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ANALYSIS OF TRENDS IN JAPANESE KRILL FISHERY CPUE DATA, AND ITS POSSIBLE USE AS A KRILL ABUNDANCE INDEX

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Abstract

Haul-by-haul logbook catch and effort data from the Japanese krill fishery for the 1980/81 to 2003/04 fishing seasons were analysed. For a number of definitions of effort and catch-per-unit-effort (CPUE), variables were modelled using linear mixed models in order to obtain time series of predicted intra- and interannual trends of standardised fishery indices. The results strongly suggest that the krill fishery in the South Georgia area is operating at a critical level of krill availability which is just enough to maintain the best factory performance. In this analysis the status of fishing in Subareas 48.1 and 48.2 was not clear. A linear correlation was observed between 'catch per searching time' and 'catch per day' within their lower ranges, suggesting these may have some value as abundance indices. Standardised CPUE for the pelagic areas showed significant correlations with previously published interannual series of acoustic density estimates from scientific surveys. To refine these CPUE indices, it will be necessary to collect more detailed information from fishing vessels. It is also important to undertake the same kind of analysis for fleets from other fishing nations.

Résumé

Les données de capture et d'effort de pêche par trait extraites des carnets de bord de la pêcherie japonaise de krill des saisons de pêche 1980/81 à 2003/04 ont fait l'objet d'analyses. Pour différentes définitions de l'effort de pêche et de la capture par unité d'effort (CPUE), les auteurs ont modélisé les variables à l'aide de modèles linéaires mixtes afin d'obtenir une série chronologique de tendances inter et intra-annuelles prévues des indices de pêche normalisés. Les résultats laissent fortement penser que la quantité de krill disponible dans la pêcherie de la Géorgie du Sud est telle qu'elle permet tout juste un rendement optimal de l'usine. Dans cette analyse, l'état de la pêche dans les sous-zones 48.1 et 48.2 n'est pas clair. Une corrélation linéaire est observée entre «la capture par temps de prospection» et «la capture par jour» dans leurs intervalles de valeurs les plus faibles, ce qui suggère qu'elles pourraient être utilisées comme indices d'abondance. Des corrélations importantes sont relevées entre la CPUE normalisée pour les secteurs pélagiques et une série d'estimations acoustiques déjà publiée de densités interannuelles extraites de campagnes d'évaluation scientifiques. Pour redéfinir ces indices de CPUE, il sera nécessaire de collecter davantage d'informations détaillées des navires de pêche. Il est également important de réaliser le même type d'analyse pour les flottilles d'autres nations menant des activités de pêche.

Резюме

Были проанализированы данные судовых журналов по улову и усилию за каждый отдельный улов для японского промысла криля в промысловых сезонах 1980/81–2003/04 гг. Переменные моделировались с использованием смешанных линейных моделей для нескольких определений усилия и улова на единицу усилия (CPUE) в целях получения временных рядов прогнозируемых внутри- и межгодовых тенденций в стандартизованных показателях промысла. Результаты убедительно указывают на то, что промысел криля в районе Южной Георгии работает при критическом уровне наличия криля, который только позволяет поддерживать оптимальный режим работы рыбного цеха. В данном анализе состояние промысла в подрайонах 48.1 и 48.2 было неясно. Наблюдавшаяся линейная корреляция между «уловом на время поиска» и «уловом в день» в более низких частях их диапазонов позволяет предположить, что они могут быть в какой-то мере полезны как показатели численности. Была выявлена значимая корреляция между стандартизованными CPUE для пелагических районов и ранее опубликованными многолетними рядами акустических оценок плотности для научно-исследовательских съемок. В целях уточнения этих показателей CPUE необходимо собрать более подробную информацию по промысловым судам. Также важно провести аналогичный анализ для флотилий других ведущих промысел государств.

Resumen

Se realizó un análisis de los datos de captura y esfuerzo de lance por lance registrados en los cuadernos de bitácora de los barcos de la pesquería japonesa de kril durante las temporadas de pesca 1980/81 a 2003/04. Para varias definiciones del esfuerzo y de la captura por unidad de esfuerzo (CPUE), se representaron las variables mediante modelos lineales mixtos para obtener una serie cronológica de predicciones de las tendencias intra e interanuales de los índices pesqueros normalizados. Los resultados indican convincentemente que la pesquería de kril en el área de Georgia del Sur está operando a un nivel crítico de la disponibilidad de kril que apenas basta para mantener una óptima productividad de la factoría. Los resultados de este análisis no dejaron claro el estado de la pesquería en las subáreas 48.1 y 48.2. Se observó una correlación lineal entre los niveles más bajos de "la captura por tiempo de búsqueda" y "la captura diaria", por lo que pueden tener cierto valor como índices de la abundancia. Se demostró que había correlaciones significativas del CPUE normalizado de las áreas pelágicas con las series interanuales de estimaciones acústicas de la densidad de las prospecciones científicas, publicadas anteriormente. Se deberá recopilar información más detallada de los barcos de pesca para refinar estos índices de CPUE. Asimismo, es importante realizar el mismo tipo de análisis para las flotas pesqueras de otras naciones.

Keywords: krill fishery, krill fishery strategy, standardised CPUE, catch-per-unit effort, searching time, krill abundance, krill density, krill fishery information, CCAMLR

Introduction

There have always been questions as to whether fishery-generated data could be used to give a catch-per-unit-effort (CPUE) index that is a good predictor of krill abundance for those years during which the fishery has operated. In the late 1980s, several attempts were made to tackle this question using simulation models (Butterworth, 1988a; Mangel, 1988). Both these studies pointed out the importance of including a measure of searching time in the abundance index in order to improve its sensitivity. Generally it is thought that the utility of krill CPUE data is limited because of the nature of the operational strategies of the fishing fleets. Fishing operations are dictated by factory capacity and therefore the amount caught is usually regulated by this factor. Furthermore, since krill distributes in patches, there are always questions concerning methods of interpreting CPUE data. This study examines the utility of commercial fishery logbook CPUE data as an index of krill abundance using a number of definitions of effort, and examines the nature of fishing strategies.

Commercial trawlers must operate in a cost-effective way to make a profit. The factories on krill trawlers produce krill products as the vessels operate. Optimum efficiency is attained if the factory is continuously operated at its maximum capacity. Krill needs to be processed immediately after being caught because it starts to degrade quickly. Therefore skippers try, as much as possible, to provide constant supplies to the factories by adjusting the catch to factory processing capacity. Adjusting catches can be done by regulating fishing effort, but catch is also dependant on krill availability, particularly when abundance is relatively low.

Krill availability for fishing vessels is not necessarily proportional to krill local density. Krill local density simply expresses the average quantity of krill existing within a given area (e.g. g/m^2). On the other hand, krill availability is determined not only by local krill density but it is also influenced by the decisions made by skippers according to the types of krill aggregations (tightness, depth etc. of the patches). For example, even if local density is the same, if an aggregation is tighter rather than dispersed, it will be more profitable and likely to be available for the fishery because it results in a better quality product due to the length of each tow being minimised.

Figure 1 is an illustration of how the level of operational effort, CPUE, and factory production might respond to varying krill availability. For example, operational effort could be towing time

Table 1: List of variables and their definitions.

SU (searching unit):	A unit of continuous operation within a fishing ground. In other words, the period between two consecutive operational breaks. Operational breaks are mainly due to change of fishing ground but also due to transhipment, idling under bad weather, or crossing the boundaries of subareas. Searching units were identified for each of the statistical subareas.
ST (searching time):	The time duration between net tows within an SU is defined as searching time. This is calculated by subtraction of towing time from duration of SU (min).
STPSU (searching time per searching unit)	
CPST (catch per searching time):	Total amount of catch within a SU divided by ST (kg/min).
CPD (catch per day):	Total amount of catch in a day (kg/day).
CPT (catch per tow):	CPD divided by number of tows within a day (kg/tow).
TT (towing time)	
CPTT (catch per towing time):	CPD divided by daily total of towing time (kg/min).
TTPD (towing time per day):	Total towing time within a day (min).
NT (number of tows)	
NTPD (number of tows per day):	Total number of tows within a day.
TSDT (total ship days trawled):	Total number of ship days trawled per fishing season.

(TT), number of tows (NT), or even searching effort to find high krill densities. CPUE could be defined as catch per towing time (CPTT), and production could be catch per day (CPD). When krill availability is low, the skipper puts maximum effort into supplying krill to the factory, but CPUE will be low and therefore production will be dictated by krill abundance. As krill availability increases, CPUE may increase linearly. It seems that there is a critical level of krill availability at which the skipper can meet the factory capacity. When krill availability is higher than this critical point, the skipper decides to regulate or decrease the amount of operational effort to adjust the krill supply to the factory, with the result that production is constant above this point.

By using different kinds of fishery indices of CPUE (i.e. catch per tow (CPT), CPD, CPTT, catch per searching time (CPST)) and effort (i.e. towing time per day (TTPD), number of tows per day (NTPD)), this study tested whether the actual fishing operations follow this theoretical pattern. Butterworth (1988a) indicated that the use of search time in abundance indices may improve their sensitivity to decreases in krill density. In this study, this index was used to express krill availability.

Vessel time at sea can be divided into searching, net handling, towing, idling, transferring cargo and drifting (Butterworth, 1988b). Japanese krill fishing vessels voluntarily record these events whenever they change fishing grounds, and using this information it was possible to identify, for each fishing ground, one or more searching units (SU) (Table 1). Also, in the haul-by-haul data, all cargo transport and idling due to bad weather are recorded. By subtracting this value from an SU, it was possible, theoretically, to calculate searching time per searching unit (STPSU). Net handling time was not subtracted in this study since it was not recorded in the logbook. As it is normally about 10 min before and after towing (Japan Deep Sea Trawlers Association, pers. com.), it should be noted that these times are embedded in the searching time (ST) as underlying offset values. Table 1 lists the definitions of variables used in this study.

This paper consists of three main sections:

(i) a description of the statistical model (a linear mixed model (LMM)) used to standardise the haul-by-haul CPUE data is presented in the 'Statistical methods' section;

(ii) a general explanation of a series of predicted intra- and interannual trends in standardised fishery indices is presented in the 'Results' section;

Table 2: Definition of broad SSMU (BSSMU) used in this study.

BSSMU	Corresponding SSMUs
APBS (Bransfield Strait)	APBSE (east) + APBSW (west)
APDP (Drake Passage)	APDPE (east) + APDPW (west)
APEI (Elephant Island)	APEI
APW (Antarctic Peninsula)	APW (west)
AP.Pel	Pelagic of Subarea 48.1
SO (South Orkney Islands)	SOW (west) + SONE (northeast) + SONW (northwest)
SO.Pel	Pelagic of Subarea 48.2
SG (South Georgia)	SGE (east) + SGW (west)
SG.Pel	Pelagic of Subarea 48.3

(iii) in the 'Discussion' and 'Conclusions' sections, standardised fishery indices are plotted against krill availability and their characteristics are discussed.

This study assessed whether or not these indices follow the assumptions illustrated in Figure 1, and attempted to identify which CPUE indices best represent krill abundance. In addition, the analyses were used to gain a better understanding of the operational nature of the krill fishery.

