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A FINE -SCALE MODEL OF THE OVERLAP BETWEEN PENGUIN FORAGING DEMANDS AND THE KRILL FISHERY IN THE SOUTH SHETLAND ISLANDS AND ANTARCTIC PENINSULA

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Abstract

CCAMLR has been using the total catch of krill taken within 100 km of penguin colonies in their breeding season (December to March) as an index of overlap between the potential foraging areas of penguins and the distribution of the krill fishery in Subarea 48.1 (South Shetland Islands). As this index has proven unsuitable for a number of reasons, an alternative method of calculating an index of fishery-predator interaction has been developed. The new index reflects the functional interaction between these two utilisers of the krill resource and is based on a detailed model of penguin foraging patterns combined with catch positions. This analysis shows that the overlap between the fishery and chinstrap penguins is much greater than for other penguins, and that this overlap has been decreasing since 1988.

Résumé

La CCAMLR utilise la capture totale de krill dans un rayon de 100 km autour des colonies des manchots pendant leur saison de reproduction (de décembre à mars) comme indice du chevauchement entre les secteurs d'alimentation potentiels des manchots et la répartition de la pêcherie de krill dans la sous-zone 48.1 (îles Shetland du Sud). Cet indice s'étant révélé inadapté pour un certain nombre de raisons, une autre méthode a été mise au point pour calculer un indice de l'interaction pêche-prédateurs. Le nouvel indice, qui reflète l'interaction fonctionnelle entre ces deux consommateurs de la ressource de krill, est fondé sur un modèle précis des habitudes alimentaires des manchots combinées avec la position des captures. L'analyse met en évidence le fait que le chevauchement de la pêche et des manchots à jugulaire est nettement plus important que celui de la pêche et des autres manchots, et montre que ce chevauchement tend à diminuer depuis 1988.

Резюме

Данные по общему вылову криля, полученному в радиусе 100 км от колоний пингвинов во время сезона размножения (декабрь - март), в прошлом были использованы АНТКОМом в качестве индекса частичного совпадения потенциальных площадей нагула пингвинов с распределением промысла криля в Подрайоне 48.1 (Южные Шетландские о-ва). В связи с тем, что по нескольким причинам данный индекс оказался неподходящим, был разработан другой метод вычисления индекса взаимодействий между промыслом и хищниками. Новый индекс отражает функциональные взаимодействия между этими двумя потребителями ресурсов криля и основан на подробной модели закономертностей поиска пищи пингвинами и местоположений уловов. Настоящий анализ показывает, что степень совпадения промысла с нагульными ареалами пингвина чинстрап больше, чем у других пингвинов, и что с 1988 г. размер этого совпадения уменьшается.

Resumen

La CCRVMA ha utilizado la captura total de kril extraída en un radio de 100 km de las colonias de pingüinos durante su época de reproducción (diciembre a marzo) como índice de superposición entre las posibles zonas de alimentación de los pingüinos y la distribución de la pesquería de kril en la Subárea 48.1 (islas Shetland del Sur). Como este índice se ha mostrado inadecuado por varios motivos, se ha creado un método alternativo para calcular un índice de la interacción entre la pesquería y los depredadores. El nuevo índice refleja la interacción funcional entre estos dos consumidores del recurso kril y se basa en un modelo que considera en detalle los hábitos de alimentación de los pingüinos junto con la ubicación de las capturas. Este análisis demuestra que la superposición entre la pesquería y los pingüinos de barbijo es mucho mayor que para otros pingüinos y además, que esta superposición ha ido disminuyendo desde 1988.

Keywords: Adélie penguin, Antarctic Peninsula, chinstrap penguin, fishery-ecosystem interaction, foraging, gentoo penguin, macaroni penguin, krill fishery, CCAMLR

INTRODUCTION

The question of potential competition between the fishery and predators in Subarea 48.1 has been of concern to CCAMLR for a number of years, especially for those predators which are restricted to land-based breeding sites during the summer (see for example, SC-CAMLR, 1989). Agnew (1992) found that the pattern of fishing in Subarea 48.1 over the period 1988 to 1991 was highly consistent between years, and that 75 to 90% of the total catch for the subarea was taken between December and March within 100 km of shore-based penguin breeding colonies each year. December to March is the peak breeding period, when penguins are restricted to foraging within 100 km of their breeding colonies. Since the analysis of Agnew (1992) the Scientific Committee of CCAMLR has annually reviewed the percentage of total catch taken within this 'critical period-distance' as an indicator of the potential overlap between predator foraging and the krill fishery.

