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STATUS OF THE COASTAL STOCKS OF *DISSOSTICHUS* SPP. IN EAST ANTARCTICA (DIVISIONS 58.4.1 AND 58.4.2)

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Abstract

Exploratory fisheries for *Dissostichus* spp. have been operating off the coast of East Antarctica (30°E–150°E; FAO/CCAMLR Divisions 58.4.1 and 58.4.2) since 2003. An experiment run from 2005 to 2008 required the tagging of toothfish as a prerequisite for participation in the fishery, with only some Small-scale Research Units (SSRUs, consisting of 10° longitude divisions of the larger areas) being open to fishing. This paper reviews the results of this experiment and explores several methods for arriving at estimates of sustainable yields.

Biological data suggest that there are two stocks in the area, one in Division 58.4.1 and one in Division 58.4.2, with the division between them being at about 90°E. The western stock may be centred around Prydz Bay, and appears to be of very low productivity. Estimates of average biomass were made by comparison of standardised catch rates with the Ross Sea, where an analytical assessment has been possible for several years, and through analysis of local depletion events. Results indicated SSRU vulnerable population sizes of about 100–1 000 tonnes per SSRU in the west (Division 58.4.2) and 1 000–1 700 tonnes per SSRU in the east (Division 58.4.1). Although 3 434 tags were released over the period 2003–2007, very few tags have been recaptured (only five where time at liberty was a year or more). These recaptures were inconsistent with expectations given known landed catches. Potential yields were calculated for each SSRU assuming a similar productivity and exploitation state to the Ross Sea, where sustainable yield is 5% of virgin vulnerable biomass. The estimated yield from all assessed SSRUs (260 tonnes) is much lower than the current total allowable catch (1 380 tonnes).

Résumé

Des pêcheries exploratoires de *Dissostichus* spp. sont ouvertes au large de la côte de l’Antarctique de l’Est (30°E–150°E ; divisions OAA/CCAMLR 58.4.1 et 58.4.2) depuis 2003. Dans une expérience réalisée de 2005 à 2008, le marquage des légines était exigé en tant que condition préalable à la participation à la pêcherie et seules certaines unités de recherche à petite échelle (SSRU, consistant en des divisions de 10° de longitude de secteurs plus étendus) étaient ouvertes à la pêche. Cet article examine les résultats de cette expérience et explore plusieurs méthodes permettant d’arriver à des estimations de rendements durables.

Les données biologiques semblent indiquer la présence de deux stocks dans le secteur, dont un dans la division 58.4.1 et l’autre dans la division 58.4.2, qui seraient séparés à environ 90°E. Il est probable stock de l’ouest, dont la productivité semble très faible, est situé dans les environs de la baie Prydz. Des estimations de la biomasse moyenne ont été effectuées d'une part, en comparant des taux de capture normalisés avec ceux de la mer de Ross, pour laquelle il a été possible de réaliser une évaluation analytique sur plusieurs années et d'autre part, en analysant des événements d'épuisement locaux. Les résultats indiquent que la taille de la population vulnérable des SSRU s'élève à environ 100–1 000 tonnes par SSRU dans l'ouest (division 58.4.2) et à 1 000–1 700 tonnes par SSRU dans l'est (division 58.4.1). Bien que 3 434 marques aient été posées pendant la période 2003–2007, très peu ont été recapturées (seules cinq qui avaient été posées un an ou plus auparavant). Ces recaptures sont en contradiction avec les prévisions fondées sur les captures débarquées connues. Le rendement possible de chaque SSRU est calculé en supposant que sa productivité et son état d'exploitation soient similaires à ceux de la mer de Ross, où le rendement admissible correspond à 5% de la biomasse vierge vulnérable. Le rendement estimé de toutes les SSRU évaluées (260 tonnes) est bien plus faible que la capture totale admissible actuellement (1 380 tonnes).

Резюме

Поисковые промыслы видов *Dissostichus* действовали у побережья Восточной Антарктики (30° в. д. – 150° в. д.; участки ФАО/АНТКОМ 58.4.1 и 58.4.2) с 2003 г. Эксперимент, проводившийся с 2005 по 2008 г., в качестве предварительного условия участия в промысле требовал метить клыкача, причем для промысла были открыты только некоторые мелкомасштабные исследовательские единицы (SSRU, состоящие из участков размером 10° долготы в рамках более крупных районов). В настоящем документе рассматриваются результаты этого эксперимента и изучается ряд методов для получения оценок устойчивого вылова.