Materials and methods

Data

The complete set of haul-by-haul data from logbooks from the Japanese krill fishery operating in Area 48 from the 1980/81 to 2003/04 fishing seasons was obtained and used for the analyses. Although by definition the CCAMLR fishing season starts in December and ends in November, there was a fishing season in the early 1980s when Japan started its operation in November. Therefore in these analyses, the period from November to October was defined as the fishing season. This database was reorganised by summarising haul-by-haul data into daily operations. For example, catch, towing time and number of net hauls were calculated for each day for each vessel. The final working database consisted of 12 634 ship days from 14 vessels. Each of the data rows was assigned to a small-scale management unit (SSMU) and each SSMU was allocated to a 'broad SSMU' (BSSMU) (Table 2) to simplify spatial comparisons and ensure that there were sufficient data in each spatial unit to adequately estimate both spatial and temporal trends. For the CPST data, the spatial units used were the CCAMLR statistical subareas given by the CCAMLR ASD code.

The database for the STPSU analysis was arranged separately from the abovementioned working database. It was also based on haul-by-haul data and notes written on logbook hardcopies. These notes were used to determine when changes of fishing ground and breaks in fishing operations occurred. Prior to 1989, these notes were sometimes incomplete, therefore only the haul-by-haul data from the 1990/91 season onwards were used to arrange the ST working database. One data row consists of an individual SU which is defined as one continuous operational unit (see Table 1).

Figure 2 shows geographical distributions of SSMUs, recent commercial fishing operation positions, US AMLR acoustic transects in the South Shetland Islands and UK acoustic survey boxes in the South Georgia area. Figure 2 reveals the geographical mismatch between areas covered by acoustic survey transects and fishing grounds, especially to the north of King George and Livingston Islands, where the fishing ground is located to the south of acoustic survey coverage. In the Elephant Island area, fishing operations occur only around the island, and this accounts for only a small portion of the area of the acoustic survey. Therefore, it is important that comparisons of indices between fisheries and acoustic surveys be made between the regions where those comparisons are appropriate. On the other hand, in the South Georgia area, although not complete, the main fishing grounds matched reasonably well with the two survey boxes.

Statistical methods

Analysis of TTPD, NTPD, CPD, CPT and CPTT

The CPUE and effort variables calculated for each vessel-day were fitted using LMMs in S-plus. In order to incorporate intraseason trends in the LMM for CPUE or effort, a cubic smoothing spline using integer month numbers (i.e. 1 = Nov,…,12 = Oct) as knot points was fitted using the samm() set of functions for S-plus (Butler et al., 2002). The (unsmoothed) interseason trend was obtained from the regression coefficients for fishing season fitted as a factor (Candy, 2004). Fitting the cubic spline model (i.e. the sum of linear and non-linear components) using random effects imbeds spline modelling within a formal inferential framework (Verbyla et al., 1999). The minimal (significant) fixed-effect model was determined by backward selection using Wald tests while the minimal (significant) random-effect model was determined also by backward selection but used the likelihood ratio test for terms dropped from the model (Verbyla et al., 1999).

The LMM was fitted to the $\log_{10}$ transformed values of CPD, CPT and CPTT while TTPD and NTPD were not transformed. The consistently best, minimal fixed-effect model was

pseason + month.ns + bssmu.f + bssmu.f:month.ns,

where pseason is a factor defining the fishing season, month.ns is the integral-valued month covariate, bssmu.f is a factor defining the BSSMU as defined in Table 2, and ":" specifies an interaction. The consistently best, minimal random-effects model was

spl(month.ns) + spl(month.ns):bssmu.f +
month.fs:pseason + pseason:bssmu.f + ship.code

where month.fs is a factor defined by the nominal months, ship.code is a factor defining the vessels, and spl(month.ns) specifies the deviations-from-linearity component of the cubic smoothing spline in samm().

Predictions and their standard errors, on the Log_{10} scale where relevant, were obtained using samm's predict() function. The appendix gives an example of the S-plus code used to fit, and predict from, the abovementioned LMM.

Predictions of the within-season trend (i.e. across months) were obtained by ignoring all random-effect terms except spl(month.ns) and averaging over parameter estimates for fixed terms other than month.ns (i.e. averaged over all parameter estimates corresponding to factor levels of pseason and bssmu.f). Predictions of the CPUE fishing season series were obtained by ignoring all random-effect terms including pseason:bssmu.f (Candy, 2004) and setting month.ns to its average value of 5.4. This means that different BSSMUs simply shift the seasonal series up or down based on their fixed-effect parameters (Candy, 2004). Therefore this study does not present separate series for each BSSMU but predicts the overall CPUE series by averaging across parameter estimates corresponding to factor levels of bssmu.f.

Analysis of CPST

The same methods were used to model CPST (kg/min) with the exceptions that the data were not log-transformed, the factor ASD.code replaces bssmu.f, and a separate series for each ASD.code is presented.

Figure 3 shows qqplots and residual frequency distributions for the conditional residuals (Candy, 2004) from each model fit. Although the models seemed to be acceptable, qqplots of Log_{10}CPT, Log_{10}CPD, Log_{10}CPTT and NTPD showed some departure from linearity. Even though these data have been log-transformed, they were still slightly skewed either positively or negatively. In the case of NTPD, the histogram of residuals is indicative of a mixture of normal distributions; nevertheless, this was not investigated further in this study. Residuals of catch per searching time (CPST) showed a frequency distribution that was close to a normal distribution.

Regression coefficient analysis

Significance of regression coefficients for CPUE series versus scientific acoustic estimates was tested using the statistical package Statview.

Results

Trends in standardised fishing efforts across years

Figure 4 shows predicted number of tows per day (NTPD) and towing time per day (TTPD) and total ship days trawled (TSDT) for the whole of Area 48 across years. NTPD showed a slight increasing trend (from five to eight) accompanied by a cyclic pattern within a narrow range. TTPD was very small (≈30 min) in the 1980/81 season, and showed a rapid increase until the 1985/86 season. It stayed relatively constant ranging between 220 and 300 min until the 1992/93 season. After this, it again showed a rapid increase reaching a maximum of approximately 400 min, and thereafter showed a decreasing trend down to 200 min in the 2002/03 season. TSDT was highly variable until the 1986/87 season, but after this, although variable, the value remained relatively high (700–800 days), but from the 1992/93 season onwards it decreased to a constant level of 500–600 days.

Trends in standardised catch measures

Intra-annual trends in CPT, CPTT and CPD

Figure 5 shows predictions of the three CPUE indices for the whole of Area 48 across months.

CPT showed an increase from November to February, and gradually decreased from April onwards. CPTT showed a somewhat more stable trend, with a slight increasing trend at the beginning of the fishing season, but there is considerable uncertainty regarding predictions for the September to November period. CPD showed an increase from November to February, and stayed constant until August, then decreased from September onwards.

Interannual trends in CPT, CPTT and CPD

Figure 6 shows plots of predictions and simple annual means of actual data of the three CPUE indices for the whole of Area 48 across years. Predictions of CPT and CPD showed similar patterns with low values in the 1982/83, 1989/90, 1990/91 and 1998/99 seasons and high values in 1994/95. A relatively constant period of high values was also seen for the seasons 1985/86 to 1988/89. CPTT stayed relatively constant throughout these years compared to the other two CPUE indices. The interannual trends in actual mean values showed different patterns from those of the standardised indices. However, since the trends observed in the simple mean values are likely to be affected by the shifts in operational months and areas, their trends could be misleading. Note that unlike the simple means, the predictions are not implicitly weighted by the incidence of vessel-days in each BSSMU.

Intra-annual trends in CPST

Figure 7(a) shows predictions of CPST for the whole of Area 48 across months. The predictions showed an increasing trend from December to February, and then remained constant until the end of the fishing season.

Figure 7(b) shows CPST trends for each of the subareas. In Subarea 48.1, from December to February, the predicted value showed a rapid increase, then a slight decrease in March and April, remained constant until June, and increased slightly in July. In Subarea 48.2, predicted values increased from December until February, and from March to May remained constant but decreased slightly in June. During December to February, predictions gave lower values compared to Subarea 48.1, but were higher in April and May. No actual fishing operations took place from August onwards. In Subarea 48.3, predicted values were constant from April to September, the entire range of the actual operation. Caution should be exercised in interpreting predictions of CPST in Figure 7 from September to October in Subarea 48.1 and August to October in Subarea 48.2, since there is no actual data for these months, and predictions are therefore extrapolations based on the data from Subarea 48.3. Similarly, there were no data from Subarea 48.3 outside the May to October period.

CPST (krill abundance index) across fishing seasons

Figure 8 shows interannual trends in CPSTs predicted for the whole of Area 48, and separately for Subareas 48.1, 48.2 and 48.3. There were no significant differences in trends among subareas ($P > 0.1$), and generally all showed similar trends. The 1990/91 fishing season showed the lowest CPST, and increased until the 1992/93 season. A drop was observed in the 1993/94 season, but CPST increased again by the next season, and the level remained constantly high (≈150–180 kg/min) until the 2000/01 season, and decreased slightly during the 2001/02 and 2002/03 seasons.

Comparisons with acoustic surveys

As indicated previously, comparisons of predicted CPUE indices with acoustic densities cannot be made directly without taking into account the geographical locations they relate to (Figure 2), especially in the area north of the South Shetland Islands where the main fishing ground is not covered by the acoustic transects. In the Elephant Island area, fishing operations also tended to cluster close to the island, where acoustic transects give only limited coverage. Therefore, in these areas, it would make more sense to examine the correlation between acoustic densities and CPUE indices only from the pelagic area.

Trends in interannual krill acoustic densities were used as proxies of abundance indices since the survey area for each survey was fixed for the entire series, and therefore both show the same trends.

Table 3 and Figure 9 summarise results of statistical tests for correlation analysis between krill acoustic densities and the standardised CPUE series in this study.

Acoustic densities for the Elephant Island area showed significant correlation with AP.Pel SSMU (catch per day and catch per tow). Acoustic densities for the Drake Passage area also showed significant positive correlation with AP.Pel SSMU (CPD and CPT). The slopes of these regressions were all less than 1. This suggests the possibility of non-linearity in the (unlogged) CPD and/or CPT versus acoustic density estimate relationship, rather than

Table 3: Correlation coefficients obtained from regression analysis of acoustic densities and standardised CPUE series in this study. Sample size in parentheses; significant regression in bold. Data source: Elephant Island (Hewitt et al., 2003 updated with AMLR, 2003), Drake passage (West estimates of AMLR, 2003) and South Georgia area (Brierley et al., 1999; Wafy et al., 2003).

Scientific surveys			CPUE indices			
Area	Method		SSMU	CPD	CPT	CPTT
Elephant Island	Acoustic	vs	AP.Pel	**0.638 (11)***	**0.717 (11)***	–0.468 (11)
Drake Passage	Acoustic	vs	AP.Pel	**0.935 (6)****	**0.918 (6)****	0.628 (6)
South Georgia	Acoustic	vs	SG	0.321 (13)	0.308 (13)	0.319 (13)

* Significance level $p < 0.05$, ** Significance level $p < 0.01$.

strict proportionality, which might confirm that CPD and/or CPT as an index of density saturates at higher density levels. However, the deviations from slopes of 1 were not statistically significant (Figure 9).