Recently, Ichii *et al.* (1994) have considered the spatial distribution of colonies and catches in more detail. They have shown that although a high percentage of the catch may be taken within the foraging distance of land-based colonies, those colonies containing the greatest numbers of penguins are not adjacent to fishing grounds. For instance, the Japanese krill fishery in Subarea 48.1 is generally concentrated off Livingston and Elephant Islands, whereas the largest penguin colonies are located on Low, Nelson and King George Islands.

It is therefore now apparent that further detailed consideration of penguin and fishery distributions is necessary to establish the functional overlap between predators and the fishery, and that a general critical period-distance index is no longer appropriate. This paper sets out a methodology for considering potential overlap more rigorously and at a finer scale than that currently used by the Scientific Committee. A model is developed that estimates penguin foraging demand for CCAMLR fine-scale areas (1° longitude by 0.5° latitude) and compares this with catches by fine-scale areas.

MODEL DESCRIPTION

A model was constructed to calculate foraging demand in Subarea 48.1 using penguin foraging characteristics, energetic demands and population numbers. Agnew (1992) assumed that penguins foraged uniformly from their colonies out to 80, 60 and 20 km (Adélie penguins, chinstrap penguins and gentoo penguins respectively), and based his estimates on a number of studies from the whole Antarctic. However, it is clear from more recent work (Trivelpiece *et al.*, 1987; Ichii *et al.*, 1992; Kerry *et al.*, 1992; Viet *et al.*, 1993; Whitehouse and Viet, 1994) that penguins first travel a specific distance and then forage within certain boundaries from their colonies. Consequently, the present model assumes that penguins forage randomly from a colony with foraging distance being described by a normal density function and foraging direction being described by a uniform distribution within a lateral range determined by minimum and maximum bearings (Figure 1).

Specific data on critical parameters for penguin foraging distances and bearings from colonies in Subarea 48.1 are limited to a few sites. Bengtson *et al.* (1991) and Ichii *et al.* (1992) describe foraging by chinstrap penguins at Seal Island in 1991 as between 6 to 25 km maximum distance from colonies, at bearings between 345° and 044° (mean 24.2, SD 21.1, *n* 6). Macaroni penguins travelled in the same direction but only up to 15 km. Similar studies in 1989 and 1990 indicated distances of 11 to 24 km at bearings between 330° and 033° for chinstrap penguins, and 20 to 40 km at bearings of 320° to 004° for macaroni penguins (Bengtson and Eberhardt, 1989; Amos *et al.*, 1990). There is no information on foraging angles at other sites in Subarea 48.1. However, studies in the Ross Sea and on the Mawson coast have shown that Adélie penguins forage over an angle of about 45° either side of a line perpendicular to the coast on which their colony lies (Sadlier and Lay, 1990; Kerry *et al.*, 1992).

Trivelpiece *et al.* (1987) have found that gentoo penguins forage within 17 km of their site in Admiralty Bay, King George Island, and chinstrap and Adélie penguins forage to within 27 and 50 km respectively. Viet *et al.* (1993) have confirmed through shipboard observations that most chinstrap penguins in the Elephant Island and King George Island areas are found between about 20 and 40 km from land. Wilson *et al.* (1989), however, found all distances travelled by gentoo, chinstrap and Adélie penguins from Anvers Island to be rather short (all about 10 km).

Accordingly, the following standard parameters were chosen for the model.

Foraging bearings (generally 40° either side of a line perpendicular to the coast):

> Seal Island and Elephant Island: 345 - 045[1] Gibbs Island: 230 - 310[2]; Clarence Island and eastern tip of King George Island: 040 - 120[1]; other outer coast colonies on the South Shetlands: 300 - 020; inner coast colonies on the South Shetlands: 120 - 200; colonies on the Peninsula north of Anvers Island: 280 - 360.

Foraging distances were chosen so that maxima (mean + 2 SDs) were generally in line with maxima recorded in the literature for Subarea 48.1, with a coefficient of variation of 40% (Wilson *et al.*, 1989; Bengtson *et al.*, 1991):

> chinstrap: mean 20 km, SD 8; Adélie: mean 38 km, SD 15; gentoo: mean 10 km, SD 4; macaroni: mean 28 km, SD 11.

