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QUANTIFYING MOVEMENT BEHAVIOUR OF VESSELS IN THE ANTARCTIC KRILL FISHERY

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Abstract

Ten years of recent fine-scale haul-by-haul krill data were used to characterise the behaviour of the krill fishery. Analysis of distance between hauls in relation to their catch level revealed a distinct pattern. Mean between-haul distances were generally longer when catch levels fell below 10 tonnes/haul, and the travel distance decreased as the catch level increased; this pattern was most obvious for operations by Japanese fishing vessels. There were differences between statistical areas with longer distances moved between hauls in Subarea 48.1 compared to Subareas 48.2 and 48.3, reflecting the large number of fishing grounds within this area. The same patterns were observed for vessels from other nations, but were less clear. The study suggests the movement trends for Japanese vessels could form the basis for describing a generalised fishery model. Updates for some of the parameters for the krill fishery model suggested in the late 1980s are proposed based on the results from this study. These analyses demonstrate the need for high-quality year-round data on all vessels participating in the krill fishery to assist in interpreting the annual fishing patterns, which can best be collected by scientific observers.

Résumé

Dix années de données récentes à échelle précise par trait sur le krill ont servi à caractériser le comportement de la pêcherie de krill. L'analyse de la distance entre les traits de chalut par rapport à leur niveau de capture a révélé une tendance distincte. Les distances moyennes entre les traits de chalut étaient généralement plus grandes lorsque le niveau de capture tombait en dessous de 10 tonnes/trait, et la distance parcourue diminuait lorsque le niveau de capture augmentait, tendance qui était particulièrement manifeste dans les opérations de pêche des navires japonais. On a noté des différences entre les zones statistiques : les distances parcourues entre deux traits étaient plus grandes dans la sous-zone 48.1 que dans les sous-zones 48.2 et 48.3, ce qui reflète le grand nombre de lieux de pêche se trouvant dans ce dernier secteur. Les navires d'autres nations présentaient les mêmes tendances, mais avec moins de netteté. L'étude suggère de décrire un modèle de pêcherie généralisé à partir des tendances du déplacement des navires japonais. Il est proposé, d'après les résultats de cette étude, de mettre à jour certains paramètres du modèle de pêcherie de krill suggéré vers la fin des années 1980. Ces analyses démontrent la nécessité de données de très bonne qualité et de toute l'année sur tous les navires participant à la pêcherie de krill pour aider à interpréter les tendances annuelles de la pêche, données que les observateurs scientifiques seront le mieux à même de collecter.

Резюме

Для описания динамики промысла использовались мелкомасштабные данные за каждый отдельный улов криля за последние десять лет. Анализ расстояния между выборками по отношению к уровню вылова выявил четкую закономерность. Среднее расстояние между выборками было в целом больше, когда уровни вылова падали ниже 10 т/выборку, а пройденное расстояние сокращалось при увеличении уровня вылова; данная закономерность была наиболее заметна в ходе операций японских рыболовных судов. Имелись различия между статистическими районами: по сравнению с подрайонами 48.2 и 48.3 в Подрайоне 48.1 проходились бóльшие расстояния между выборками, что отражало наличие большого числа промысловых участков в этом районе. Такие же закономерности наблюдались и для судов из других стран, но они были менее явными. Данное исследование говорит о том, что тенденции в перемещении японских судов могут служить основой описания обобщенной модели промысла. Предлагаются обновленные варианты некоторых параметров модели крилевого промысла, предложенной в конце 1980-х гг., основанные на результатах этого исследования. Результаты проведенного анализа свидетельствуют о необходимости получения высококачественных круглогодичных данных по всем судам, участвующим в крилевом промысле, что поможет интерпретировать закономерности промысла за год; сбор этих данных лучше всего могут проводить научные наблюдатели.

Resumen

Se caracterizó el comportamiento de la pesquería de kril en base a los datos en escala fina de lance por lance de 10 años recientes. El análisis de la distancia entre los lances en relación con el nivel de su captura reveló una pauta marcada. La distancia promedio entre los lances por lo general fue mayor cuando el nivel de la captura era menor que 10 toneladas/lance, y la distancia recorrida disminuyó a medida que el nivel de la captura aumentó; esta pauta fue más marcada para las operaciones de los barcos de pesca japoneses. Hubo diferencias entre las áreas estadísticas, siendo mayor la distancia recorrida entre los lances en la Subárea 48.1 que en las Subáreas 48.2 y 48.3, reflejando el gran número de caladeros de pesca dentro de esta área. Esta pauta también fue observada para barcos de otras naciones pero no fue tan definida. El estudio sugiere que las tendencias en el desplazamiento de los barcos japoneses podrían servir de base para describir un modelo generalizado de la pesquería. En base a los resultados de este estudio, se propone una actualización de algunos de los parámetros del modelo de la pesquería de kril propuesto a fines de la década de los 80. Este tipo de análisis demuestra que para facilitar la interpretación de las pautas anuales de la pesca, se requiere recolectar datos de alta calidad de todos los barcos que participan en la pesquería de kril durante el año, y que lo mejor sería que estos datos fuesen registrados por los observadores científicos.

Keywords: Antarctic krill, krill fishery, fishery model, CCAMLR,
fishery dynamics, CPUE

Introduction

The harvesting of marine living resources in the Southern Ocean has been managed by CCAMLR since the 1980s (Everson, 2000). Although precautionary catch limits for the krill fishery have been set for a number of areas and divisions of the Southern Ocean, the development of strategies that directly take into account the needs of predators and the local impact of the krill fishery in a management framework is yet to occur (Constable et al., 2000). The fishery is an integral part of the ecosystem processes (SC-CAMLR, 1995), and therefore modelling the behaviour of the krill fishery is essential for an ecosystem-based approach to managing the effects of fishing on dependent and related species. Such models will also allow prediction of the type and degree of impacts of alternative management options on the krill fishery.

In the late 1980s, attempts were made to characterise the krill fishery using simulation models (Butterworth, 1988a; Mangel, 1988). These studies pointed out that the utility of catch-per-unit-effort (CPUE) data is limited because such data does not take into account the nature of the operational strategies adopted by the fishing fleets and vessels. It is known that physical conditions (e.g. ice and weather), logistic factors (e.g. transhipment) and biological factors (e.g. krill density), as well as the type of krill being targeted (e.g. gravid, non-green, etc.) affect a fishing master's decisions about how long to fish in a particular area (Butterworth, 1988b). Many of the parameters used in these krill fishery models in the 1980s were based on information gathered through interviews with the fishing industry (e.g. Butterworth, 1988a); these were mostly anecdotal and/or qualitative. Even those parameters that were derived through analysis of actual operational data need to be updated because the krill fishery has changed markedly over the last 20 years (Kawaguchi and Nicol, 2007).