On the other hand, in the South Georgia area, none of the indices from SSMUs showed significant correlation with acoustic densities.

A correlation analysis was also undertaken between acoustic estimates and CPST, but these data did not show any significant correlations.

Figure 10 shows the interannual trend in the proportion of the catch that was processed into the two major products, krill meal and frozen krill.

Figures 11 to 14 show the relationships between CPST and effort and other CPUE indices for each of the following most important (from a fisheries perspective) BSSMUs: APDP, APEI, SO and SG.

Discussion

One of the questions is whether the factors relating to operations (including type of product) systematically affect the trends in these fisheries indices or not. All trawlers operating in Area 48 since the 1980/81 season have been stern trawlers, and basically had the same net arrangements throughout the period (Kawaguchi et al., 1997). Therefore the configuration of vessels and nets is unlikely to affect the trends in the indices. Different types of products may require different fishing strategies and processing. Figure 10 shows trends in two major products. It shows that the proportion of krill processed for krill meal increased linearly from the 1980/81 season to the 1986/87 season, but remained relatively constant thereafter. On the other hand, the proportion of frozen krill was high in the early 1980s, but decreased rapidly until the 1986/87 season, then showed a steady increase until the 1994/95 season followed by a relatively constant ratio thereafter. None of the fishery indices showed a similar pattern to this, therefore it is assumed in this study that the effect of these factors has had little influence on the interannual trend in the CPUE indices. However, it is necessary that this topic be carefully examined in future studies.

NTPD has been remarkably constant since the early days of the fishery; a variation range of only 1.6 at most. TTPD varied up to 13-fold, and even if the period is restricted to the most recent 10 years, its decreasing trend is significant. TSDT was highly variable until the 1986/87 season but showed relatively constant values since then, especially for the past 10 years (Figure 4). The annual production of the Japanese krill fishery has also been around 60 000 tonnes for these 10 years (CCAMLR, 2003). Constant annual production and TSDT while TTPD varies significantly could explain the significant variations in interannual trends between some of the fishery indices observed in this study. The important question is whether these indices vary in a systematic way in relation to krill abundance.

The five standardised fishery indices (CPT, CPD, CPTT, TTPD and NTPD) of the four main BSSMUs (APDP, APEI, SO and SG) were plotted against standardised CPST (krill availability index) for those subareas.

In APDP (Figure 11), CPT, CPD and CPTT were all relatively constant, but all showed slightly higher values when CPST was at the high end. TTPD and NTPD did not show any trends against CPST. For APEI (Figure 12), all the indices were variable relative to APDP patterns. In SO, CPT and CPD showed a gradual increase up to a CPST value of 150, and above that point remained constant. Exceptionally low values close to zero (CPT, CPD and CPTT) were observed at 130 CPST (1989/90 season), however, these values were based on a very small sample size (two tows in total) and therefore should be treated with caution. CPTT did not show a clear trend. TTPD did not show any particular trend up to a CPST of 175, but above this point the indices increased. NTPD did not show any particular trend (Figure 13). SG showed a different pattern again (Figure 14). CPT and CPD showed increasing values with increasing CPST. Above a CPST value of 150, both remained constant. CPTT showed an increasing trend up to a CPST of 150, and declined beyond this point. Zero values (CPT, CPD and CPTT) were observed at 160 CPST (1998/99 season), however these were based on a very small sample size (four tows in total) and therefore should be treated with caution. On the other hand, TTPD decreased until a CPST of 150 was reached, but beyond this point, it increased. NTPD remained constant throughout the range of CPST.

CPD can be viewed as reflecting production, CPTT as CPUE and TTPD as effort. By doing this, it was possible to generate diagrams of the three different patterns (Figure 15) following the fishing operation theory outlined in Figure 1. In APDP and APEI, none of the indices showed a clear trend against krill availability. CPST is an index calculated for the whole of Subarea 48.1, whereas other indices plotted reflect the status within each of the BSSMUs. Therefore, there is a mismatch in the spatial scale between CPST and other indices, and this could be the reason why clear trends are not seen. Another reason may simply be low krill availability that is unable to sustain maximum production. However, if this is the case, an increase in krill availability must still be accompanied by a reduction in effort with a corresponding increase in CPUE.

In SO, production was constant when krill availability was high, and production decreased under conditions of low krill availability. Effort appeared to increase at the high end of krill availability, and at the same time this was accompanied by a decrease in CPUE. However, this trend is based on only two fishing seasons and may not be appropriate for further interpretation.

SG showed increasing production up to a certain level of krill availability, and production levelled off thereafter. CPUE showed an increasing trend up to this critical point, and thereafter the CPUE began to decrease, whereas the patterns of effort showed the reverse of this. In these cases skippers tried to achieve higher production by increasing effort under low krill availability. At a certain point maximum CPUE is attained, and skippers therefore apply minimum effort at this level of krill availability. Above this point, there is an over-supply of krill, so skippers may have to regulate the timing of landing the next haul on the deck by extending the towing time without catching excess amounts. In fact, during commercial operations, in some cases skippers regulate the timing of landing nets for these reasons (B. Yoshitomi, pers. comm.). It is recommended that a change in logbook data recording procedures be made to allow discrimination between these different behaviours.

Although CPST was expected to be sensitive to changes in abundance (Butterworth, 1988a), this index did not show any significant correlations with the results of scientific acoustic surveys. Does this simply mean that CPST cannot be used as an index of krill abundance? It is inferred here that the lack of significant correlations may be due the mismatch of spatial coverage. CPST is based on the actual fishing grounds whereas, as explained earlier, acoustic estimates were calculated for a wider area where, for most of the area, fishing is not undertaken (Figure 2). However, this limitation can only be overcome by coordinating the intensive scientific acoustic surveys with fishery vessels.

It is also worth noting the effect of the exchange of information between vessels during fishing operations. Information exchange between vessels may shorten searching time compared to operations without any information exchange. Since the early 1990s, the number of Japanese trawlers operating has decreased from five (1990/91 season) to two (2003/04 season). This obviously means information on krill distribution available through communication has decreased during this period and therefore the vessels need to spend more time searching on their own behalf than in previous years.

CPUE indices showed a significant positive correlation with krill densities derived from acoustic surveys around the South Shetland Islands when appropriate standardisation was performed. Since CPD and CPT are indices which directly or indirectly represent production, significant positive correlations observed for CPD and CPT with the acoustic density in pelagic SSMUs suggest that the fleet has generally been operating below its maximum factory capacity in AP.Pel. Therefore production in pelagic areas is heavily influenced by interannual variation in regional krill density. This also explains why the fishing grounds tend to be in areas closer to the coast where more stable daily production can be attained. It is also known that fishing grounds around the South Shetland Islands tend to be located offshore in the years of high krill regional density (Kawaguchi and Segawa, 2001). This is probably because the area where fleets can maximise their production extends further offshore in years of high, compared to years of low, regional krill density.

On the other hand, acoustic densities for the South Georgia area (Brierley et al., 1999; Wafy et al., 2003) did not show significant correlations with CPUE indices. It is difficult to explain the reason for this, but it may be attributed to a mismatch in seasons between scientific surveys and fishing operations. Scientific surveys were generally executed in summer, and fishing operations in this area took place in autumn and winter.

Conclusions

This study revealed some interesting features of krill fishing operations. To regulate fishing effort, fishing vessels generally regulate net towing time rather than changing the frequency of net tows. Results from CPST suggest that the krill fishery in the South Georgia area is operating around a critical point at which krill availability is just sufficient to maintain optimum factory performance, but in years of low krill availability vessels are shown to suffer from a reduction in production. The status of fishing operations in Subarea 48 was not clear. Production (CPD) showed correlation with CPST within the lower side of the range. Therefore, CPST may work as a krill availability index within the fishing ground to some extent when krill availability is low. However, this relies on an assumption that skippers always use the time between net tows for searching for krill aggregations. Searching for higher density cannot be separated from searching for better quality. A further difficulty with using CPST as an index of krill availability is that the time taken for simply relocating within the same subarea has been included in searching time.

Despite these limitations, CPST seems to be the best way available to express the status of fishing operations or krill availability within the fishing grounds, especially as a measure of whether the fleets are doing well or poorly in relation to their factory processing capacities. To refine this index (CPST), collection of more detailed information from the fishing vessels is necessary. Different nations may operate in different ways. In fact, Soviet krill trawlers make fewer tows per day but each tow lasts longer (Litvinov et al., 2004) compared to the targeted tows performed by Japanese trawlers. Obviously the indices derived from these different strategies may be interpreted in various ways. It is therefore also important to undertake the same or similar analyses for the fleets of other fishing nations. At the moment there is no way of validating this index. To do so requires either (i) an acoustic survey by a research vessel to be carried out at the same time and location as the fishing operation, or (ii) fishing vessels to carry out randomised research tows.

Butterworth (1988a) concluded that CPUE indices are not reliable for use as indices of krill abundance. However, the significant correlation between standardised CPUE for the pelagic SSMUs and acoustic surveys in this study demonstrates the possibility of using CPUE data as a source of information to supplement abundance indices if an appropriately defined CPUE index is chosen and is adequately standardised. This analysis was based on the Japanese haul-by-haul CPUE data. To further understand fishery characteristics, the authors believe that a wider coverage in space and time using haul-by-haul CPUE data is required.