Биологические данные говорят о том, что в данном районе имеется два запаса: один – на Участке 58.4.1 и другой – на Участке 58.4.2, которые разделены примерно по 90° в. д. Западный запас, возможно, концентрируется вокруг залива Прюдз и, как представляется, имеет очень низкую продуктивность. Оценки средней биомассы были получены путем сравнения стандартизованных коэффициентов вылова с морем Росса, где имелась возможность провести аналитическую оценку за ряд лет, и путем анализа случаев локального истощения. Результаты показывают, что размеры уязвимых популяций в SSRU составляют около 100–1 000 т на каждую SSRU на западе (Участок 58.4.2) и 1 000–1 700 т на каждую SSRU на востоке (Участок 58.4.1). Хотя за период 2003–2007 гг. было выпущено 3 434 меченых особей, очень мало меток было поймано повторно (только пять, когда время нахождения на свободе составляло год или больше). Эти повторные поимки не соответствовали ожиданиям, учитывая известные выгруженные уловы. Для каждой SSRU были рассчитаны потенциальные уловы при допущении о том, что ситуация с продуктивностью и эксплуатацией была сходной с морем Росса, где устойчивый вылов составляет 5% нетронутой уязвимой биомассы. Рассчитанный вылов по всем оцененным SSRU (260 т) намного ниже, чем существующий общий допустимый улов (1 380 т).

Resumen

En 2003 comenzaron las operaciones de las pesquerías exploratorias de *Dissostichus* spp. frente a la costa oriental del continente antártico (30°E–150°E; Divisiones 58.4.1 y 58.4.2 de la CCRVMA/FAO). Un experimento realizado de 2005 a 2008 exigió el marcado de austromerluzas como requisito de participación en la pesquería, y sólo unas pocas unidades de investigación en pequeña escala (UIPE, que consisten de subdivisiones de 10° de longitud de áreas más extensas) fueron abiertas a la pesca. Se analizan los resultados de este experimento y se examinan varios métodos para calcular el rendimiento sostenible.

Los datos biológicos indican que existen dos stocks en el área, uno en la División 58.4.1 y otro en la División 58.4.2, con una división entre ellos alrededor del meridiano 90°E. El stock del occidente podría estar concentrado alrededor de la Bahía de Prydz y su productividad parece ser bastante baja. Se estimó la biomasa promedio comparando las tasas de captura estándar con las del Mar de Ross (donde hace ya varios años se ha podido efectuar una evaluación analítica), y a través de análisis de reducciones localizadas. Los resultados han mostrado poblaciones vulnerables de entre 100–1 000 toneladas por UIPE en el sector occidental (División 58.4.2) y de 1 000–1 700 toneladas por UIPE en el sector oriental (División 58.4.1). Si bien se liberaron 3 434 marcas durante el período 2003–2007, muy pocas de ellas han sido recuperadas (sólo cinco marcas de peces liberados hace un año o más). Estas recapturas no coincidieron con el nivel esperado dados los datos conocidos de las capturas subidas a bordo. Se calculó el rendimiento potencial de cada UIPE suponiendo un estado similar de productividad y explotación al del Mar de Ross, donde el rendimiento sostenible equivale a 5% de la biomasa prístina vulnerable. El rendimiento estimado para todas las UIPE examinadas (260 toneladas) es mucho menor que la captura total permitida actualmente (1 380 toneladas).

Keywords: Antarctic toothfish, sustainable yield, assessment, East Antarctica, CCAMLR

Introduction

Several mature toothfish fisheries operate around the Antarctic. In the sub-Antarctic there are fisheries for Patagonian toothfish (*Dissostichus eleginoides*) around the islands of South Georgia, Kerguelen, Crozet, Heard and McDonald and Prince Edward, all of which have been assessed to some degree (Agnew, 2004; Lord et al., 2006; SC-CAMLR, 2007). In the Ross Sea there is a productive exploratory fishery for Antarctic toothfish (*Dissostichus mawsoni*) which has also been assessed (SC-CAMLR, 2007). Information on life-history parameters is available for all these fisheries, but a detailed understanding of spawning and juvenile life history has been more difficult to achieve for some (Hanchet et al., 2008).

