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PRELIMINARY MODEL OF KRILL FISHERY BEHAVIOUR IN SUBAREA 48.1

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Abstract

A simple model of the behaviour of the krill fishery in FAO Statistical Subarea 48.1 (South Shetland Islands and Antarctic Peninsula) is described. Parameters of the model are calculated from Chilean fishery data over the period 1989 to 1992. The distribution of catches predicted by the model, which is restricted to the four months December to March, compares favourably with the historical distribution of catches in the subarea. A number of management scenarios are considered which involve the closure of (i) a radial zone 50 km offshore from the South Shetland Islands, and (ii) zones 100 km around Livingston and Elephant Islands. The model predicts that the management option of closing the zones around Livingston and Elephant Islands in alternate years would result in an average yearly catch similar to that at present. However, in this scenario, the catch would be more concentrated in foraging areas of land-based predators during alternate years.

Résumé

Description d'un modèle simple du comportement de la pêcherie de krill dans la sous-zone 48.1 de la FAO (îles Shetland du Sud et péninsule antarctique). Les paramètres du modèle sont dérivés des données de la pêcherie chilienne des années 1989 à 1992. Ce modèle, restreint aux quatre mois de décembre à mars, donne une distribution des captures proche de celle des captures anciennes dans cette sous-zone. Examen de plusieurs procédures de gestion impliquant la fermeture i) d'une zone d'un rayon de 50 km autour des îles Shetland du Sud et, ii) de zones de 100 km autour des îles Livingston et Eléphant. D'après ce modèle, la fermeture proposée des zones adjacentes aux îles Livingston et Eléphant tous les deux ans aurait pour résultat une capture annuelle moyenne similaire à celle réalisée actuellement. Toutefois, dans ce cas, tous les deux ans, la capture serait davantage concentrée dans les secteurs d'alimentation des prédateurs terrestres.

Резюме

Описывается простая модель динамики крилевого промысла в Статистическом подрайоне ФАО 48.1 (Южные Шетландские о-ва и Антарктический п-ов). Параметры модели рассчитаны по данным промысла Чили в период с 1989 по 1992 гг. Распределение уловов, предполагаемое моделью, ограниченной четырьмя месяцами (декабрь-март), благоприятно соотносится с историческим распределением уловов в этом подрайоне. Рассматриваются несколько схем управления, в которые входит закрытие (i) радиальной зоны в 50 км от побережья Южных Шетландских о-вов, и (ii) зон в радиусе 100 км от островов Ливингстон и Элефант. Эта модель предполагает, что вариант управления, при котором будут закрыты зоны вокруг островов Ливингстон и Элефант в чередующиеся годы, приведет к среднему годовому вылову, который будет аналогичен современному. Тем не менее, в этом случае в течение чередующихся лет вылов будет сконцентрирован в районах кормления базирующихся на суше хищников.

Resumen

Se presenta un modelo simple del comportamiento de la pesquería de kril en la Subárea estadística 48.1 de la FAO (islas Shetlands del Sur y península Antártica). Los parámetros del modelo se calcularon a partir de los datos de la pesquería chilena de 1989 a 1992. La distribución de las capturas pronosticada por el modelo, el cual se restringió al período de diciembre a marzo, no es inferior a la distribución histórica de las capturas en esta subárea. Se consideraron varias opciones de gestión que comprenden el cierre de: (i) una zona radial de 50 km fuera de las islas Shetland del Sur, y (ii) de zonas de 100 km alrededor de las islas Livingston y Elefante. Esta última opción, llevada a cabo cada dos años, resultaría en una captura promedio anual semejante a la actual. Sin embargo, en esta hipótesis la captura se concentraría más en las zonas de alimentación de los depredadores terrestres en años alternos.

Keywords: krill, fishery management, crustacean, ecosystem management, penguins, CCAMLR

INTRODUCTION

Fishing for krill in the Antarctic has predominantly taken place in the South Atlantic (FAO Statistical Area 48), around South Georgia (Subarea 48.3), the South Orkney Islands (Subarea 48.2) and the South Shetland Islands (Subarea 48.1). Although only about 20% of the South Atlantic catch has been taken in Subarea 48.1, the catch in this area has been very consistent both in quantity and position; about 80 000 tonnes is taken annually. These catches are concentrated around the shelf break just offshore from the South Shetland Islands (Everson and Goss, 1991), particularly Elephant and Livingston Islands.