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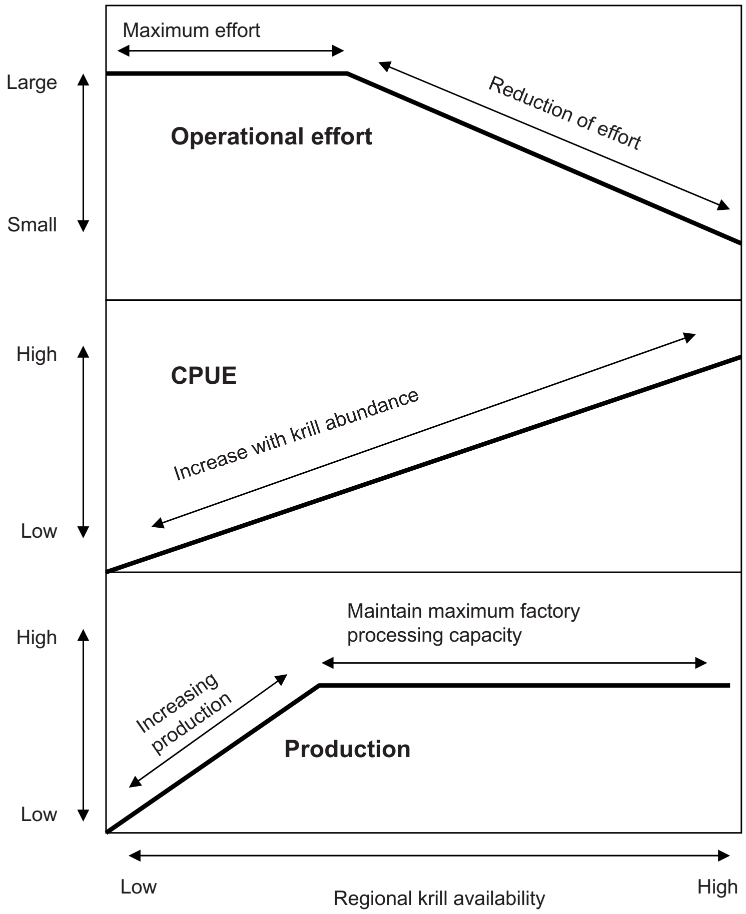
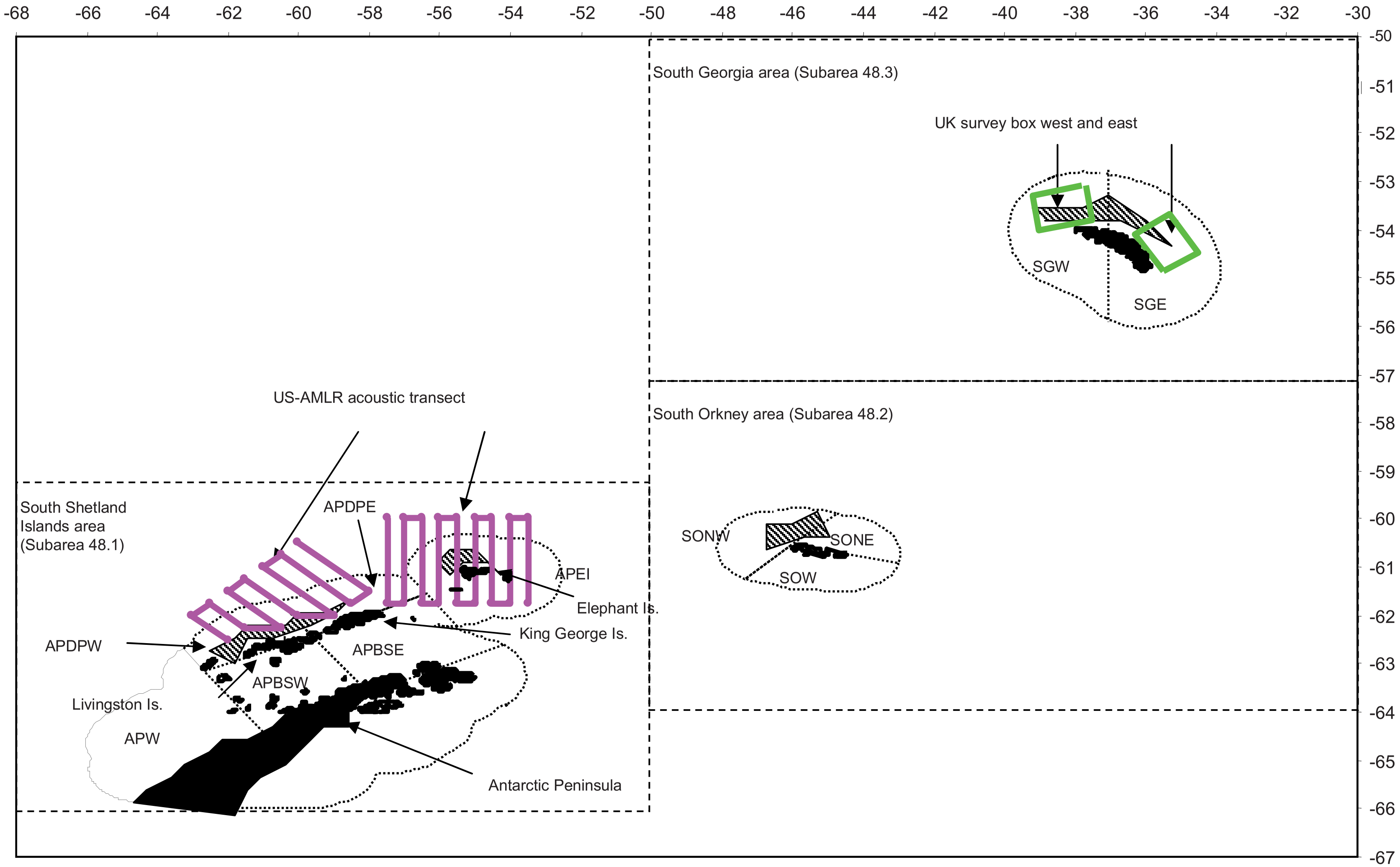


Figure 1: A conceptual illustration of how the fishery indices may respond to a range of krill availability.



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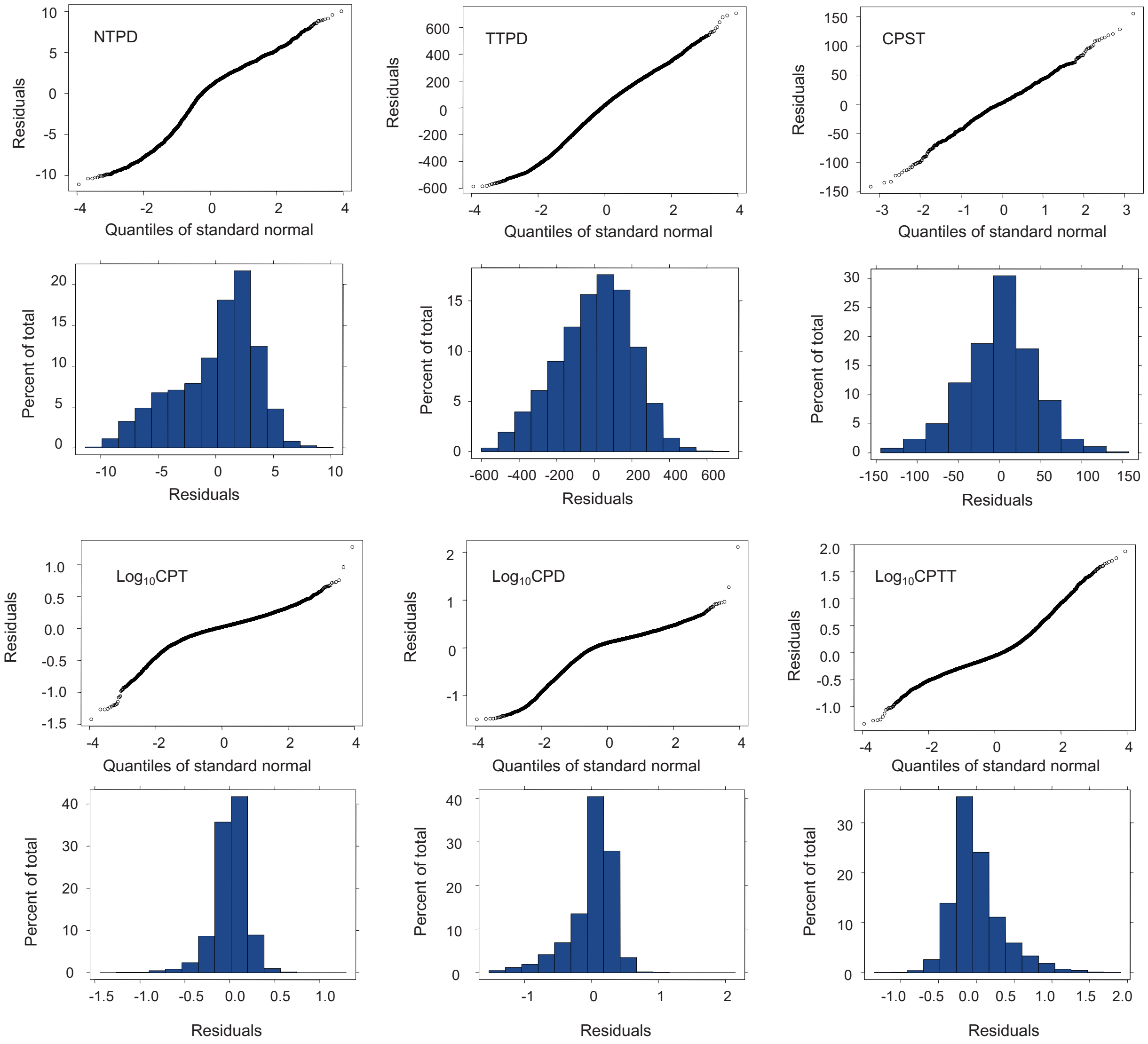

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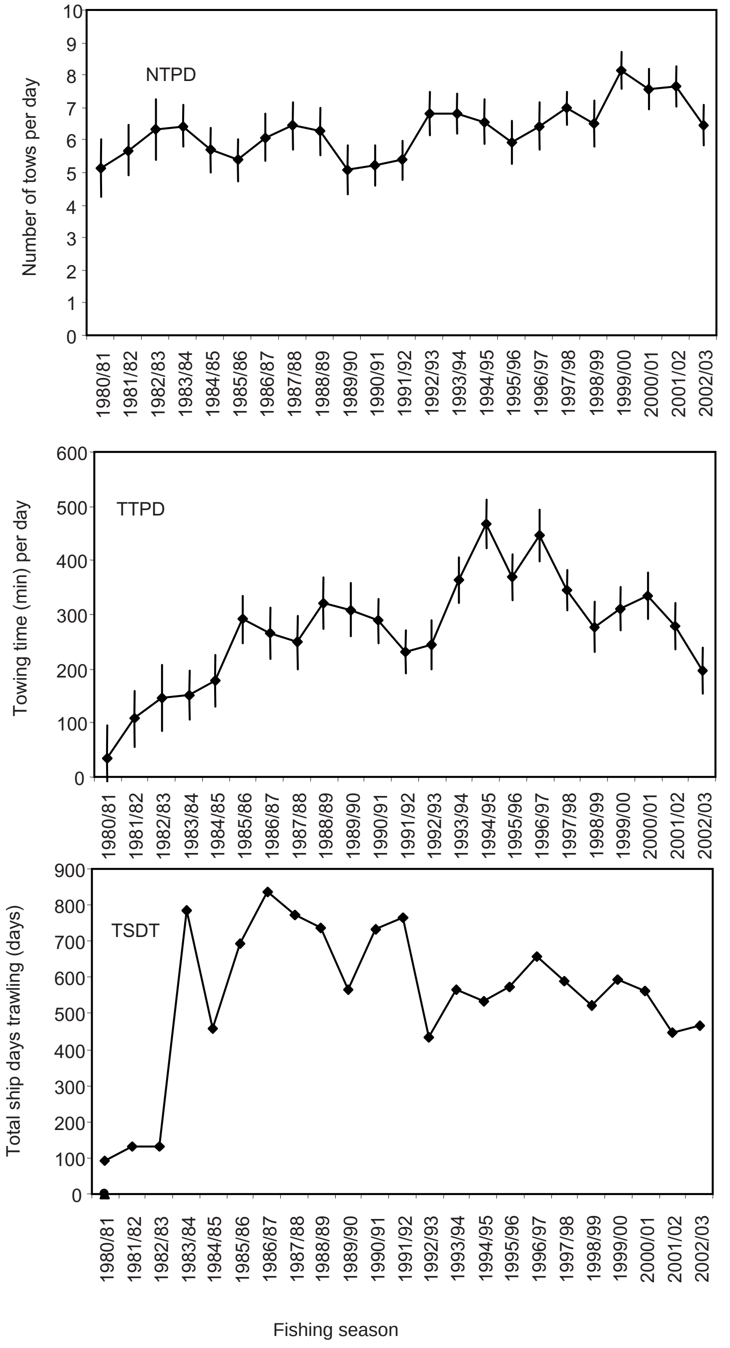