Estimates of predator consumption (kg/pair/month) have been discussed in detail in Agnew (1992), and the following were used in this study:

> chinstrap: 48.5 kg/p/m (December), 65.5 kg/p/m (January to February); Adélie: 75 kg/p/m (December to January), 65 kg/p/m (February to March); gentoo: 50 kg/p/m (December), 68 kg/p/m (January to February); macaroni: 65 kg/p/m (December to March: estimated from Croxall *et al.*, 1985).

A database of colonies (species, position, latest population count, foraging angles) was set up using the information in Woehler (1993). Analysis proceeded on a species-by-species basis by calculating the number of penguins in each of a number of major units, defined as 10 x 10 n mile 'squares'. To do this, the squares were each divided into a number of minor units M (Figure 1) and the number of pairs of birds from all colonies expected to be foraging within the minor unit at any time was determined as

$$P_M = \sum_{t=1}^{n} P_t \cdot \int_{d_1}^{d_2} f(x)dx \cdot \frac{A_M}{z}$$

where P_t is the total number of pairs in colony t of n colonies (only one bird from a pair is assumed to be foraging at any one time), $f(x)$ is the foraging distribution function (a normal density function described by the mean and SD of foraging distance, given above), x is distance from the colony, A_M is the area of the minor unit and z is the area of the arc of angle theta which contains the M, defined as being at distances of $d_1 \le x \le d_2$ from the colony

$$z = \frac{\theta\pi}{360}\left(d_2^2 - d_1^2\right)$$

The total number of penguins of a particular species in a 10 x 10 n mile square was obtained by summing P_M for all minor units within the square.

An index of the foraging-fishery overlap (FFO) for all CCAMLR fine-scale squares (approximately 30 x 30 n mile squares) was calculated by multiplying P_M by the average consumption of krill by that species from December to March and by the krill catch in tonnes for December to March. The index thus increases where either predation pressure or fishing increases. Krill catches in a CCAMLR fine-scale square were estimated from the CCAMLR *Statistical Bulletin* (CCAMLR, 1993 and 1994), and a total annual index for each year was calculated by summing the index for individual fine-scale squares.

RESULTS

Figures 2 to 5 show the estimated distribution of foraging penguins in Subarea 48.1 at a

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[1] Specific data for Seal Island are given in Bengtson *et al.* (1991) and Ichii *et al.* (1992).

[2] The direction of most krill concentrations (Loeb and Siegel, 1993).

resolution of 10 x 10 n mile, together with colony positions. The FFO index for each species is given in Table 1. Also shown in this table is the catch in the critical period-distance, adjusted to account for under-reporting of fine-scale data in the late 1980s. Figure 6 shows that the two indices behave somewhat similarly, and follow the changing fishing patterns in Subarea 48.1.

SENSITIVITY TESTS

Two sensitivity tests were made on the model. Because most of the index is attributed to chinstrap penguins, these alone were subjected to the sensitivity analysis. In the first analysis, mean foraging distance for chinstrap penguins was increased by 50% (from 20 to 30 km), although the SD remained the same. In the second analysis, mean foraging distance returned to its previous value and the foraging angle was decreased by 30%, although the centre bearing remained the same.

The results given in Table 2 demonstrate that the index was moderately sensitive to the above parameters. In both sensitivity trials the average proportional change in the index was less than the proportional change in the parameter. The change in the index was not consistent between years, however, and depended on the precise positioning of predators and catches. This behaviour is to be expected and demonstrates that the index reflects the actual overlap between the fishery and the predators. It does imply, however, that choice of parameters is critical.

DISCUSSION

The foraging distances used in the model are rather shorter than those reported from study sites outside Subarea 48.1. Lishman (1985) reports Adélie penguins and chinstrap penguins foraging from Signy Island, South Orkneys, to 80 to 120 km and 66 to 92 km respectively. Foraging areas for Adélie penguins at other sites on the Antarctic continent (Mawson coast and Ross Sea) may be 50 to 100 km from their colonies and occasionally greater than 120 km (Sadlier and Lay, 1990; Kerry *et al.*, 1992). Calculations by Wilson *et al.* (1989) suggested foraging ranges for macaroni penguins of 50 to 128 km at Crozet Island. However, the foraging ranges for gentoo penguins seem to accord with those found by Croxall *et al.* (1985) at South Georgia.