Models of the interactions between the krill fishing operations and the ecosystem will need to capture, at least, the important dynamics of the fishery. In particular, it is important to quantify the conditions under which a fishing vessel might change its fishing location, i.e. how fishing masters make decisions about where they fish and when. This is best done using information directly collected from fishing vessels (Kawaguchi et al., 2005a; SC-CAMLR, 2006).

The CCAMLR Secretariat holds and maintains fishery data which are central to the formulation of scientific advice on the management of fisheries and marine living resources within the CAMLR Convention Area (Kawaguchi and Nicol, 2007). At the end of each fishing season, each Contracting

Party that has fished for krill is required to submit fine-scale haul-by-haul data to the Secretariat (CCAMLR, 2007).

By using recent fine-scale haul-by haul data from the krill fishery, this study aims to:

(i) analyse movement patterns of krill trawlers with regard to catch levels, and assess whether these patterns can be described generic;

(ii) suggest updated parameter values for the existing krill fishery models through assessing the statistics of the most recent fine-scale data.

A description of the traditional krill fishery operation using midwater trawls and a definition of terminology

The krill fishery operates throughout the day and night. The landed catch is released from the codend into a fish tank. From the fish tank, krill are transferred continuously to the factory by conveyer belts, continuously reducing the amount of krill in the reservoir. To keep the factory operating, it is important that krill are always landed before the reservoir becomes empty, which would result in a drop in the production rate (Kawaguchi et al., 2005b).

Figure 1 is a schematic diagram of how the factory operates on a conventional krill trawler. At the end of a haul, the net will be brought on board and the krill catch (C_n) will be landed in the reservoir, resulting in a volume (R_n) of the initial catch. As the factory tries to operate at an 'Optimal Processing Rate' of P, it gradually reduces the amount of krill remaining in the reservoir. At the end of next haul, the second catch (C_{n+1}) will be added to whatever amount of krill is left in the reservoir, making the total amount in the reservoir R_{n+1}, and the process continues. If the reservoir is emptied before the next catch is landed (i.e. period between C_{n+2} and C_{n+3}), then there will be a period of reduced production. The trawlers strive to ensure continuous production to remain profitable, so they may search for better aggregations and change fishing grounds if catches are not sufficient to maintain continuous production. On the other hand, if the catch level exceeds the production capacity of the factory, then the trawlers may increase the interval between hauls to allow the factory to process the landed krill or shorten the hauling time to reduce the size of the catch (Kawaguchi et al., 2005b). In these instances, the average distance between hauls whilst trawling should be greater for smaller catches compared to trawls with higher catches. Also 'Catch Rate' derived as C_n/t_n (where t_n is the time to next haul) should be approximately constant up to a certain point, since the maximum processing rate may be vessel specific, however, below a critical point for which the catch is no longer sufficient to continuously operate the factory, C_n/t_n should decline. In this last case, the fishing master may choose to take more time for searching and/or move to a different site and this will be reflected in increasing distance (d_n) and/or time (t_n) to the next haul. If the trawlers are using the continuous pumping method to fish for krill, then the rate of supply of krill to the reservoir (R) will be less variable since supply and processing of krill are both continuous, but the principle will be the same.

Materials and methods

CCAMLR fine-scale catch and effort data from CCAMLR seasons 1997/98 to 2006/07 from the conventional trawling method (a total of 45 701 hauls) were used for these analysis.

Distances between consecutive hauls were simply calculated from the distance between the start locations of each haul, assuming 60 n miles for one degree latitude and 30 n miles for one degree longitude. The range of area considered in this paper was between 50°S–70°S and 70°W–30°W. Catch rates (C_n/t_n) were calculated as tonnes per hour following the definitions described previously. Since the dataset for the most recent 10 CCAMLR fishing seasons was too large to be handled as a single database in the fit of a linear mixed model (LMM) (Diggle et al., 2002), the distance data were modelled for trends with catch level separately for each of the three periods: period-1: 1997/98–1999/00, period-2: 2000/01–2003/04 and period-3: 2004/05–2006/07. For the modelling of distance, only distances less than 100 n miles were considered (i.e. within fishing grounds).

The probabilities of hauls being made within the same locality of the original hauls after a certain number of hauls were simply calculated by dividing the number of haul pairs (which are 10, 50, 100, 200 and 300 hauls apart) that had been made within a 30 n mile radius by the total number of haul pairs. For this calculation, travel distances upper limit restrictions of 100 n miles were not applied.

Statistical methods

Distance was analysed as the response variable with a continuous predictor variable of catch which is denoted by $\mathbf{x}$. Since the datasets were large, and to allow cubic smoothing spline terms in $\mathbf{x}$ to be incorporated in the LMM (Verbyla et al., 1999), the catch data was grouped into 5 tonne bins from 0 to 30 tonnes (and greater). The predictor variable, **x**, was defined as the mean catch for each bin which was appropriately replicated to correspond to the individual hauls. The LMM for each response variable and period was fitted using the ASREML library (Gilmour et al., 1995, 1999) within the R software package (R Development Core Team, 2006). The splines were fitted using the ASREML library in R as the sum of fixed-effect linear components plus random-effect non-linear components using each catch bin mean as a 'knot point' (Verbyla et al., 1999). The fixed effects of interest were CCAMLR statistical area (ASD_CODE; 481, 482, 483) and nationality of the vessel (NATIONALITY). Since the sample sizes from some nations were relatively small (<150 hauls with observed distance within a period), this resulted in a high degree of imbalance when analysing interactions between multiple factors. Thus, catches by vessels flagged to nations other than Japan were pooled to give factor levels of 'JPN' and 'Other' for the factor NATIONALITY. As well as spline terms, the identity of each vessel (SHIP_CODE factor) was fitted as a random effect. The maximal model fitted was main effects and interactions for the factors, the covariate **x**, interactions between the factors and **x**, the two-factor interaction by **x**, a spline term in **x**, and interactions between the factors and the spline term in **x**. Indications of statistical significance level for the fixed effects were determined from sequential Wald tests (Welham and Thompson, 1997) and for random effects by calculation of a Z-statistic which is the ratio of the estimated random effect variance to its estimated standard error. Although the sample size of hauls is very large, the number of vessels is much smaller (a total of only 19 vessels fished over the three periods). Predictions and their standard errors were obtained from the LMM (Welham et al., 2004), using the predict function call from the ASREML library in R, to allow graphical inspection of trends.