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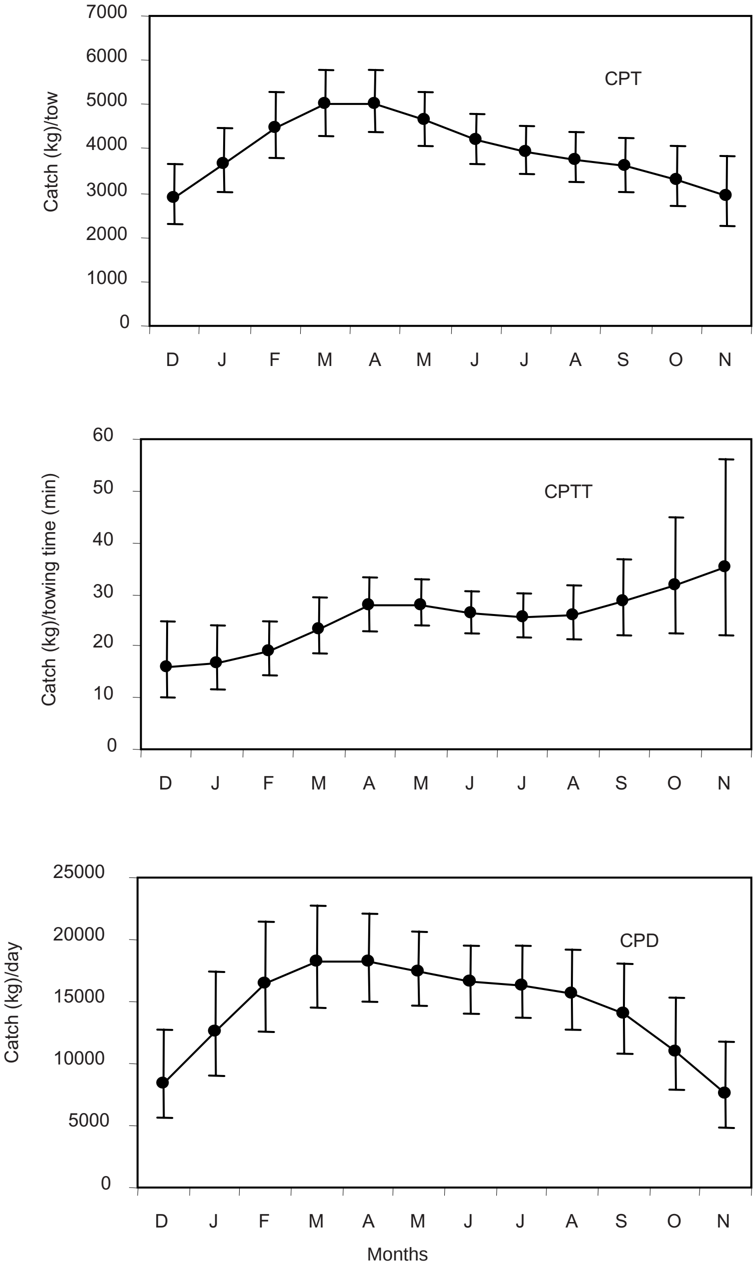

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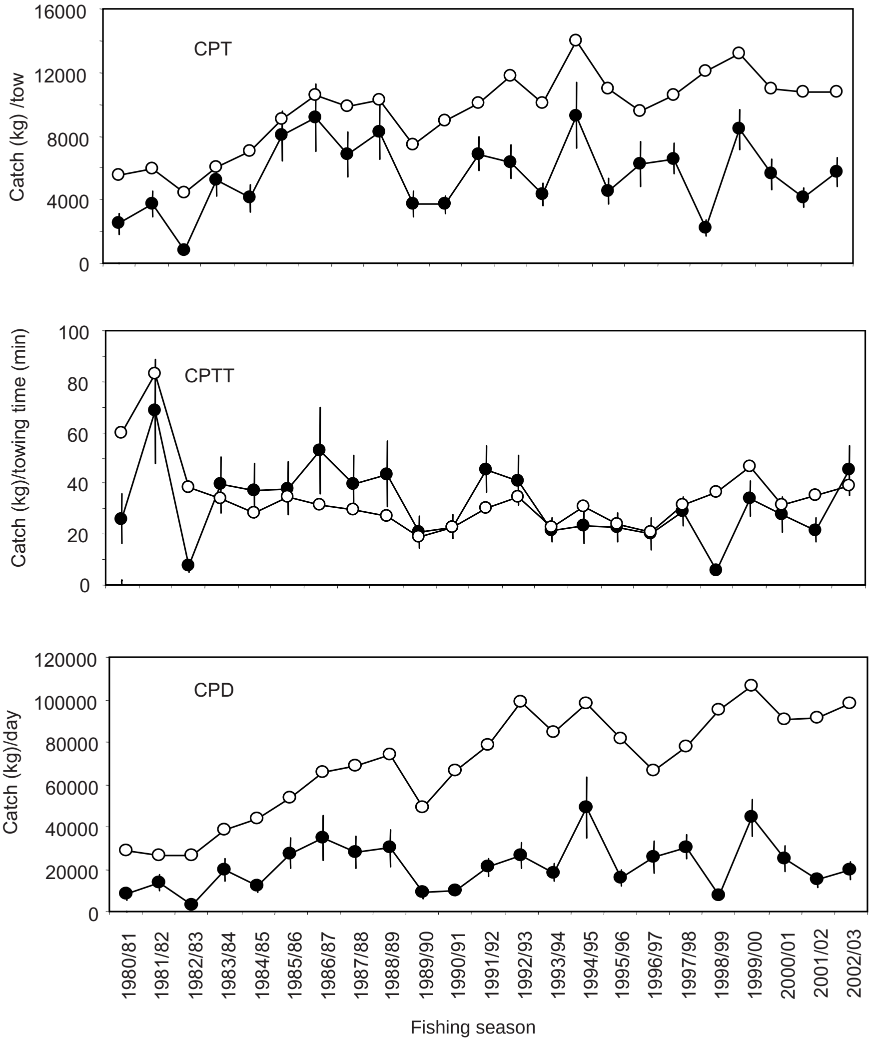

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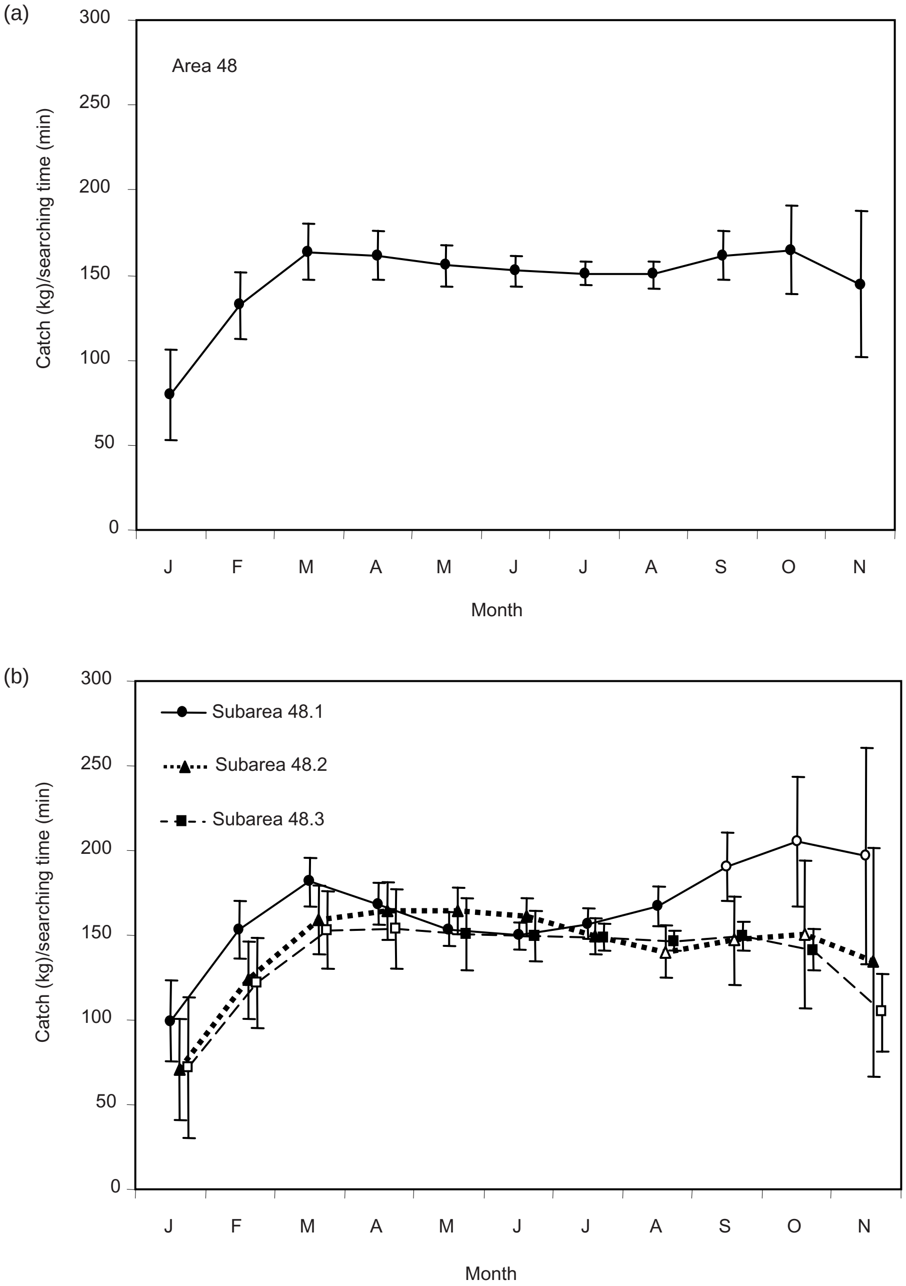