Table 1: Indices of overlap between the fishery and predators. The index is the total numbers of penguins foraging in fine-scale squares multiplied by the catch in those fine-scale squares and the consumption over December to March, and divided by 10 000.

Split-year	Adélie	Gentoo	Macaroni	Chinstrap	Catch in Critical Period Distance (tonnes)	Total Catch (tonnes)
1988	215	400	190	60754	66298	78918
1989	86	447	285	55838	94455	105554
1990	71	144	123	26696	37455	42477
1991	333	541	19	47149	48805	64641
1992	192	597	26	58596	54004	78385
1993	21	325	3	16138	26321	37716

Table 2: Sensitivity tests. Value of the FFO for chinstrap penguins under the original model parameters, with increased foraging distance and decreased foraging angle.

Split-year	Original Parameters	Mean Foraging Distance + 50% (percentage change in parenthesis)		Foraging Angle -30% (percentage change in parenthesis)	
1988	60753	75567	(24)	50128	(-17)
1989	55838	33919	(-39)	25089	(-55)
1990	26696	19747	(-26)	14710	(-45)
1991	47149	59067	(25)	37607	(-20)
1992	58596	72718	(24)	50404	(-14)
1993	16138	26335	(63)	14166	(-12)

As one would expect, in general the distribution of foraging penguins has been shown to be highly correlated with the distribution of krill swarms (Kerry, 1992; Veit *et al.*, 1993). In Subarea 48.1 the highest krill densities are found fairly close to the western coast of the South Shetland Islands and in the Bransfield Strait (Loeb and Siegel, 1993; Trathan and Everson, 1994), and the proximity of krill to most penguin colonies in Subarea 48.1 may account for the shorter foraging distances recorded there.

These generalised distributions of krill occurrence are reflected in the expected distributions of foraging penguins shown in Figures 2 to 5. The index given in Table 1 presents a comparative view of trends in overlap between the fishery and predators, and clearly shows that the overlap between the fishery and Adélie penguins, gentoo penguins and macaroni penguins is much less than that for chinstrap penguins. In the case of Adélie penguins, this is because the majority of colonies are on the tip of the Antarctic Peninsula and southwards from Anvers Island, both areas where there has never been much fishing (Agnew and Nicol, 1995). The index for gentoo penguins and macaroni penguins is low because of the relatively small number of pairs of these species in Subarea 48.1.

The index is quite sensitive to the input parameters, as one would expect from a model which is designed to describe the spatial overlap between foraging penguins and catch locations. More detailed work on the elaboration of appropriate parameters for different sites would be very valuable in refining the input parameters.

The overlap index follows trends similar to the critical period-distance, except for 1989. In that year there was a very large catch which was reflected in a high critical period-distance calculation. Our new overlap index, on the other hand, assesses that these extra catches were not taken in areas or at times which overlapped with penguin foraging areas to a greater extent than in subsequent years. Thus, whereas previously 1989 would have been considered an anomalous year, the new index shows this not to have been the case.

These conclusions support those of Ichii *et al.* (1994), that the critical period-distance is an inappropriate measure of overlap between penguins and the fishery. The more refined index of FFO, based as it is on detailed colony data, provides a more meaningful description of overlap conditions.

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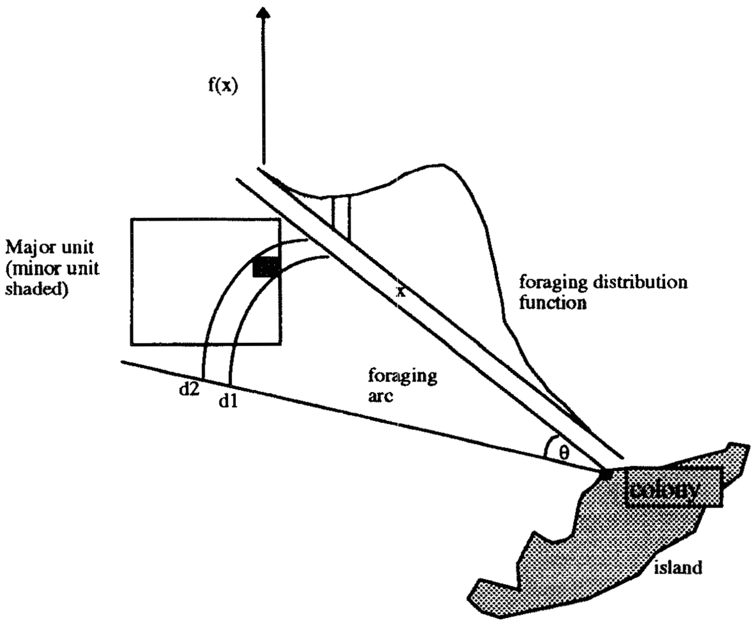