There has been some concern that the krill fishery may compete for the krill resource with land-breeding predators (e.g., penguins and seals). This concern has arisen because 74 to 90% of the annual catch of krill in Subarea 48.1 is taken between December and March and within 100 km of land-based predator colonies. The foraging ranges of land-breeding predators are restricted to a maximum of 100 km from their colonies between December and March, so there is considerable spatial and temporal overlap in krill usage by fishermen and predators (SC-CAMLR, 1992). Recently, this concern has been somewhat allayed by a study which has shown that the densest colonies of chinstrap penguins, *Pygoscelis antarctica*, (the most numerous penguin species) are not particularly close to the areas of highest fishing intensity (Ichii *et al.*, 1994), and another study showing that krill catches within 100 km of the colonies are currently at least three-times lower than estimates of predator consumption in the same area (Agnew, 1992).

Nevertheless, concern remains about the potential for competition between land-breeding predators and the fishery because of the possibility of future increases in fishing effort. Should this happen, it is perhaps unlikely that the fishery would expand its operations much beyond the present concentration on the shelf break areas immediately offshore of the South Shetland Islands. If this were the case CCAMLR might decide that it would be prudent to impose some precautionary measures to restrict the activities of the fishery in Subarea 48.1 in the critical period of December to March.

Butterworth (1988) and Mangel (1988) have presented two different and very detailed models of the behaviour of the Japanese and Soviet fleets, respectively. These studies were primarily directed towards modelling the interaction between krill fishing vessels and krill swarms, with one of the objectives being to investigate indices of CPUE which would correlate with krill abundance. This paper describes a more general, empirical model of the fishery that is used to investigate the effects of different management options on the distribution of catches in Subarea 48.1.

MODEL DESCRIPTION

A model was constructed to predict the catch of a single vessel given the *duration* for which fishing is undertaken, the 'desirability' of fishing in a certain area (*fishing vessel preference*), the *catch-per-unit-effort* (CPUE, here given in tonnes-per-hour) taken in a certain area and the *management regimes* in operation for the area. The model was constructed using spatial blocks corresponding to CCAMLR fine-scale squares

(1° longitude by 0.5° latitude) and temporal blocks of 10-day periods (months were assumed to be 30 days long).

Data from the Chilean fishery in Subarea 48.1 were used to parameterise the model (Table 1). These data only cover a part of Subarea 48.1, shown in Figure 1, and the model was therefore restricted to this area.

The model was applied to data from the months December through March. This period is the critical breeding period for land-based predators and is therefore of primary interest for constructing hypothetical management regimes. The Chilean data were sufficient to derive model parameters for January and February. Since the general patterns of fishing in December and March are similar to that in January and February

Table 1: Effort and CPUE indices calculated from Chilean haul-by-haul data 1989 to 1992. Catch-per-hour is log-normally distributed. Latitude and longitude of the centre of each fine-scale square is given.

Latitude °S	Longitude °W	Total Hours Spent Fishing 1989-1992	Mean $\log_e$ (catch/hour)	Standard Deviation of $\log_e$ (catch/hour)	Total Number of Hauls
60.25	54.5	4.42	2.13	0.64	4
	55.5	20.50	2.36	0.92	25
60.75	54.5	9.83	2.11	0.97	12
	55.5	316.25	2.61	1.47	543
	56.5	71.38	2.02	0.94	89
61.25	54.5	9.33	1.85	0.76	8
	55.5	47.17	2.35	0.81	51
	56.5	37.92	2.41	1.11	58
	57.5	11.83	1.42	0.78	12
	58.5	1.42	1.28	1.35	2
	59.5	0.75	-0.50	0.00	1
	60.5	0.33	1.10	0.00	1
61.75	54.5	2.42	2.03	0.23	2
	56.5	9.42	2.52	0.85	12
	57.5	9.22	1.53	0.68	10
	58.5	56.35	1.71	0.98	71
	59.5	130.92	1.77	0.91	151
	60.5	76.67	1.60	0.72	82
	61.5	3.92	2.23	0.77	5
62.25	59.5	36.55	2.30	1.00	45
	60.5	572.37	2.13	0.98	768
	61.5	294.58	2.22	0.68	399
	62.5	7.33	2.05	0.45	7
62.75	60.5	3.63	2.01	0.79	6
		175.17	1.86	0.84	201
		1.17	2.05	0.00	1