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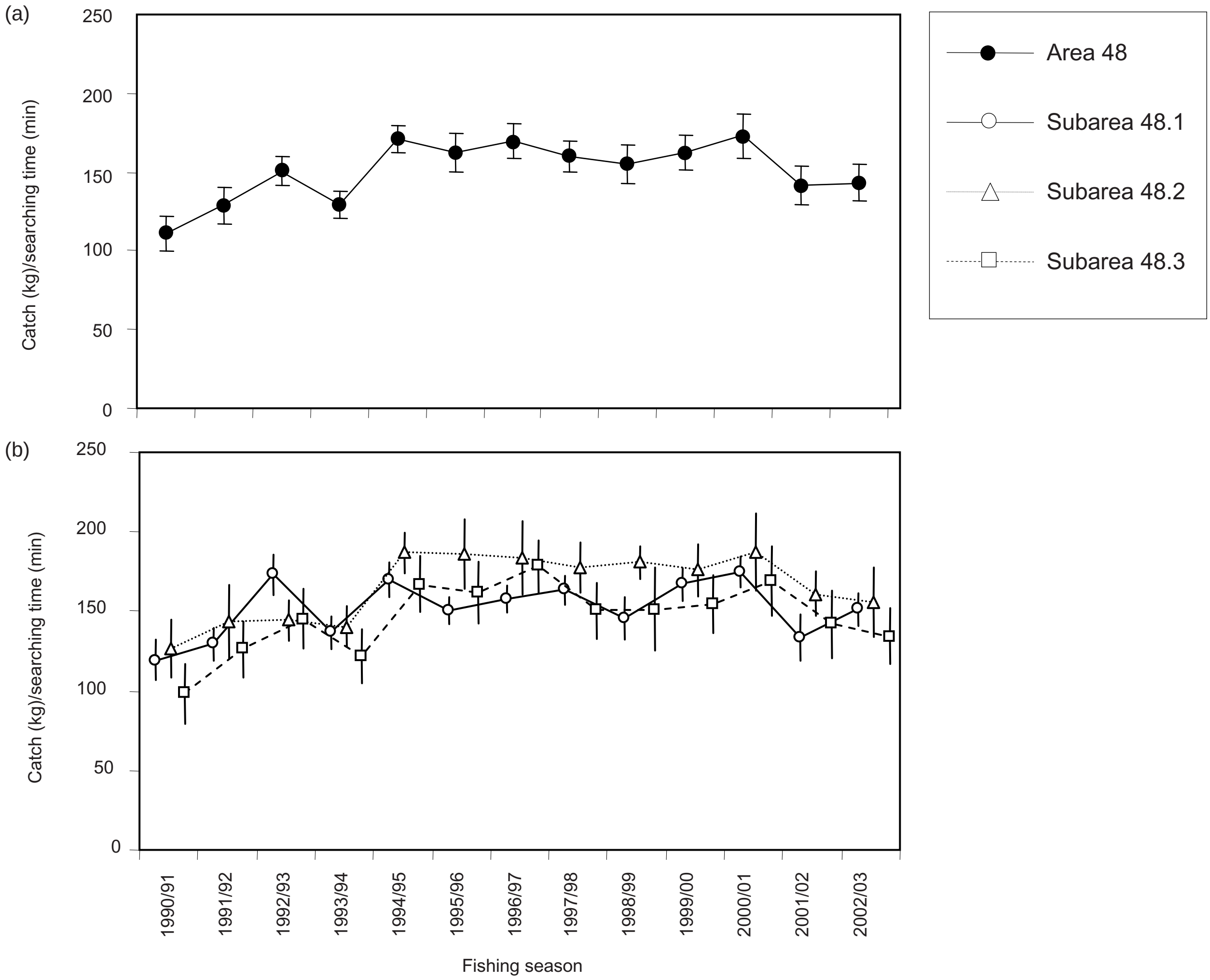
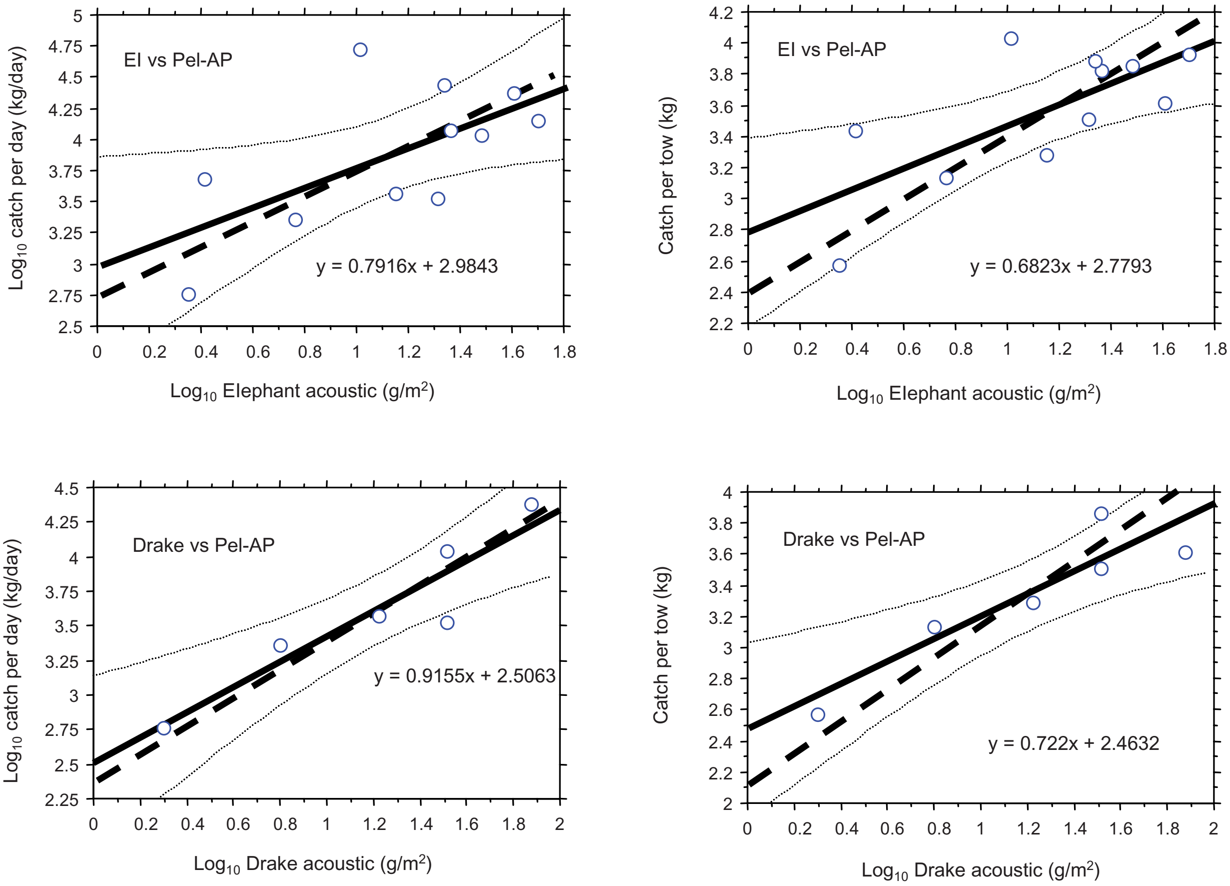


Figure 8: Predictions ± SE of CPST across fishing seasons for (a) Area 48 as a whole and (b) each of the subareas. Nominal numerical values for each fishing season have been slightly adjusted for two of the subareas to improve clarity.



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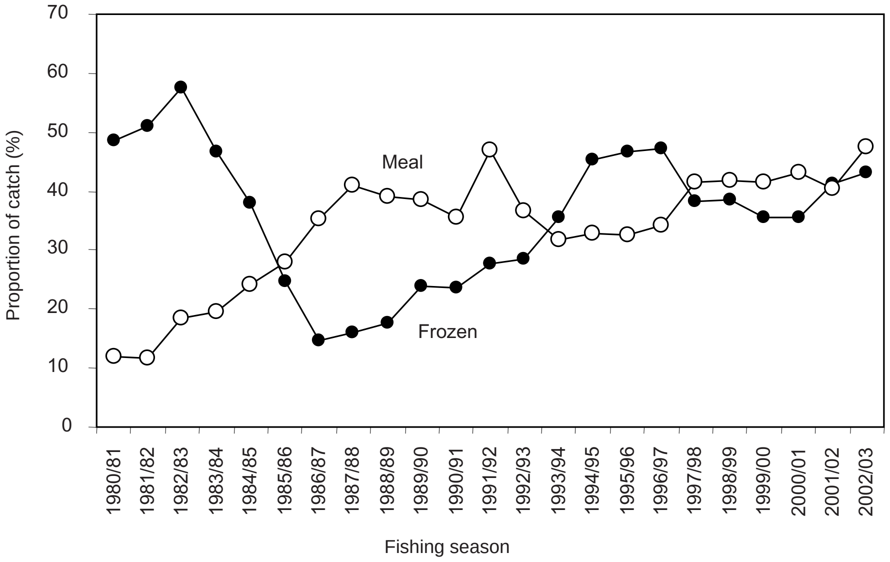

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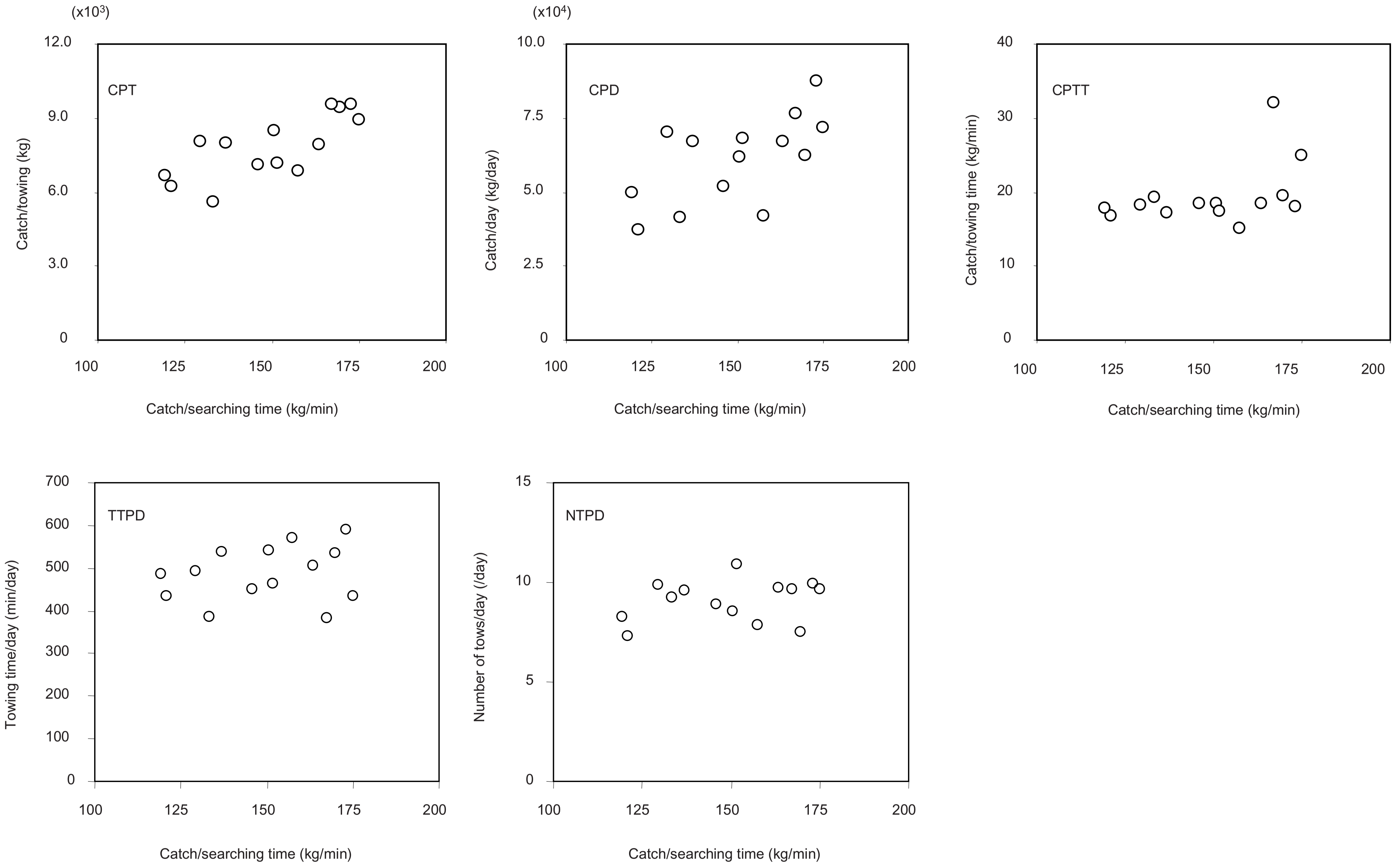