Results

Catch statistics

Figure 2 shows average and median values of catch/haul (kg) for each nation throughout the study period. Both average and median catch were variable between nations between the 1997/98 and 2000/01 fishing seasons. In fishing seasons between 2002/03 and 2006/07, the differences in both average and median were less variable between nations with higher catch levels compared to earlier fishing seasons. The Republic of Korea, Poland and the USA showed large variation between fishing seasons. On the other hand, Japan and Ukraine showed relatively stable catches between fishing seasons, with Japan showing the most consistently high catch throughout the period (average of 12–19 tonnes/haul and median of 12–18 tonnes/haul).

For the most recent period (2004/05 to 2006/07 fishing seasons), which is considered to best represent the current situation, Japan showed the highest mean and median catch/haul (16.3 and 16.0 tonnes) and C_n/t_n (9.5 and 8.9 tonnes per hour). Mean and median time allowed for processing (t_n) for Japan were 1.8 and 1.0 hours respectively. The Republic of Korea and Ukraine showed lower mean and median catch/haul and C_n/t_n compared to Japan, but the time allowed for processing was almost the same. Values for the USA need to be interpreted with caution due to the small sample size of hauls outside the 2000/01–2003/04 period. The mean time available for processing (t_n) in the 2004/05 to 2006/07 fishing seasons ranged between 1.7 and 2.1 hours (median 0.8 to 1.0 hours). The value of 1.4 hours for the USA was higher than for other nations but this may be due to the small sample size (Table 1). The number of hauls per day for Japanese trawlers for the 2004/05, 2005/06 and 2006/07 seasons was 10.4, 12.7 and 11.2 respectively.

Distances between hauls as a function of catch level

One of the main objectives was to assess whether the fishers can be described as a single generic fisher, and whether the movement behaviour of this generic fisher could be related to the CCAMLR statistical area, the time of the year, or the vessel nationality.

This section assesses whether each factor and their interactions are significantly affecting the behavioural pattern of the fishery by analysing trend lines of predicted distances between hauls against catch levels.

Hauls from Japanese vessels dominated the first two periods (Table 2), but the number of Japanese hauls in period-3 was less dominant in relation to the total number of other nations' hauls.

Catch level (**x**) was a significant variable for all three periods, indicating between-haul distances are indeed significantly dictated by catch levels. Nationality by statistical area (ASD_CODE) showed significant linear interaction with catch level (**x**) for all three periods, indicating the trend of distances with catch levels varied across combinations of these two factors (Table 3). Departures from linearity, as measured by terms involving the spl(x) (Table 3), were less obvious than in graphical presentations of actual trends with approximate 95% confidence bounds, which suggest that these trends are not simply linear in **x** (Figure 3).

Visual inspection of the trend patterns for each statistical area for Japanese vessels (Figure 3) indicates a distinct and, generally, consistent increase in distances between hauls when catch levels fell below 10 tonnes. The trend line for period-2 is shown as representative trends (Figure 4), since the total number of hauls for Japan and other nations were best balanced for this period. This general trend was consistent across the three periods (graphs not shown). The distance decreased as catch level increased with a levelling-off occurring for catches of 10–15 tonnes/haul and greater with a corresponding average distance of approximately 2–3 n miles. Trends in average predicted distance beyond catches of 25 tonnes are less clear due to the broad confidence bounds, which is largely due to the scarcity of data in this range. Distance between hauls at catch levels of less than 5 tonnes was the longest in Subarea 48.1, and shorter in Subareas 48.2 and 48.3. Predicted average distance for each statistical area was generally longer in Subarea 48.1 (~4 n miles) and shorter in Subareas 48.2 and 48.3 (~2 n miles). With some minor differences, this general trend described above was generally consistent among the three periods.

In the plots for all other nations combined (i.e. 'Other'), this trend of increasing distance with catch rates below 10 tonnes also occurred (Figures 3 and 4) but this trend was not as strong or consistent as that for the Japanese vessels.

This presentation demonstrates that, although statistical area was identified as a primary determining factor in modifying the average trend, the general pattern of a distinct increase in distances between hauls when catch levels fell below 10 tonnes was clearly retained for Japan when the three statistical areas were combined. This average trend was seen for Japanese vessels in all three periods. A similar, though less consistent, trend with wider confidence bounds was observed for other nations across all three periods.

Year-to-year variation in fleet dynamics

The probabilities of operating within the same local fishing grounds (in this case within 30 n miles radius) decreased as the number of hauls increased (Figure 5a). Importantly, this clearly shows a significant degree of year-to-year variation in the probability of maintaining a local concentration of fishing effort. For example, in the CCAMLR season 1999/2000, the probability of fishing within the same 30 n miles radius after 300 hauls was only 0.1, however, in the 2004/05 season this probability was as high as nearly 0.7.

There were two peaks observed in the year-to-year krill biomass around the South Shetland Islands in the southwest Atlantic sector (data source – Reiss et al., 2008), one in the 1997/98 season and the other during the 2001/02–2002/03 seasons (Figure 5b). The latter peak in krill abundance coincided with a year with a relatively high probability of fishing operations observed to concentrate locally (Figure 5a). Interestingly, acoustically detected krill abundance did not show any peaks when the probability of fishing effort concentration peaked in the 2004/05 season.

In the South Shetland Islands, the proportion of operations in summer has dropped from ~0.2 to almost 0 in the last decade (Figure 5c). At the same time, autumn operations have increased from ~0.3–0.4 to 0.6–0.7. Winter operations have stayed almost at the same proportion (0.3–0.5). Spring operations were consistently low over the last decade with a slight peak of ~0.1 in the 2001/02 season.

Discussion

In this study, a general pattern of a distinct increase in distances between hauls when catch levels fell below 10 tonnes was observed, and year-to-year variation in fleet dynamics was shown as variation of probability of a local concentration of fishing efforts. The following discussion deals with rules for vessels to move from one location to another in relation to catch/haul and production rate. Secondly, the topics of repeat hauls and size of fishing foci are discussed.

Fishery behaviour in relation to catch level and processing rate

Citing from Butterworth (1988a) in relation to catch/haul indices he described:

> '…hauls are generally kept to a maximum of 5–10 tonnes. This is for two reasons: product quality suffers in larger hauls because the krill is crushed, and operations need to be linked to the vessel's processing rate capabilities. Thus Catch-per-Haul exhibits a form of gear saturation…',
>
> 'Product quality consideration lead to haul sizes being restricted, so that Catch-per-Haul is not a reliable index of abundance.'

and

> 'If catch rate or quality (whichever is relevant at the time) is satisfactory, a vessel will attempt to keep track of the swarm while completing processing to allow for subsequent re-towing, but will otherwise undertake searching for new swarms.'