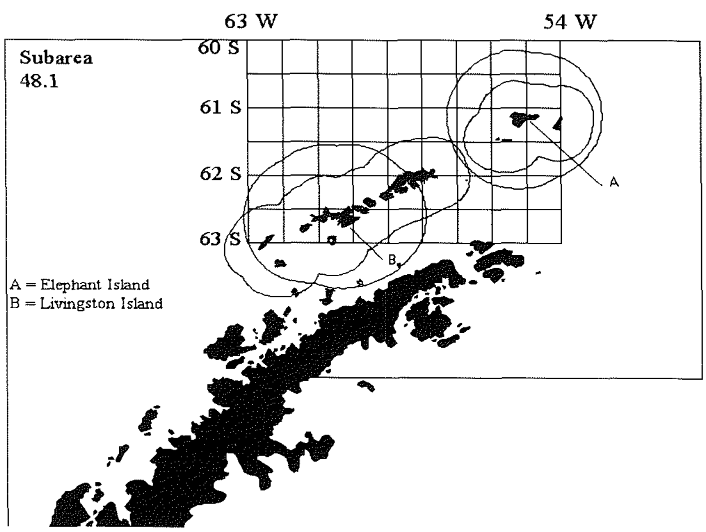

Figure 1: Subarea 48.1, showing the study grid, 50 km and 100 km zones drawn around the South Shetland Islands.

(Agnew, 1992), extrapolation to include the whole of the period December to March was considered appropriate.

The total catch of a single vessel over the period December to March was calculated by

$$C=\sum_x \sum_y (t_{x,y}.p_{x,y}.e_{x,y})$$

where $t_{x,y}$ = time available (hours) to be spent in the fine-scale square with mid-longitude x and mid-latitude y, $p_{x,y}$ = preference index and $e_{x,y}$ = catch-per-unit-effort (tonnes-per-hour).

t is a product of the number of 10-day periods for which fishing is possible (for four months this was 12 periods), and the number of hours that a vessel normally fishes in a 10-day period. Chilean data over 1989 to 1992 showed that the average time spent fishing, as opposed to time spent searching, steaming or lost to bad weather, was 89.6 hours per vessel per 10-day period (number of 10-day-periods = 22, SD 30.4).

The total time spent by the Chilean fleet in each fine-scale square from 1989 to 1992 (Table 1) was used to calculate the normalised preference index.

CPUE is log-normally distributed and accordingly $e_{x,y}$ was sampled from a log-normal distribution with mean $\ln(cpue)_{x,y}$ taken from Table 1. However, since sample sizes in Table 1 varied considerably, an approximate mean CV of 0.4 was used for all squares for these calculations.

A number of closure scenarios were modelled. Prior studies have shown that the potential for competition between predators and the fishery is greatest within 50 km of the South Shetland Islands (Agnew, 1992; Ichii *et al.*, 1994). Closing this area was the first management scenario (Figure 1). Prohibition of fishing within 100 km of the islands would eliminate almost all of the potential for competition between predators and the fishery, but would also exclude the fishery from its most productive grounds. A compromise scenario was modelled which would enforce a 100 km closure around Livingston and Elephant Islands, the two major fishing areas, in alternate years.

Closures were modelled by manipulating the amount of time available to be spent in a fine-scale square. For instance, where fishing took place over four months and a square (x,y) was closed for that time, $t_{x,y}$ was set to zero. When a square was half closed, $t_{x,y}$ was set to two months. When squares were closed to fishing, the time that would have been spent in them was re-assigned to other areas, so that the total time spent fishing in the study area was the same as when all squares were freely fished.

The model was run 10 000 times for each management scenario, and median, 95% and 5% confidence limits for total catch (C) were calculated.

The catch model contained the following assumptions:

- Krill stock size was effectively unlimited compared to the size of the catch and thus there was no limit to catch in any fine-scale square. As mentioned previously, Agnew (1992) demonstrated that current catches are small in comparison to predator demands. Additionally, a basic accounting exercise performed for Subarea 48.1 (SC-CAMLR, 1992 - Annex 4, Appendix F) has shown that estimates of total effective biomass for the summer months (about 2 000 000 tonnes) are much larger than current maximum catches (about 100 000 tonnes).