Figure 1: Penguin foraging distribution concepts. Penguins forage inside an arc (θ) at distances (d1, d2) from the colony determined by the foraging distribution function for that colony. The use of major and minor units is described in the text.

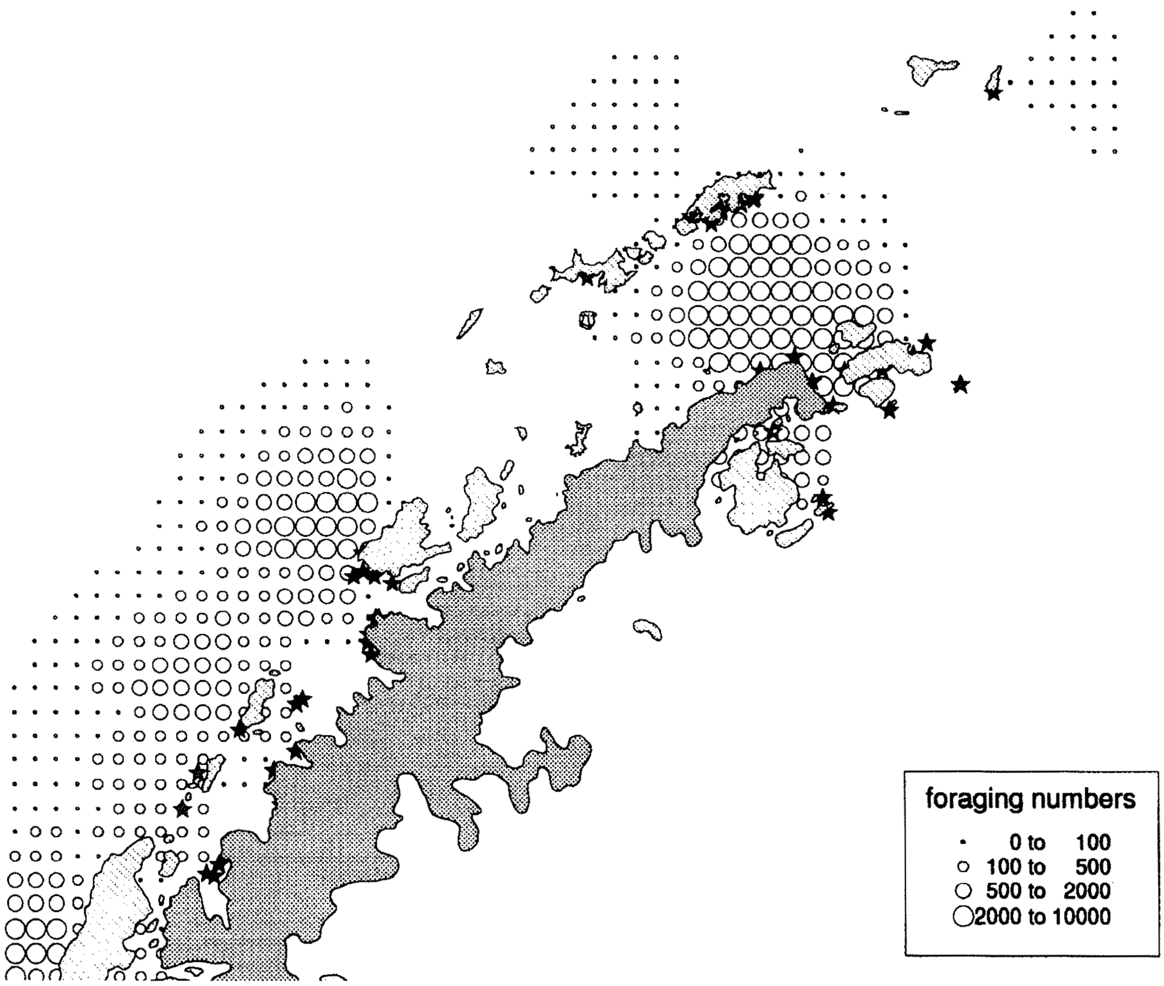

Figure 2: Density of foraging Adélie penguins predicted by the model. Foraging numbers are given for each 10 x 10 n mile square. Colony positions are shown (*).