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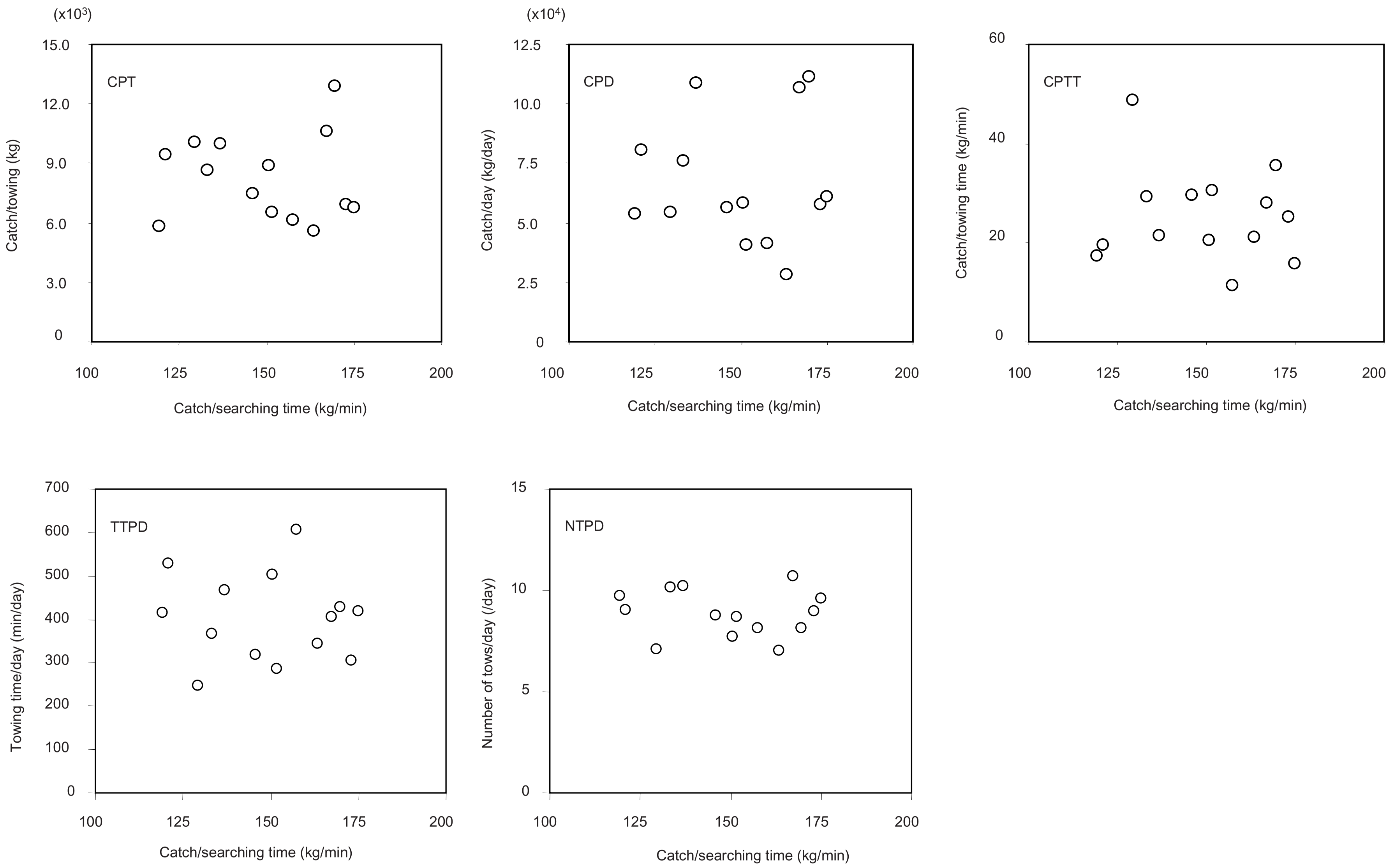

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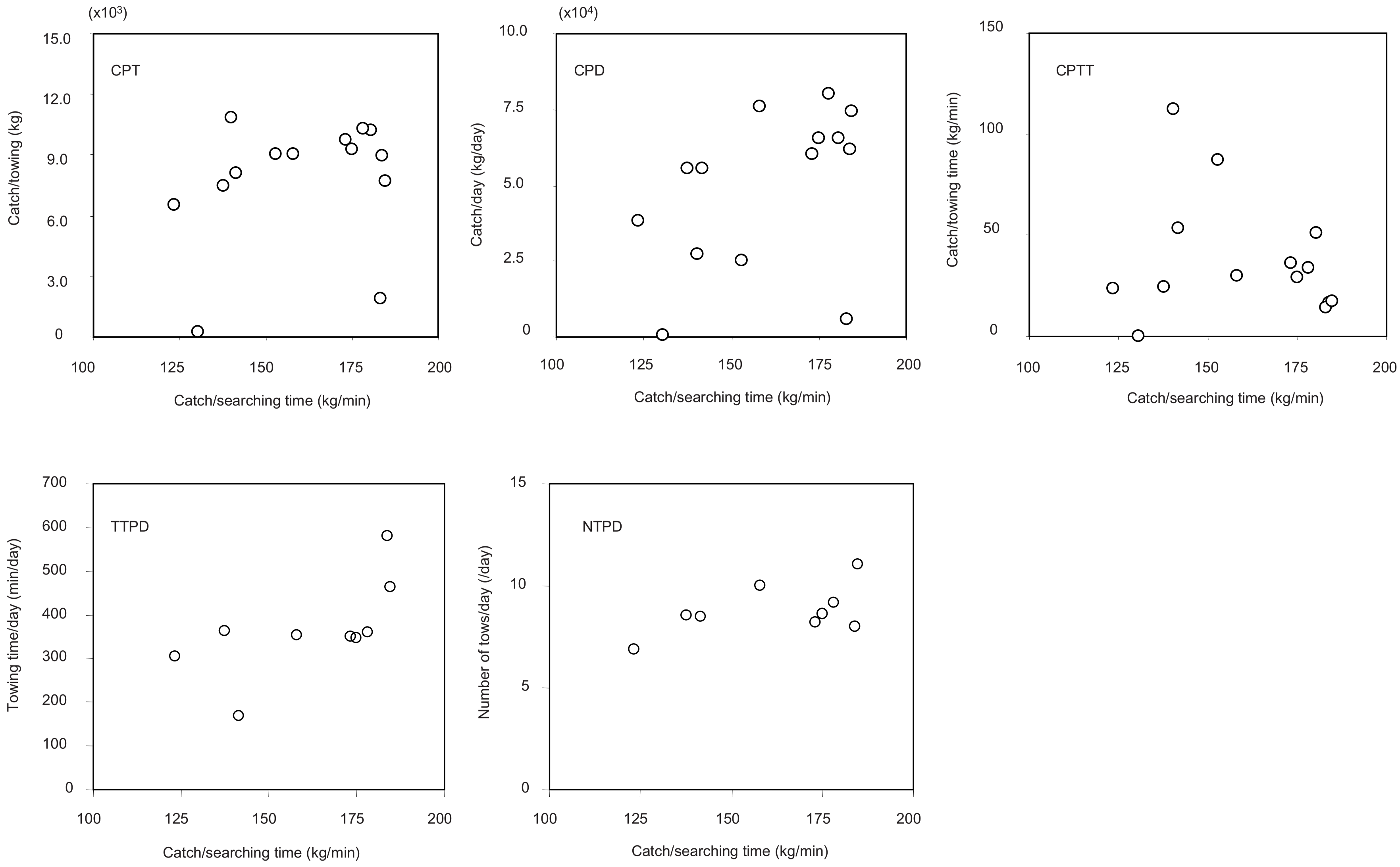

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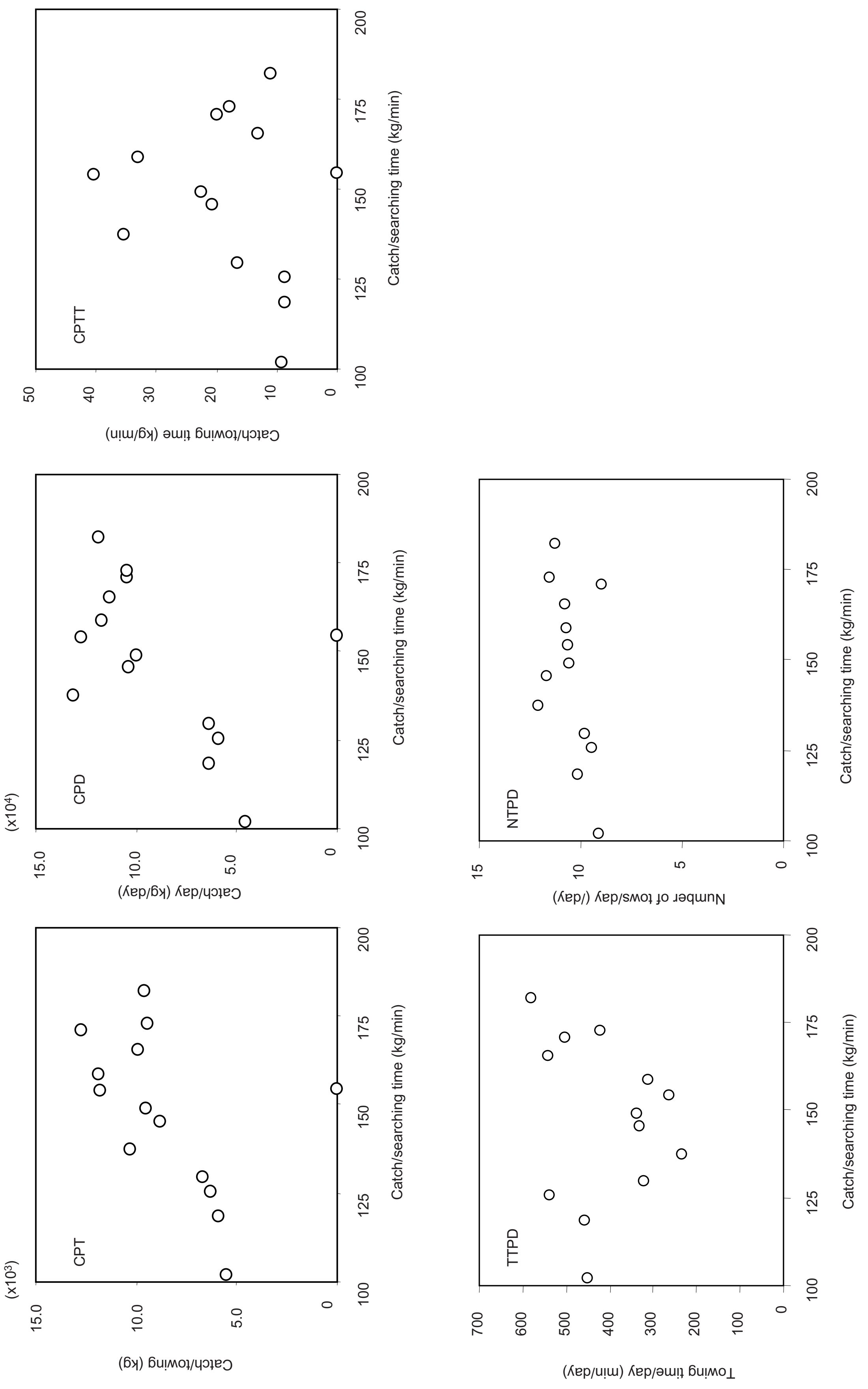