- Persistent, heavy fishing in localised areas did not lead to significant decreases in CPUE. Neither Endo and Ichii (1989) nor Marín *et al.* (1991) have demonstrated changes in CPUE over a short period or a whole season, although very localised declines have been cited by Butterworth (1988) and Endo and Ichii (1989) as reasons for vessels moving to different fishing grounds.

- The amount of time spent fishing was small compared to that spent searching, and the steaming distance possible when a vessel was not fishing was much greater than the size of the study area. This assumption was necessary to freely distribute effort in accordance with a preference index. The Chilean data yielded a mean time spent fishing of 89.6 hours in a 10-day period, which was 37.5% of the available time. For comparison, the overall time budget derived for the Japanese fishery in Division 58.4.1 by Butterworth (1988) was 32%, with a complex of time spent searching, bad weather delays and transit time taking the remaining 68%. The time not spent fishing was therefore much greater than that required to transit the South Shetlands (300 n miles) at normal cruising speeds.

RESULTS

Table 2 presents the results from the model for a single vessel fishing for four months. Under unrestricted fishing (the base case), the distribution of catches predicted by the model compares well with the mean distribution of all catches in the study area over the years 1988 to 1992 as estimated from data given in the *CCAMLR Statistical Bulletin* (CCAMLR, 1993) (Tables 3 and 4).

For the base case, the median total catch predicted by the model over December through March was 12 670 tonnes. Imposing a closed area of 50 km radius around the South Shetland Islands (Figure 1) for the four months resulted in a 26% decrease in predicted catch relative to the base case (Tables 2 and 4). A 100 km radius closed area around Elephant Island resulted in a decrease of 21%, and led to a concentration of fishing effort around Livingston Island (Tables 2 and 5). A similar closed area around Livingston Island resulted in a concentration of fishing effort around Elephant Island, which, because of the high CPUE and preference index in the fine-scale square to the north of the island (at 61.75°S, 55.5°W), produced a 22% increase in catch (Tables 2 and 6). Simultaneously closing both Livingston and Elephant Island zones led to a 77% decrease in catch.

Table 2: Predicted catch (tonnes) from one vessel operating for four months in Subarea 48.1. Confidence limits are given for total catch only, although similar confidence limits apply to the totals within 100 km of Elephant Island and Livingston Island.

	Total Catch in Subarea 48.1				
	Median	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Total Within 100 km of Elephant Island	Total Within 100 km of Livingston Island
Base case; fishing December-March	12 880	7 090	28 490	4 080	7 230
50 km closed zone	9 610	5 700	17 760	4 790	3 080
100 km around Elephant Island closed	10 620	5 400	25 590	0	10 120
100 km around Livingston Island closed	14 710	6 170	54 330	14 220	0
Both 100 km areas closed	2 890	1 370	7 160	0	0

Table 3: Distribution of catches predicted by the model with unrestricted fishing for four months. Positions of the centre of each fine-scale square are given.

	62.5°W	61.5°W	60.5°W	59.5°W	58.5°W	57.5°W	56.5°W	55.5°W	54.5°W
60.25°S								163	28
60.75°S							405	3 237	61
61.25°S			1		4	37	317	325	45
61.75°S		27	286	578	234	32	88		14
62.25°S	43	2 041	3 626	274					
62.75°S	7	983	26						

Table 4: Mean distribution of catches from January to March over the years 1988 to 1992 estimated from the *CCAMLR Statistical Bulletin* (CCAMLR, 1993), scaled to a total catch of 12 880 tonnes.

	62.5°W	61.5°W	60.5°W	59.5°W	58.5°W	57.5°W	56.5°W	55.5°W	54.5°W
60.25°S							25	165	120
60.75°S				1		5	904	1 625	622
61.25°S	3	1	5		32	207	1 185	338	72
61.75°S	1	19	812	1 337	156	190	6	4	
62.25°S	22	1 726	1 975	196		4		4	
62.75°S	100	990	22						

Table 5: Distribution of catches predicted by the model with the imposition of a 100 km closed area around Elephant Island.