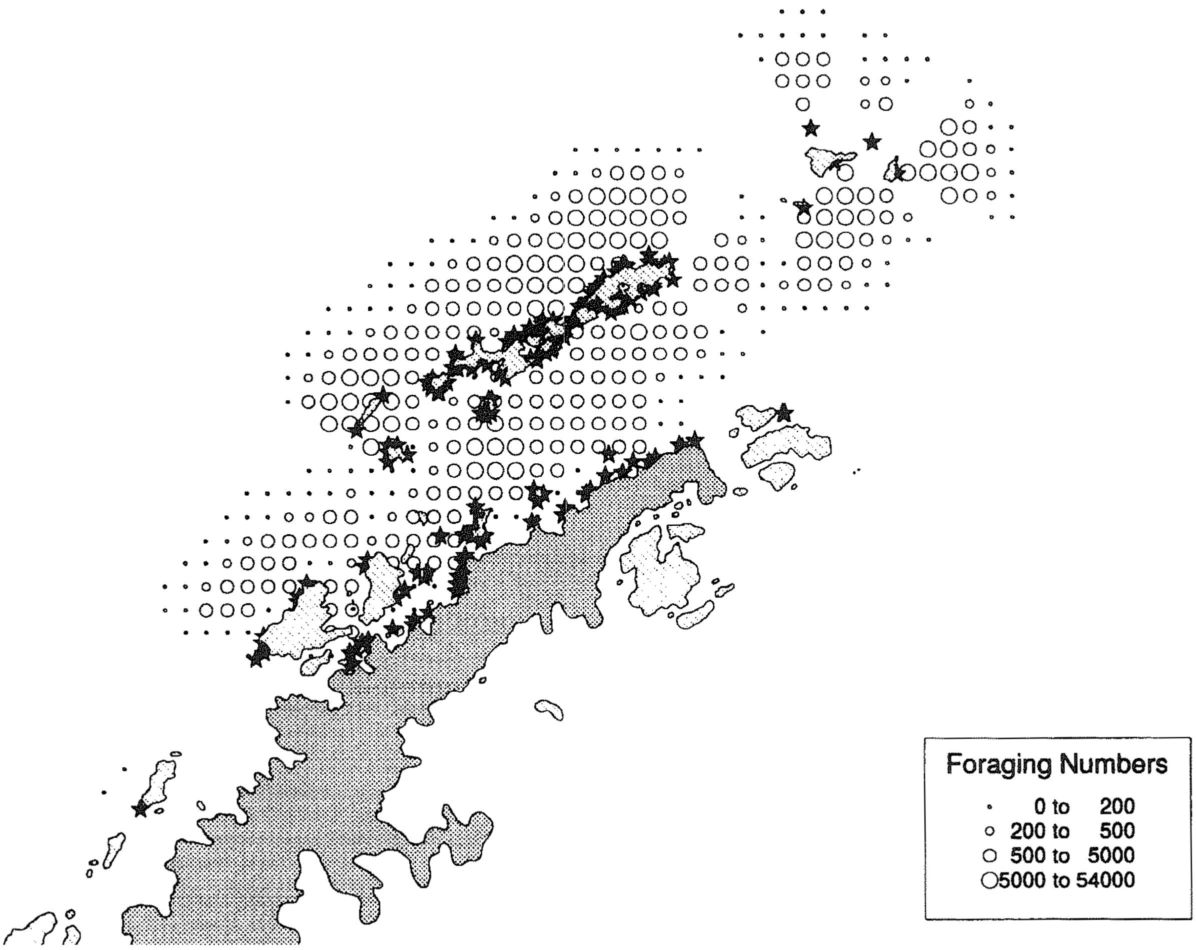

Figure 3: Density of foraging chinstrap penguins predicted by the model. Foraging numbers are given for each 10 x 10 n mile square. Colony positions are shown (*).