Mangel (1988), in his krill fishery model, assumed that if the daily value of catch/haul exceeds 3 tonnes/haul, then the fleet stays with the current krill concentration, but if it is below 3 tonnes/haul, then the fleet exits the current concentration and begins to search for another concentration.

In the following section an assessment is made of whether it is possible to estimate parameters similar to those derived through earlier fine-scale data analysis (Butterworth, 1988a; Mangel, 1988) and whether the previously published decision rules are still valid for the current fishery. Only conventional trawls are considered in this examination.

Catch level

The statements above by Butterworth (1988a) seem to be supported from the analysis of distances between hauls versus catch amount categories because: (i) the general pattern of longer mean distances between hauls after the lowest catch levels; and (ii) the decreasing travel distances as catch levels increase, with a levelling-off occurring for catches of 10–15 tonnes/haul and greater (Figures 3 and 4).

Explanations of why clearer trends were observed for Japan could largely be due to the larger number of hauls made by Japan alone compared to other nations combined. Additionally, (i) Japanese vessels appear to be more focused on keeping contact with targeted single swarms rather than aiming for a group of swarms; other nations' vessels may not do this (Kawaguchi et al., 2005b), (ii) the types of swarms and fishing ground conditions differed between seasons and areas where vessels from other nations were operating during the period analysed, (iii) there may be differences and changes in product types between the vessels of different nations, and (iv) there may be a combination of all of the above factors.

The average distances between hauls were larger in Subarea 48.1 compared to Subareas 48.2 and 48.3. This is probably because the vessels often move between multiple fishing grounds along the South Shetland Islands when looking for favourable fishing concentrations in Subarea 48.1 (Kawaguchi et al., 2005a). In contrast, within Subareas 48.2 and 48.3, there is a single fishing ground and therefore looking for better concentrations in these areas only involves searching within that fishing ground.

This analysis has demonstrated that general trends for distances between hauls as a function of catch levels were most distinct for Japanese vessels, but also common to other nations' vessels. Although this trend differs between statistical areas (shorter distances between hauls for Subareas 48.2 and 48.3 compared to Subarea 48.1), the overall pattern of a distinct increase in distances between hauls when catch levels fell below 10 tonnes seems to be generally consistent across statistical subareas and nations.

Processing rate

Processing efficiency differs between fishing nations. The processing rate has a direct inverse relationship with the time allowed for factory processing (which is almost the same as the operation interval). Average catch/haul for vessels of the Republic of Korea is about 70% (12–13 tonnes) that of Japan's (17–18 tonnes) when staying on optimal fishing grounds (i.e. travel distance of <1 n mile) but the Korean production rate is over 80% of Japan's production rate (Kawaguchi, 2008). This means that Korean vessels are compensating for the smaller catches per haul by increasing the throughput of its operations. On Ukrainian vessels, both the catch/haul and processing rates are around 65% of Japan's figure, which means they are not compensating their production by increasing the number of hauls. However, this interpretation again has a number of unknowns that might affect catches and processing rates, such as the types of products being produced, processing capacity and fishing ground conditions during operation. For example, to produce krill meal, the vessels need to use additional fuel to operate the meal plant compared to when the factory is producing simple frozen krill products. Japanese krill trawlers aim for a daily production of ~18 tonnes of krill meal, consuming ~5KL of fuel which comprises ~18% of the vessel's total daily fuel consumption (S. Nakaya of Nippon Suisan Kaisha Ltd, pers. comm.); this may vary between nations. Obviously, the profit margin, which is the balance between product price and operational cost, is an important factor in dictating fishery dynamics. It is apparent that using information from fine-scale catch data only is insufficient to adequately quantify parameters such as production rate, and such data will have limited usefulness unless associated with other operational information, especially on factory operations, as well as product composition and market information.

Parameter updates

Gathering information from recent fishery analyses and the results of this study allows updating some of the parameters for the vessel movement model originally described in Table 2 of Butterworth (1988a) (Table 4).

'Catch rate (Cn/tn)' in this study can be considered equivalent to 'process rate' in Butterworth (1988a). Through this study, process rates of 9.5 and 7.2, as reasonable parameter values for Japanese and other nations' process rates respectively, are suggested.

Assuming that the krill trawlers are continuously processing krill for the majority of the time, using median values for tn would be a realistic estimate for that parameter value. Therefore, 1.0 and 0.9 hours for Japan and the other nations respectively are suggested.

Catch/haul for Japan ranged between 14.2 and 17.3 tonnes with a three-year average of 16.3 tonnes and median of 16.0 tonnes (Table 1). Further, predicted travel distances following various catch levels (Figure 4) show that Japanese vessels tend to make very small moves when their catch is 15 tonnes or above. Based on these analyses, a target catch/haul for Japanese vessels can be suggested as 16.0 tonnes, and 12 tonnes for other nations (assuming 75% catch/haul of Japanese vessels).

Sonar detection width was 35 m in Butterworth (1988a). Based on information from the recent Japanese krill fishery their detection radius is 400 m (S. Nakaya, Nippon Suisan Kaisha Ltd, pers. comm.), therefore a detection width of 800 m is suggested. This value may be used for other nations as well, assuming they use similar instruments.

In Butterworth (1988a) the repeat haul criterion was set to the level equivalent to average catch/hauling time. Catch/hauling time in the most recent years in this study shows consistently high means compared to median with standard deviations greater than mean value in all four nations. This suggests median, rather than mean, would better represent typical levels of catch/hauling time, those are 22.8, 17.3, 14.4 and 9.3 tonnes/hour for Japan, Republic of Korea, Ukraine and the USA respectively. Therefore, repeat haul criteria of 23 tonnes/hour for Japan and 13 tonnes/hour for the other nations are suggested.

Vessel movement strategy from operational perspectives

Although the location of where krill concentrations are expected to occur is relatively fixed and predictable (Kawaguchi et al., 2006), there was considerable year-to-year variability in the probabilities of continuously operating within a local range (Figure 5a).