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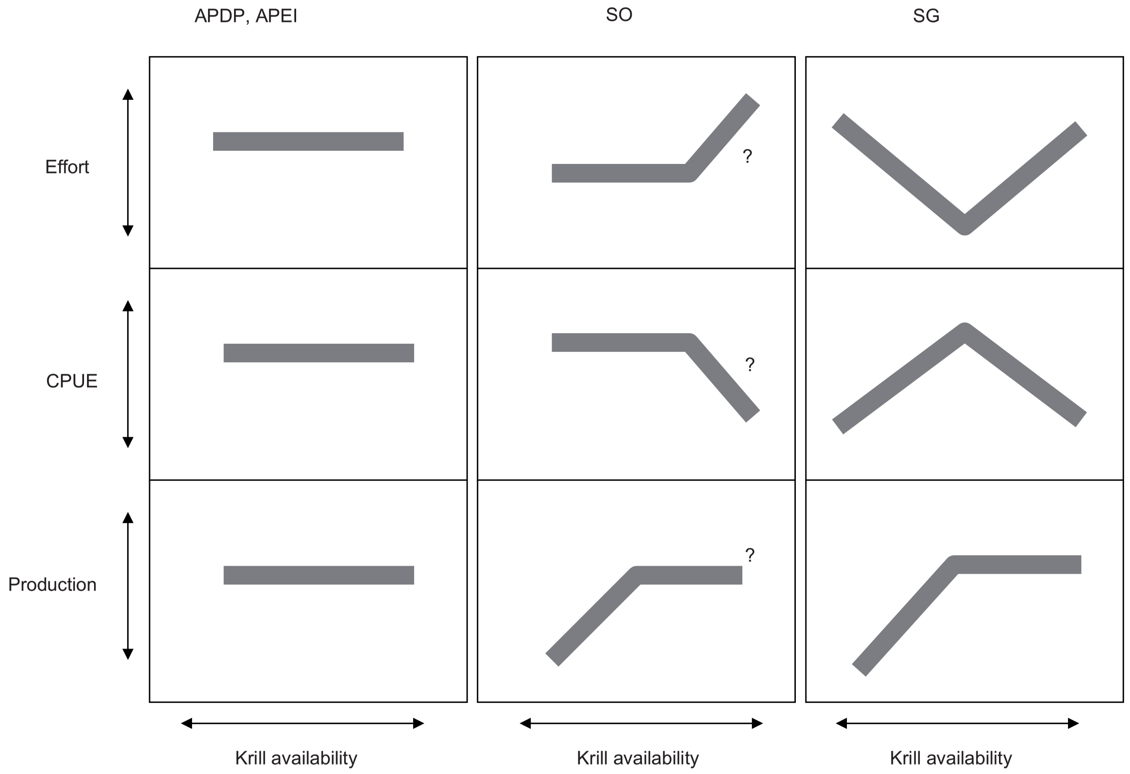

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Figura 5: Predicciones ± SE de CPT, CPTT y CPD por mes.

Figura 6: Predicciones (círculos negros) ± SE y promedios anuales (círculos blancos) de CPT, CPTT y CPD por temporada de pesca.

Figura 7: Predicciones ± SE de CPST por mes para (a) toda el Área 48 y (b) cada una de las subáreas. Los valores nominales por mes han sido corregidos levemente para dos de las subáreas a fin de mejorar la claridad. Los círculos blancos denotan las predicciones basadas en extrapolaciones.

Figura 8: Predicciones ± SE de CPST por temporada de pesca para (a) toda el Área 48 y (b) cada una de las subáreas. Los valores nominales por temporada de pesca han sido corregidos levemente para dos de las subáreas a fin de mejorar la claridad.

Figura 9: Correlación entre las densidades acústicas y las series de CPUE normalizado. Gráficos de datos (círculos abiertos) con línea de regresión (línea sólida) y su intervalo de confianza de 95% (línea fina). Las líneas entrecortada tienen una pendiente de 1.

Figura 10: Tendencias interanuales del porcentaje de kril procesado en dos productos principales, congelado (círculos negros) y harina (círculos blancos) para las temporadas de pesca de 1980/81 a 2002/03. (Fuente de datos: NRIFSF, 2005).

Figura 11: Gráficos de las predicciones de CPT, CPD, CPTT, TTPD y NTPD versus CPST por temporada de pesca en APDP (BSSMU del Estrecho Drake).

Figura 12: Gráficos de las predicciones de CPT, CPD, CPTT, TTPD y NTPD versus CPST por temporada de pesca en APEI (BSSMU de Isla Elefante).

Figura 13: Gráficos de las predicciones de CPT, CPD, CPTT, TTPD y NTPD versus CPST por temporada de pesca en SO (BSSMU de Orcadas del Sur).

Figura 14: Gráficos de las predicciones de CPT, CPD, CPTT, TTPD y NTPD versus CPST por temporada de pesca en SG (BSSMU de Georgia del Sur).

Figura 15: Ilustración conceptual de la respuesta de los índices pesqueros a una gama de abundancias de kril en las distintas BSSMU.

APPENDIX

EXAMPLE S-PLUS CODE FOR CPUE STANDARDISATION USING THE SAMM( ) FUNCTIONS

```
# Program Krill.CPUE LMM analysis using samm

detach()

attach(Krill.CPUE.perDay.database.Area48)

catch.per.tow.log <-

    log10(catch.per.tow*(catch.per.tow>0)+10*(catch.per.tow<=0))

# final model is

Krill.CPUE.sam05<-samm(fixed = catch.per.tow.log ~
    pseason+month.ns+bssmu.f+bssmu.f:month.ns,
    random = ~ spl(month.ns) + spl(month.ns):bssmu.f + month.fs:pseason +
    pseason:bssmu.f + ship.code, data =Krill.CPUE.perDay.database.Area48,
    na.method.Y = “exclude”, na.method.X = “exclude”)

anova(Krill.CPUE.sam05)

summary(Krill.CPUE.sam05))[[9]]

summary(Krill.CPUE.sam05))[[11]]

# predict trends in catch.per.tow.log for bssmu and month

temp1.pv <- predict(Krill.CPUE.sam05, classify =list(“bssmu.f:month.ns”),
    levels=list(“bssmu.f:month.ns”=list(month.ns=(1:12))))

Krill.CPUE.pv<-temp1.pv$predictions$”bssmu.f:month.ns”$pvals

Krill.CPUE.logCPUE.bm<-matrix(data=Krill.CPUE.pv[,3], nrow=9 , ncol=12, byrow=F)

Krill.CPUE.se.bm<-matrix(data=Krill.CPUE.pv[,4], nrow=9 , ncol=12, byrow=F)

# predict trends in catch.per.tow.log for just month

temp1.pv <- predict(Krill.CPUE.sam05, classify =list(“month.ns”),
    levels=list(“month.ns”=list(month.ns=(1:12))))

Krill.CPUE.pv<-temp1.pv$predictions$”month.ns”$pvals

Krill.CPUE.logCPUE.m<-Krill.CPUE.pv[,2]

Krill.CPUE.se.m<-Krill.CPUE.pv[,3]

x.ps <- c(1:12)

# plot splines over Months and Month factor estimates and their SEs

imat.bm <- tapply(X=rep(1,Nv),INDICES=list(bssmu.f,month.fs) , FUN=sum)

graphsheet()

par(mfcol=c(1,1))
```

```
max(Krill.CPUE.logCPUE.bm)
min(Krill.CPUE.logCPUE.bm)

plot(y=Krill.CPUE.logCPUE.m, x=x.ps, lty=1, col=1, ylim=c(2.5,4.5), type="l", xlab="Month" ,
     ylab="Log10(catch.per.tow)")

for (i in 1:9) {

     lines(y=Krill.CPUE.logCPUE.bm[i,], x=x.ps, lty=1, col=i+1)
     for (j in 1:12) {
     yul <- Krill.CPUE.logCPUE.bm[i,j]+Krill.CPUE.se.bm[i,j]*as.double(!is.na(imat.bm[i,j]))
     ybl <- Krill.CPUE.logCPUE.bm[i,j]-Krill.CPUE.se.bm[i,j]*as.double(!is.na(imat.bm[i,j]))
     segments(x1=x.ps[j], x2=x.ps[j], y1=yul, y2=ybl, col=i+1)
}
}

legend(x=6, y=3.3, legend=levels(bssmu.f), lty=1, col=c(2:10))

# predict and graph trends in catch.per.tow.log for bssmu and pseason

temp1.pv <- predict(Krill.CPUE.sam05, classify =list("pseason:bssmu.f"),
     levels=list("pseason:bssmu.f"=list(pseason=levels(pseason))))

Krill.CPUE.pv<-temp1.pv$predictions$"pseason:bssmu.f"$pvals

Krill.CPUE.logCPUE.pb<-matrix(data=Krill.CPUE.pv[,3], nrow=23 , ncol=9, byrow=F)

Krill.CPUE.se.pb<-matrix(data=Krill.CPUE.pv[,4], nrow=23 , ncol=9, byrow=F)

# predict and graph trends in catch.per.tow.log for just pseason

temp1.pv <- predict(Krill.CPUE.sam05, classify =list("pseason"),
     levels=list("pseason"=list(levels(pseason))))

Krill.CPUE.pv<-temp1.pv$predictions$"pseason"$pvals

Krill.CPUE.logCPUE.p<-Krill.CPUE.pv[,2]

Krill.CPUE.se.p<-Krill.CPUE.pv[,3]

graphsheet()

plot(y=Krill.CPUE.logCPUE.p, x=c(1980:2002), lty=1, col=1, ylim=c(2.5,4.5), type="l", xlab="Season" ,
     ylab="Log10(catch.per.tow)")
     for (j in 1:23) {
     yul <- Krill.CPUE.logCPUE.p[j]+2*Krill.CPUE.se.p[j]
     ybl <- Krill.CPUE.logCPUE.p[j]-2*Krill.CPUE.se.p[j]
     segments(x1=(c(1980:2002))[j], x2=(c(1980:2002))[j], y1=yul, y2=ybl, col=2)
}
```