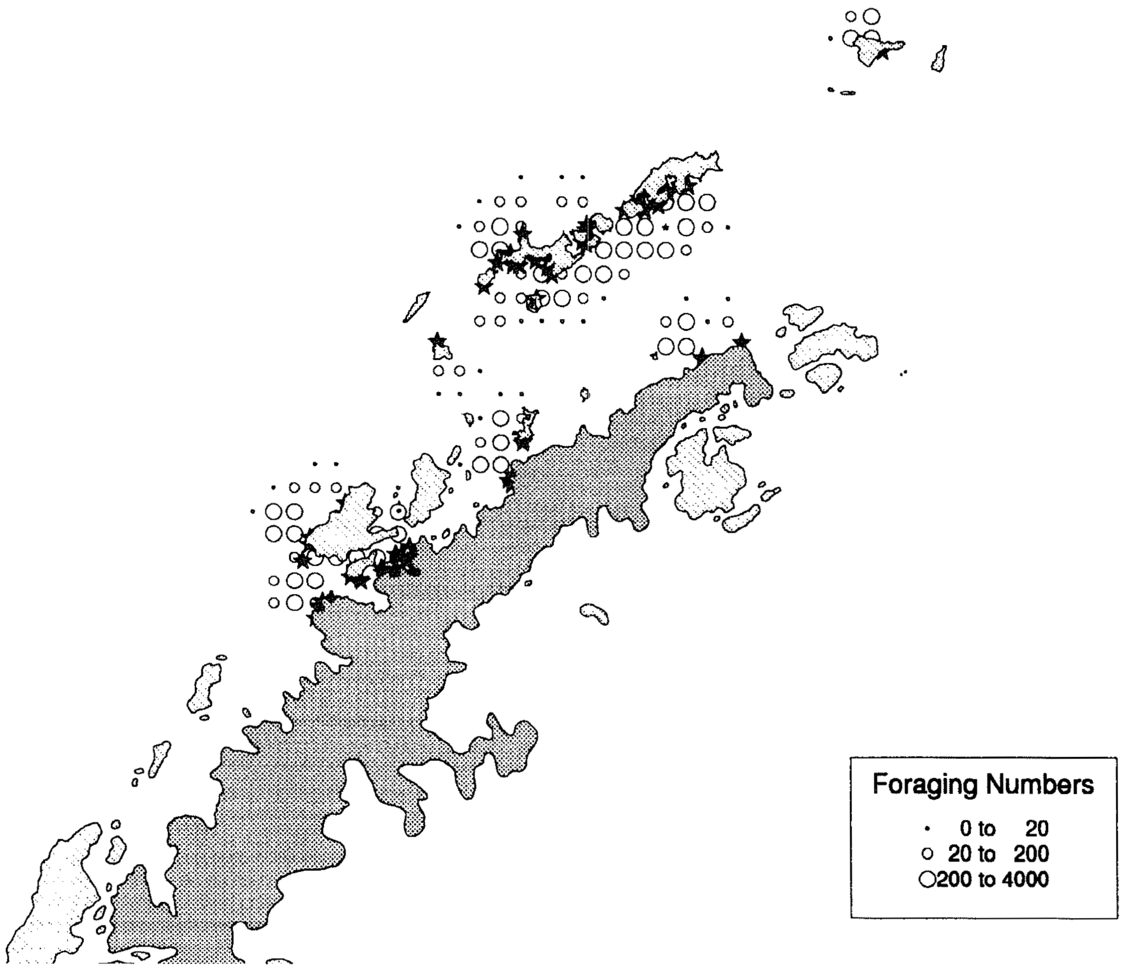

Figure 4: Density of foraging gentoo penguins predicted by the model. Foraging numbers are given for each 10 x 10 n mile square. Colony positions are shown (*).