Comparing Figures 5(a) and 5(b), vessels were more mobile (lower probabilities of operating in the same regions after a certain number of hauls) when krill abundance during summer was low, possibly because they needed to search more to locate ideal concentrations. When krill abundance is high, there is less need to move around to search for krill. There would also be another case that even though regional krill abundance is reasonably high, if aggregations are more dispersed and not useful to the fishery, then the fishers may prefer to search for another aggregation. Alternatively, if vessels are able to catch enough to satisfy production needs, or krill are concentrated spatially regardless of regional krill abundance, then vessels may prefer to continue fishing in the same area, as has been observed in the 2004/05 season (Figures 5a and 5b).

Two types of harvesting strategies can be considered. The first is a free distribution of fishing efforts, in which fishers are assumed to seek out the locations producing the highest catch rates, which subsequently reduces the abundance in that location. In contrast, optimal harvesting strategies dictate the geographic distribution of the fishing effort in order to maximise the total quantity of harvest or another definition of optimality could be considered (MacCall, 1990). Through the current analysis it became obvious that the krill fishery employs both of these strategies. The krill fishery has an established fishing strategy of moving backwards and forwards between distant fishing grounds as CPUE declines (Kawaguchi et al., 2005a). This strategy seems common to what has been suggested for the Peruvian anchovy fishery (Bertrand et al., 2007).

Studies of the fleet dynamics of fisheries on other species, which have similar aggregation patterns to krill, may provide insights into methods for the analysis of the krill fishing fleet. The multiscale gregarious behaviour of anchovy (school, cluster of schools, cluster of clusters etc.) (Bertrand et al., 2004) is similar in many ways to the scales of krill aggregations (Mangel, 1988). Vessel movement in the Peruvian anchovy fishery has been suggested to be well described by Lévy's random walk model, a strategy that maximises the encounter rate with target species when their distribution is sparse (out of fishers' detection range) (Bertrand et al., 2007). It is apparent that the stochastic search strategy developed by the fishers may not result in a fundamentally different movement pattern to animal predators searching for prey (Bertrand et al., 2007). Although there are various factors that differ between anchovy fisheries and the krill fishery, it could be fruitful to assess whether the krill fishery can still be broadly described by using the random walk theory or not.

Analysis of interactions between fishery and target species distribution need to be undertaken using matching information of the target species and fishing activity in space and time in order to obtain meaningful information. The krill fishery operates year-round with autumn as the peak season in Subareas 48.2 and 48.3, yet most scientific information on krill abundance and distribution currently available is mostly from the summer season in Subarea 48.1. This mismatch in space and time is a serious obstacle to pursuing effective analyses of the behaviour of the krill fishery.

It would also be impractical to expect routine acquisition of krill information throughout the year solely relying on research surveys, as is done in the Peruvian anchovy fishery. Research hauls by fishing vessels would be a powerful way of acquiring distributional information in the fishing grounds. Deployment of scientific observers on fishing vessels, as well as coordination of commercial krill fishery operations with scientific acoustic surveys is necessary (Kawaguchi and Nicol, 2007) to fully understand the fishery behaviour and operation, and to develop appropriate krill fishery models.

Conclusions

This study demonstrated that fine-scale data can be used to derive movement patterns of conventional krill trawlers and that these patterns reveal useful information about fishing fleet dynamics. Fleets showed repeated hauls within favourable fishing locations, but moved further when the catch levels were low. There were differences between statistical areas, with longer distances moved between hauls in Subarea 48.1 compared to Subareas 48.2 and 48.3, reflecting the large number of fishing grounds within this area. Further, it is suggested that the movement trends for Japanese vessels could form the basis for describing a generalised fishery model. Further accumulation of data will be essential to establish nation- and area-specific behavioural patterns. The analyses in this study suggest the need to update some of the parameters used in the krill fishery models published in the late 1980s.

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References

Bertrand, S., E. Díaz and M. Ñiquen. 2004. Interactions between fish and fisher's spatial distribution and behaviour: an empirical study of the anchovy (*Engraulis ringens*) fishery of Peru. *ICES J. Mar. Sci.*, 61 (7): 1127–1136.

Bertrand, S., A. Bertrand, R. Guevara-Carrasco and F. Gerlotto. 2007. Scale-invariant movements of fishermen: the same foraging strategy as natural predators. *Ecol. Appl.*, 17 (2): 331–337.

Butterworth, D.S. 1988a. A simulation study of krill fishing by an individual Japanese trawler. In: *Selected Scientific Papers, 1988 (SC-CAMLR-SSP/5)*, Part I. CCAMLR, Hobart, Australia: 1–108.

Butterworth, D.S. 1988b. Some aspects of the relation between Antarctic krill abundance and CPUE measures in the Japanese krill fishery. In: *Selected Scientific Papers, 1988 (SC-CAMLR-SSP/5)*, Part I. CCAMLR, Hobart, Australia: 109–125.

CCAMLR. 2007. *Schedule of Conservation Measures in Force, 2007/08*. CCAMLR, Hobart, Australia: 192 pp.

Constable, A.J., W.K. de la Mare, D.J. Agnew, I. Everson and D. Miller. 2000. Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES J. Mar. Sci.*, 57 (3): 778–791.

Diggle, P.J., P. Heagerty, K.-Y. Liang and S.L. Zeger. 2002. *Analysis of Longitudinal Data*. 2nd Edn. Oxford University Press, Oxford.

Everson, I. 2000. *Krill Biology, Ecology and Fisheries*. *Fish and Aquatic Resources*, Series 6. Blackwell Science, Oxford.

Gilmour, A.R., R.T. Thompson and B.R. Cullis. 1995. Average information REML: an efficient algorithm for variance parameter estimation in linear mixed models. *Biometrics*, 51: 1440–1450.

Gilmour, A.R., B.R. Cullis, S.J. Welham and R. Thompson. 1999. ASREML Reference Manual. *Biometric Bulletin,* No. 3, NSW Agriculture, Orange Agricultural Institute, Forest Road, Orange, NSW 2800, Australia.

Kawaguchi, S. 2008. Krill fishery behaviour in the southwest Atlantic. Document *WG-EMM-08/39*. CCAMLR, Hobart, Australia.

Kawaguchi, S. and S. Nicol. 2007. Learning about Antarctic krill from the fishery. *Ant. Sci.*, 19 (2): 219–230.

Kawaguchi, S., S. Nicol., K. Taki and M. Naganobu. 2005a. A conceptual model of Japanese krill fishery. Document *WG-EMM-05/30*. CCAMLR, Hobart, Australia.

Kawaguchi, S., S. Candy, S. Nicol, K. Taki and M. Naganobu. 2005b. Analysis of trends in Japanese krill fishery CPUE data, and its possible use as a krill abundance index. *CCAMLR Science*, 12: 1–28.