Exploratory fisheries have been initiated in some other areas of the southern Antarctic but, with the exception of the stocks on BANZARE Bank in the southern Indian Ocean sector (McKinlay et al., 2008), so far none have generated sufficient data to understand life-history distribution or stock status. Exploratory fisheries for *Dissostichus* spp. have been operating on the continental shelf and shelf slope off the coast of East Antarctica (30°E–150°E; FAO/CCAMLR Divisions 58.4.2 in the west and 58.4.1 in the east) since 2003. An experiment run from 2005 to 2008 required the tagging of toothfish as a prerequisite for participation in the fishery, in an attempt to reproduce the successful tagging program in the Ross Sea which is key to the successful assessment of *D. mawsoni* in that area (SC-CAMLR, 2007). For the experiment, Divisions 58.4.1 and 58.4.2 were divided into a number of Small-scale Research Units (SSRUs), consisting of 10° longitude divisions. Alternate SSRUs were open or closed to fishing. CCAMLR set the catch limits in this experimental fishery at what it considered to be an arbitrary, but precautionary, level of 260 tonnes for each SSRU in Division 58.4.2 and 200 tonnes for each SSRU in Division 58.4.1.

Fishing operations are not easy to conduct close to the Antarctic continent, the retreat of sea-ice producing only a short summer fishing season. Participation in the exploratory fishery has been sporadic, with different vessels and nations fishing in different areas in different years. Catches have been poor in the west (Division 58.4.2), as a result of poor catch rates as well as problematic fishing conditions. The fleet has never managed to take more than 48% of the catch limit in Division 58.4.2. In the east (Division 58.4.1) fishing has been more predictable, and the catch limit has been reached in most years.

This paper reviews the results of the experiment conducted in East Antarctica. It examines the biological data for evidence of stock definition and distribution and explores several methods for arriving at estimates of sustainable yields. An initial analysis of the data (Agnew et al., 2008) suggested that tagging had been quite uneven, and that although a large number of tags had been released, very few had been recovered. Two alternative methods were employed to assess the size of the stock; an analysis of the comparative catch rates between assessed and unassessed areas, and local depletion analyses.

Catch-per-unit-effort (CPUE) is regularly used in fisheries stock assessment as an index of biomass density, usually in relation to changes over time. In constructing a time series of abundance it is critical that spatial variations in catch rate are accommodated. This is generally dealt with by spatially stratifying the data so that each area can be considered of constant biomass density. An overall abundance index is then estimated from a weighted average of catch rates from each area, the weights corresponding to their relative sizes (Gulland, 1955). This approach involves an implicit estimate of biomass for each stratification as density multiplied by area size. In the analysis presented here, a similar assumption is made of constant density within each area stratification to estimate the area-specific relative biomass from catch rate data (e.g. Jung and Houde, 2003).

Depletion estimators are widely used in fish and wildlife studies to estimate population abundance (Seber, 2002; Hilborn and Walters, 1992), assuming a simple relationship between CPUE and cumulative effort (DeLury, 1947) or cumulative catch (Leslie and Davis, 1939). The latter approach is implemented as an alternative method of biomass estimation in situations where data are limited, as is the case for this investigation.

Methods

Catch, effort and scientific observer data were acquired and tag-recapture data manually aligned with release records. Data from the Ross Sea (Subarea 88.1 and SSRUs 882A–B) were also acquired in order to undertake a relative comparison with catch rates in Divisions 58.4.1 and 58.4.2. The Ross Sea data had been pre-processed by New Zealand scientists to eliminate errors in the dataset.

Although only alternate SSRUs have been open for fishing over the last three years, some early data (pre 2005) do exist for SSRUs that are currently closed. Furthermore, limited research fishing (with a 10 tonne catch limit) was allowed in the closed SSRUs. These data have been included in the analysis. Data were analysed by SSRU, except for SSRU 5841C which was split into east and west (Ce and Cw).

Biological data collected by observers were analysed for trends in length and maturity that might provide information on stock identity and biology. The maturity scale used by CCAMLR runs from 1 (immature) through 2–3 (gonads developing) to 4 (ripe) and 5 (spent). Catch and effort data were used to estimate toothfish biomass in each SSRU for the time period of the experiment (i.e. at the approximate centre of the time period of the experiment, 2006). Two different assessment methods were examined – comparative CPUE and local depletions – which are described below. The estimate of biomass was assumed to be effectively an estimate of unexploited biomass, since very little exploitation had taken place by the time of the mid-point of the experiment. Estimates of sustainable yield were made by comparison with fully assessed toothfish fisheries.