	62.5°W	61.5°W	60.5°W	59.5°W	58.5°W	57.5°W	56.5°W	55.5°W	54.5°W
60.25°S									
60.75°S									
61.25°S			1		5				
61.75°S		36	374	755	306				
62.25°S	56	2 666	4 736	358					
62.75°S	9	1 284	33						

Table 6: Distribution of catches predicted by the model with the imposition of a 100 km closed area around Livingston Island.

	62.5°W	61.5°W	60.5°W	59.5°W	58.5°W	57.5°W	56.5°W	55.5°W	54.5°W
60.25°S								503	87
60.75°S							1 253	10 013	189
61.25°S			2	1	12	114	980	1 005	138
61.75°S						99	272		43
62.25°S									
62.75°S									

The catch taken within 100 km of Elephant and Livingston Islands, and therefore within the foraging ranges of land-based predators on these islands, is also shown in Table 2. The effect of the high CPUE at Elephant Island can also be seen in Table 2: the imposition of a 50 km closed area did not decrease the catch of krill within 100 km of Elephant Island, although it did around Livingston Island.

The high variance seen in Table 1 and reflected in the results in Table 2 is a direct result of the patchy nature of the krill fishery. As would be expected from the log-normally distributed CPUE data, the results are also highly skewed.

DISCUSSION

Although Chilean catches only represent about 10% of the total catch in the subarea, these data form the most complete haul-by-haul series for the area and show similar characteristics to the data from other fleets. The CPUE data given in Table 1 agree well with the ranges for both the Japanese and Chilean fleets previously described by Ichii (1987), Endo and Ichii (1989) and Marín *et al.* (1991).

Total catches predicted by the model are similar to catches reported from the two major fisheries in the area. Catches by a single Chilean vessel for February, the only month in which the Chilean fishery has consistently operated for the whole month, have usually been about 2 800 tonnes. This is equivalent to a catch over a four-month period of 11 000 tonnes, slightly lower than the 12 880 tonnes predicted by the model. A similar catch rate can be calculated for the Japanese fishery in 1991/92, when the bulk of the catch of 66 000 tonnes was taken in four months by six vessels (SC-CAMLR, 1992).

The simulation also appears to model the annual expected pattern of catches in Subarea 48.1 fairly well, and in general produces results that would be expected intuitively. One rather surprising result is that the exclusion of fishing from around Livingston Island actually increases catches by forcing fishing to take place in high CPUE areas to the north of Elephant Island. The fact that the fishery does not fish exclusively in these high CPUE areas, although it obviously displays a very high preference for them, raises some questions about the assumptions in the model.

Firstly, the model does not make use of data disaggregated by month, and therefore does not take into account possible seasonal variation in catch rate. It has been pointed out by Ichii *et al.* (1994) that the main location of catches moves closer to the islands as the season progresses, possibly reflecting an autumn shoreward migration of krill which has been reported by other authors (Siegel, 1986; Brinton, 1991). This might have a significant effect on the total catch under, for instance, scenario one (50 km closure), by restricting access to a much larger section of the krill stock than is currently assumed.

Secondly, fishing vessels are known to search for krill swarms that satisfy a number of criteria such as optimum CPUE (for optimum processing ability), desired quality (influenced by krill size, maturity and feeding condition), and lack of contamination by other pelagic fauna such as salps (Ichii, 1987). Decisions to move between fishing grounds may be influenced by changes in any of these factors or by other, external considerations, such as operational constraints or changes in desired krill quality. The current model has assumed that all of these various decision factors are integrated into the historical preference data. However, the historical data may be inadequate to explain some aspects of vessel behaviour.

Complex preference considerations are obviously very important and knowledge of them would contribute significantly to future model development. Whilst more data could enable the model to be expanded to include complex preference functions (based on individual vessel movements for instance), our present knowledge of krill behaviour would have to improve considerably before the distribution patterns of concentrations and swarms could be included in the model.

The primary objective of management measures such as those discussed here would be to reduce the potential for competition between predators and the fishery while minimising changes to the productivity of the fishery itself. It is noteworthy that the imposition of a 50 km exclusion zone would appear to decrease the catch and potential overlap between the fishery and predators only around Livingston Island. Also, 100 km closures around each island in alternate years would, on average, decrease neither the longterm catch nor the longterm overlap with predators. Thus, none of the management scenarios considered appear to adequately satisfy their management objectives. Use of models such as this should be encouraged to help identify alternative management strategies that better satisfy their management objectives.

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