Kawaguchi, S., S. Nicol, K. Taki and M. Naganobu. 2006. Fishing ground selection in the Antarctic krill fishery: trends in patterns across years, seasons and nations. *CCAMLR Science*, 13: 117–141.

MacCall, A.D. 1990. Dynamic geography of marine fish populations. *Books in Recruitment Fishery Oceanography*. Univ. of Washington Press, Seattle: 153 pp.

Mangel, M. 1988. Analysis and modelling of the Soviet Southern Ocean krill fleet. In: *Selected Scientific Papers, 1988 (SC-CAMLR-SSP/5)*, Part I. CCAMLR, Hobart, Australia: 127–235.

R Development Core Team. 2006. *R: a Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria: www.R-project.org.

Reiss, C.S., A.M. Cossio, V. Loeb and D.A. Demer. 2008. Variations in the biomass of Antarctic krill (*Euphausia superba*) around the South Shetland Islands, 1996–2006. *ICES J. Mar. Sci.*, 65 (4): 497–508, doi: 10.1093/icesjms/fsn033.

SC-CAMLR. 1995. Report of the Working Group on Ecosystem Monitoring and Management. In: *Report of the Fourteenth Meeting of the Scientific Committee (SC-CAMLR-XIV)*, Annex 4. CCAMLR, Hobart, Australia: 105–253.

SC-CAMLR. 2006. Report of the Working Group on Ecosystem Monitoring and Management. In: *Report of the Twenty-fifth Meeting of the Scientific Committee (SC-CAMLR-XXV)*, Annex 4. CCAMLR, Hobart, Australia: 157–258.

Verbyla, A.P., B.R. Cullis, M.G. Kenward and S.J. Welham. 1999. The analysis of designed experiments and longitudinal data using smoothing splines (with discussion). *Appl. Stat.*, 48 (3): 269–311.

Welham, S.J. and R. Thompson. 1997. Likelihood ratio tests for fixed model terms using residual maximum likelihood. *J. Roy. Stat. Soc., B (Methodologial)*, 59 (3): 701–714.

Welham, S., B. Cullis, B. Gogel, A. Gilmour and R. Thompson. 2004. Prediction in linear mixed models. *Aust. NZ. J. Stat.*, 46 (3): 325–347.

Table 1: Statistics of catch per haul, catch per hauling time, production rate (C_n/t_n), and time allowed for processing (t_n) for the 2004/05 to 2006/07 fishing seasons.

Nationality	Catch/haul (tonnes)			Catch/hauling time			C_n/t_n (tonnes/hour)			t_n (hour)			n
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	
Japan	16.3	16.0	9.4	30.8	22.8	34.8	9.5	8.9	6.1	1.8	1.0	10.2	4790
Korea, Republic of	12.4	11.8	6.8	23.0	17.3	22.0	7.8	6.9	4.9	1.7	0.8	22.4	7825
Ukraine	10.9	10.0	6.9	18.9	14.4	19.4	6.6	5.5	5.2	2.1	0.9	12.3	3335
USA	12.5	9.5	10.9	12.9	9.3	14.0	4.6	3.9	3.7	1.9	1.4	1.4	86

Table 2: Number of hauls made by Japan and other nations by fishing periods and CCAMLR statistical subareas.

Period	Subarea	Number of hauls	
		Japan	Others
Period-1	48.1	8601	2567
	48.2	4597	1055
	48.3	2546	402
Period-2	48.1	7145	2306
	48.2	2879	4459
	48.3	7614	5060
Period-3	48.1	1613	5950
	48.2	926	2995
	48.3	2236	2191

Table 3: ANOVA and variance components for the response variable distance (n miles) and predictor variable {**x**= Catch (tonnes)}.

Source	Degrees of freedom	Sequential Wald statistic (Chi Square)			Probability level (**bold** = significant trends in **x**)		
		1997–1999	2000–2003	2004–2006	1997–1999	2000–2003	2004–2006
ASD.CODE	2	116	236	65	<2.2e-16	<2.2e-16	4.774e-15
NATIONALITY (JPN vs Other)	1	0.1	2	0.4	0.731	0.131	0.539
x	1	49	11	46	**3.365e-12**	**8.943e-04**	**9.653e-12**
NATIONALITY:ASD.CODE	2	3	2	22	0.185	0.396	1.496e-05
ASD.CODE:**x**	2	1	23	7	0.658	**6.980e-06**	**0.031**
NATIONALITY:**x**	1	1	0.2	8	0.328	0.627	**0.0063**
ASD.CODE:NATIONALITY:**x**	2	7	14	28	**0.035**	**8.915e-04**	**8.40e-07**
		Variance (SE)			Z-statistic (**bold** = significant)		
spl(**x**)		0.1809 (0.3743)	0.2206 (0.2554)	0.07496 (0.0834)	0.48	0.86	0.90
ASD.CODE:spl(**x**)		0.0539 (0.0511)	0.2531 (0.1596)	0.0389 (0.0334)	1.06	1.59	1.17
NATIONALITY:spl(**x**)		0.4131 (0.4034)	0.0750 (0.0756)	0.0139 (0.0193)	1.02	0.99	0.72
SHIP_CODE		5.176 (2.461)	0.6920 (0.3643)	0.0682 (0.0562)	**2.10**	**1.90**	1.21
Residual variance		42.03 (0.422)	37.060 (0.305)	25.813 (0.288)			

Table 4: Values of fishing operation parameters. na – not applicable.

Parameter	Butterworth (1988a)	This study	
		Japan	Others
Process rate (tonnes/hour)[1]	2.5	9.5	7.2
Time available (hour)[2]	1.5	1	0.9
Target catch (tonnes)	10	16	12
Sonar detection width (m)	35	800	800
Repeat haul criterion[3] (tonnes/hour)	10	23	13
Leave concentration criterion[4] commencing value (tonnes/hour) (after tuning)	2.5	4.8	3.6

[1] Equivalent to processing rate $(C_n/t_n)'$ in this study.

[2] Time available: process time available estimated until end of next haul.

[3] Repeat haul criterion ($(C/\mathrm{FISHT})_{rep}$): the minimum catch rate to attempt to refish a swarm.

[4] Leave concentration criterion (CR_{min}): the minimum catch rate per total elapsed time for the vessel not to stop fishing and search for another concentration.