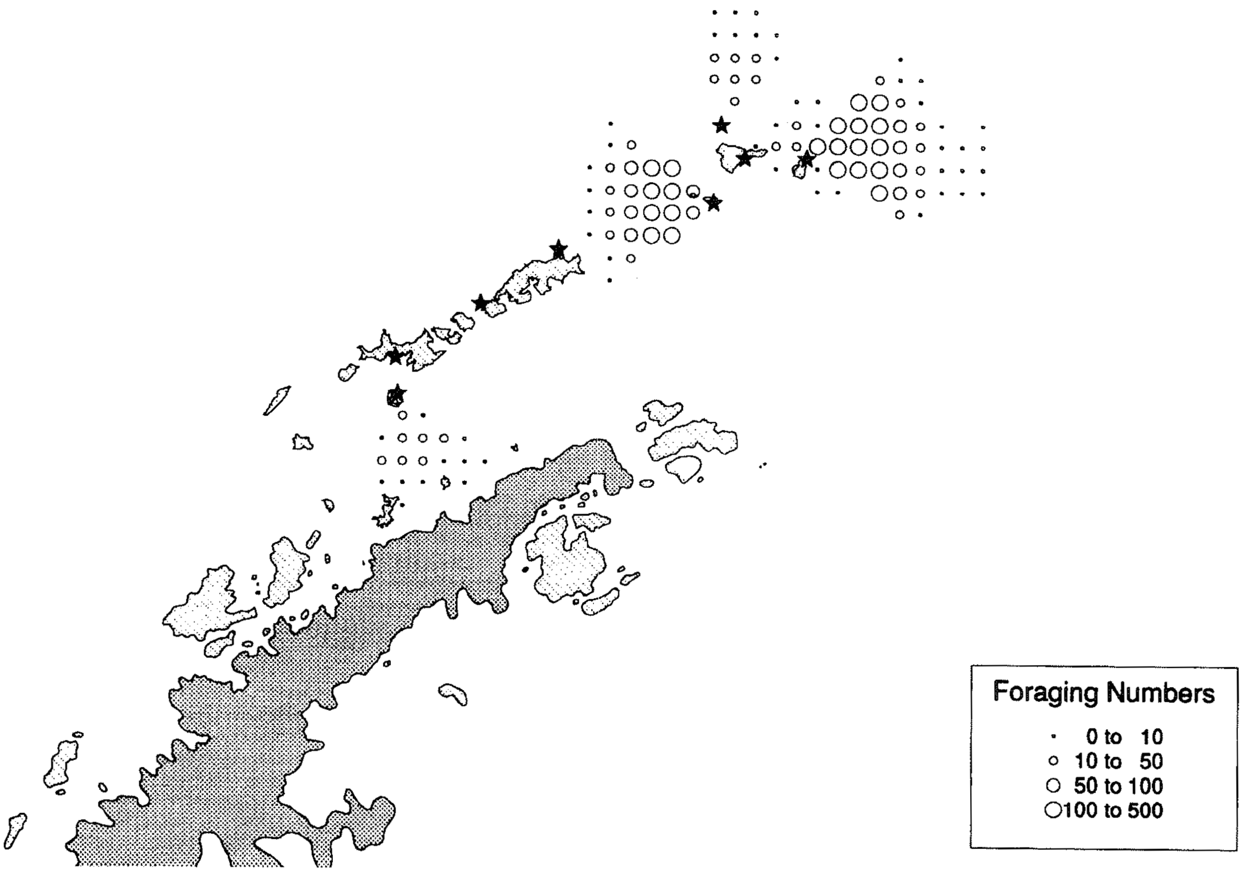

Figure 5: Density of foraging macaroni penguins predicted by the model. Foraging numbers are given for each 10 x 10 n mile square. Colony positions are shown (*).

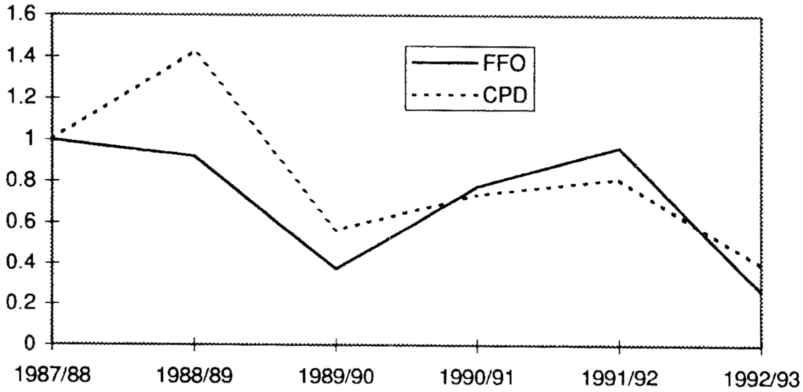

Figure 6: The foraging-fisheries overlap (FFO) index calculated in this paper is compared with the critical period-distance (CPD) index.

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