisioning Adélie penguins (e.g., Hinke et al., 2007; Juáres et al., 2018, 2021; Pickett et al., 2018), krill abundance and availability are vital for the breeding success and survival of Adélie penguins (e.g., Hinke et al., 2007; Juáres et al., 2018; Trivelpiece et al., 2011). Thereby, the sea ice conditions can have direct and indirect effects on the population dynamics of Adélie penguins. On the other hand, in the terrestrial environment, the increase in snowfall can reduce the available nesting sites and breeding success (e.g., Boersma, 2008; Cimino et al., 2019; Hinke et al., 2012; Juáres et al., 2015), which could impact on the breeding population size (Fraser et al., 2013). Moreover, this scenario further compounds when considering the effects of krill fishing during both breeding and non-breeding periods (Hinke et al., 2017a; Krüger et al., 2021; Watters et al., 2020).

Overall, the reduction in sea ice during winter produces more suitable conditions for ice-avoiding species, such as chinstrap and gentoo penguins (Forcada et al., 2006; Herman et al., 2020; Korczak-Abshire et al., 2021). In contrast, pagophilic species – i.e., those ice-dependent species (such as the Adélie penguin) – will suffer a population decline (e.g., Casanovas et al., 2015; Forcada et al., 2006; Hinke et al., 2017b). However, the sea ice loss also negatively impacts the availability and abundance of Antarctic krill (Atkinson et al., 2019; Flores et al., 2012). In this context, all three Pygoscelid species would be negatively affected but those species with some plasticity in their diet composition or feeding behavior will be able to buffer changes in food web structure (such as gentoo penguins, e.g., Miller et al., 2009). On the other hand, those species that are flexible in their breeding phenology and in the choice of breeding site will be able to minimize the adverse effects of snow accumulation in the breeding colony (as in the gentoo penguin, Hinke et al., 2012; Juáres et al., 2013, 2020).

5 Conclusions

A synergy between different effects could provide a plausible explanation for the trajectories observed in this study. Although the number of chicks in crèche of Adélie penguins showed a long-term pattern of decline, the average breeding performance was similar to that reported in increasing populations of its congeners, gentoo penguins (even in sympatric colonies). Consequently, it is plausible to assume a reduction of the over-winter survival (with the subsequent decline in offspring recruitment) as a likely cause of the declining trend observed, at least in the

Stranger Point and Esperanza colonies. However, considering the higher variability in the breeding performance recorded at Martin Point and its lack of correlation with the Stranger Point IBS, we cannot rule out local effects during the breeding season affecting the Adélie population of Martin Point. Nevertheless, as reported by Dunn et al. (2016) at Signy Island, it is unclear why some colonies fall more drastically than others. Therefore, it is essential to continue with the krill-dependent predator monitoring programs and deepen the analysis by incorporating the potential drivers of population change.

The Antarctic Peninsula region is unique, rich in living resources, and subject to increasing environmental variability. Along with an increase in the operational capacity of fisheries, the region is also experiencing a growing interest in extractive activities in newly ice-free areas. Based on this, it is necessary to carry out a long-term multinational research effort, aimed at understanding in depth the natural processes of the region, and how these can be affected by fishing activities and climate change. In this way, the understanding of the different factors that generate changes in the Antarctic will improve our ability to detect and adapt to future changes, thus helping to minimize the disruption of marine ecosystems.

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