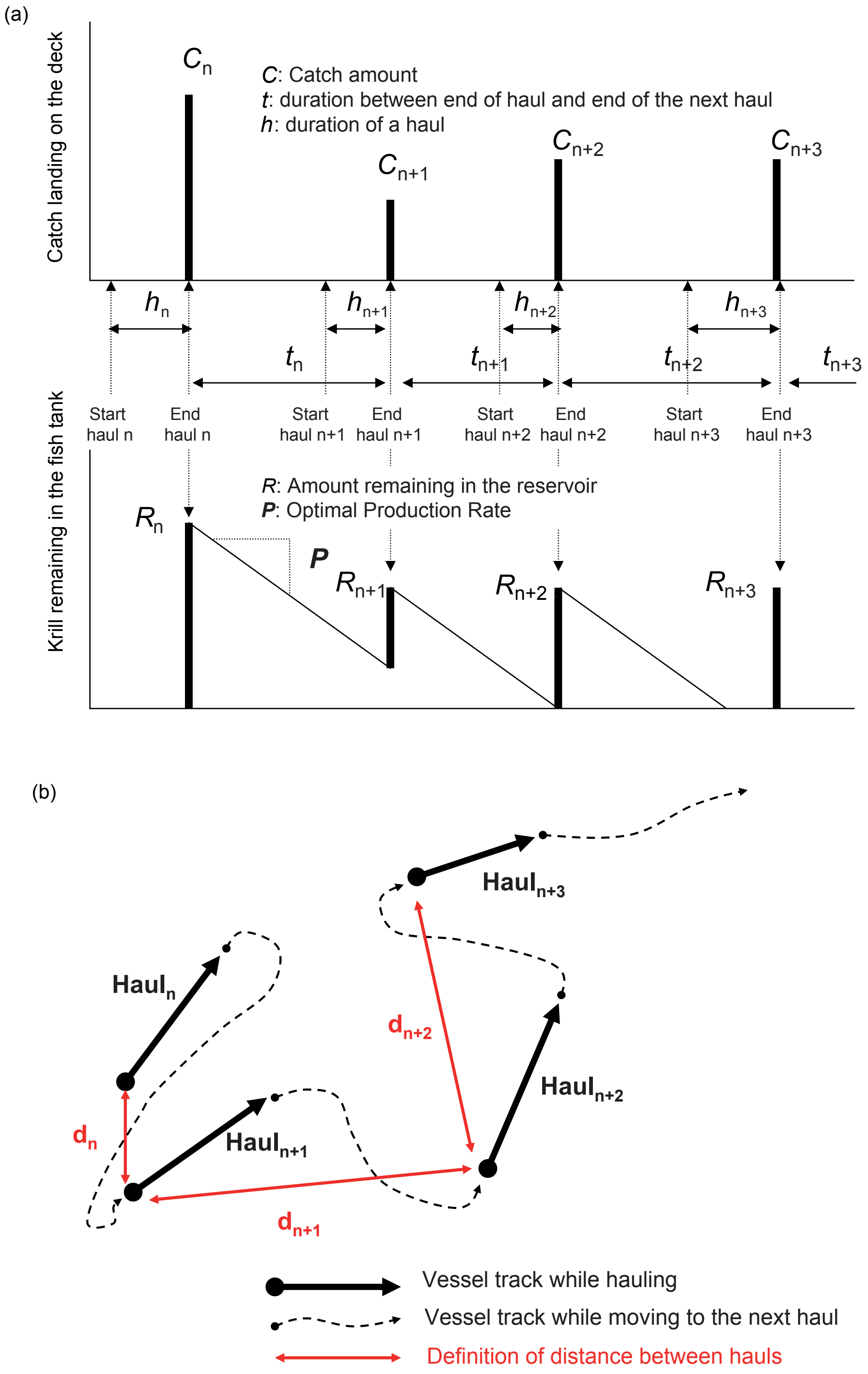

Figure 1: Conceptual diagram of a krill fishery operation: (a) how the factory operates on a conventional krill trawler, (b) spatial movement of trawlers.

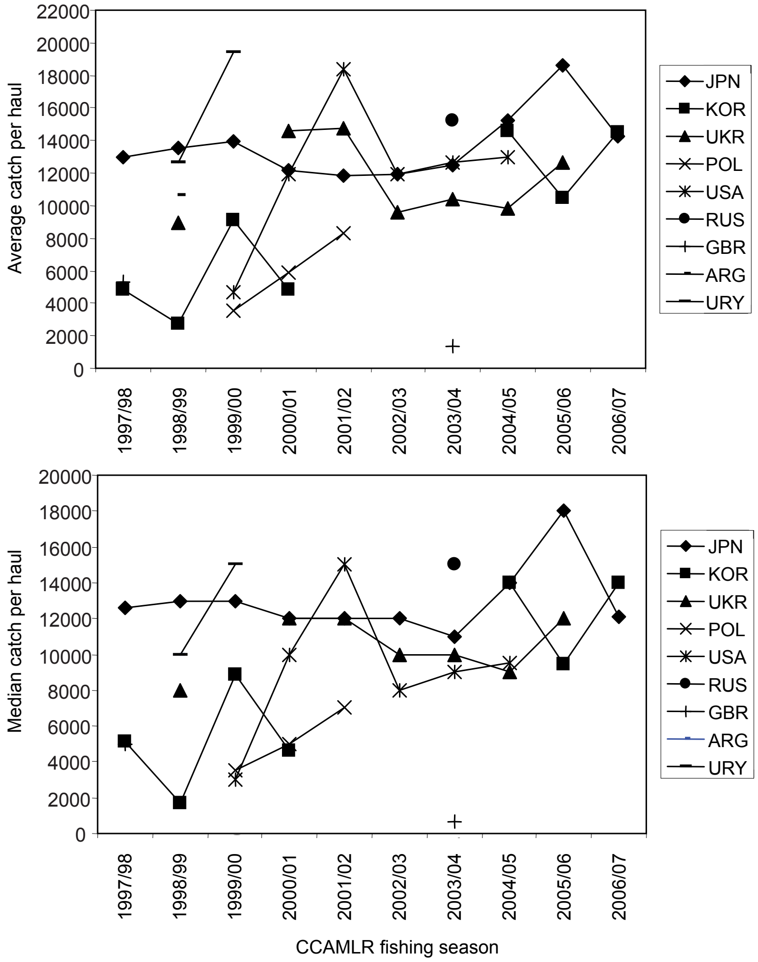

Figure 2: Interannual variation of the average and median catch/haul (tonnes) for all nations participating in the krill fishery between the 1997/98 and 2006/07 CCAMLR seasons. JPN – Japan; KOR – Republic of Korea; UKR – Ukraine; POL – Poland; USA – USA; RUS – Russia; GBR – United Kindgom; ARG – Argentina; URY – Uruguay.

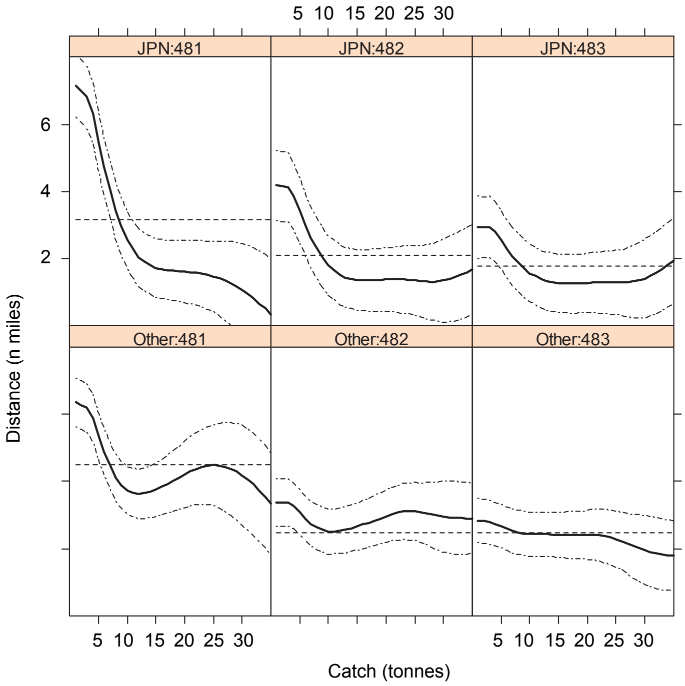

Figure 3: A series of trend lines of predicted average distance between hauls (n miles) as a function of catch (tonnes) for each statistical subarea in period-2 for Japan alone and all other nations combined.

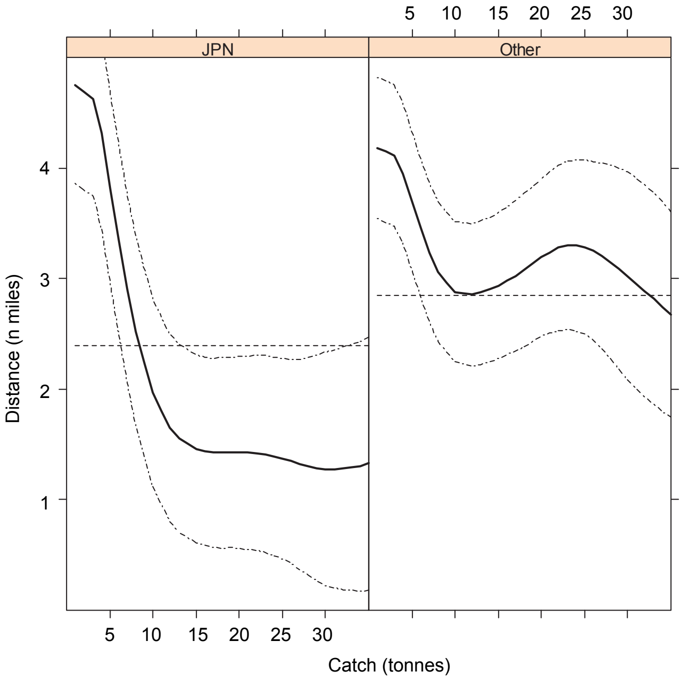

Figure 4: Predicted trends in distance between hauls (n miles) as a function of catch (tonnes) for period-2, which combines the trends of three statistical areas for Japan alone and all other nations combined. These predictions were obtained by averaging across the difference in trends in **x** with statistical area for each nationality, i.e. the LMM is as given by Table 3 but **x** and nationality were the only terms in the predict function call.

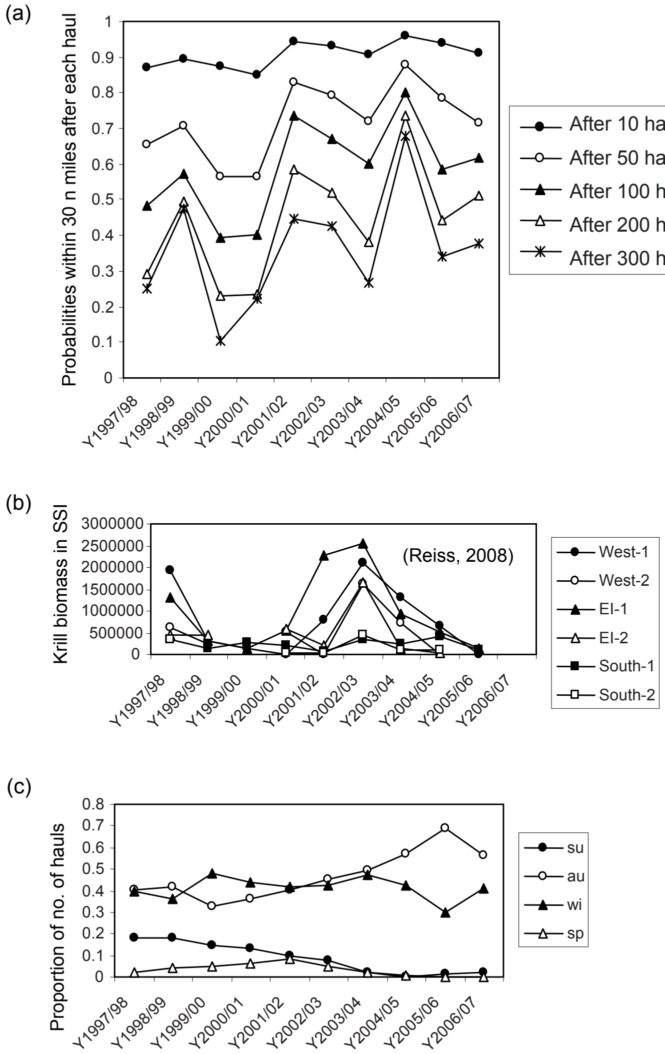

Figure 5: Year-to-year succession of fishery behaviour and published krill biomass in the South Shetland Islands area: (a) probabilities of operating within 30 n miles of the original haul, (b) krill biomass (data source – Reiss et al., 2008), (c) West: west survey box north of Livingston and King George Islands; EI: survey box around Elephant Island; South: survey box in Bransfield Strait; 1: January survey; 2: March survey; year-to-year succession in proportions of number of hauls in each season.

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