Comparative CPUE analysis

Because the toothfish biomass in the Ross Sea is known from a previous stock assessment (Dunn and Hanchet, 2007; SC-CAMLR, 2007), it should be possible to estimate the biomass in fished areas of Divisions 58.4.1 and 58.4.2 using a comparison of the catch rates of vessels fishing both there and in the Ross Sea. This method assumes that catchability (dependent on both gear selectivity and availability) of *D. mawsoni* is similar in the Ross Sea and in Divisions 58.4.1 and 58.4.2.

A linear regression was generated (Appendix 1) from which estimates of standardised CPUE index and standard error could be obtained. Assuming that CPUE is proportional to toothfish density, the biomass B of the vulnerable population is given by:

$$B = \frac{\tilde{I}A}{q} \tag{1}$$

where $\tilde{I}$ is the standardised CPUE index, A is the assumed habitat area of the vulnerable population and q is an unknown constant (the catchability). To support the assumption of a constant q, only vessels that had fished both in Divisions 58.4.1/58.4.2 and in the Ross Sea were included in the CPUE standardisation. This amounted to 21% of the total fishing effort in both areas. The biomass in each experimental area was estimated as follows:

$$\hat{B}_x = \frac{\tilde{I}_x A_x B_R}{\tilde{I}_R A_R} \tag{2}$$

where subscript R denotes values from the Ross Sea and subscript x denotes values from the SSRU area under investigation.

95% confidence limits for $\hat{B}_x$ were estimated by bootstrapping equation (2), each time sampling I_x from a normal distribution with median and standard error resulting from the regression, and B_R from a lognormal distribution with median and standard error taken from the assessment conducted by CCAMLR (SC-CAMLR, 2007). CCAMLR (SC-CAMLR, 2007) and Dunn and Hanchet (2007) reported median Ross Sea biomass as 58 320 tonnes with 95% confidence intervals of 46 700–75 010 tonnes. In the comparative CPUE analysis, I_R was a point estimate only, and had no uncertainty associated with it.

Local depletions

Local depletion analysis makes use of the fact that toothfish are not highly mobile animals, normally moving only a few km each year (Agnew, 2004). During a fishing season this behaviour often leads to local depletion of toothfish in an area, with animals only being replaced by immigration over the scale of a year rather than the months during a fishing season (Agnew and Pearce, 2004). A linear regression of CPUE against cumulative catch during the fishing season can then predict the total catch that equates to local extinction, thus providing an estimate of the total biomass at the beginning of the season (e.g. Agnew and Pearce, 2004; McKinlay et al., 2008).

The regression takes the form:

$$I = c + mC \tag{3}$$

where I is the unstandardised CPUE in kg/hook, c is the intercept, m is the slope and C the cumulative catch in tonnes. If $m < 0$, then the biomass for the local area being fished (B_{LOC}) is given by:

$$\hat{B}_{LOC} = \frac{-c}{m} \tag{4}$$

Using an estimate of the local area fished during that season (A_{LOC} – representing the spatial extent of the depleted biomass) and the assumed area occupied by the vulnerable population within SSRU x (A_x), it is possible to estimate the biomass for the experimental area under investigation:

$$\hat{B}_x = \hat{B}_{LOC} \frac{A_x}{A_{LOC}}. \tag{5}$$

Local depletion analyses were undertaken for each year and for each SSRU. Detailed investigation was usually necessary to identify candidate areas in which fishing was concentrated and in which, therefore, depletions might have occurred. This search was undertaken by visually inspecting temporal and spatial trends in the data to identify concentrations of fishing effort. Very often it was apparent that a vessel, or vessels, had fished continuously in one area, potentially causing a depletion, and then moved to another area. The area in which the fishing was concentrated would then be isolated spatially and temporally for the depletion analysis. Significant depletions were identified through simple regression analysis.

To obtain an estimate of uncertainty, 2 000 bootstrap samples were taken from the data for each depletion, allowing confidence intervals to be derived from the resultant distribution of coefficients.

Estimation of area sizes

For both the analyses described above, a key component is the estimation of area in which toothfish are distributed within an SSRU (A_x). This problem was approached using the data on spatial and depth distribution of CPUE from exploratory fishing. It was assumed that all the depths in which toothfish were found at non-negligible density (CPUE) within an SSRU could contain suitable toothfish habitat, even for areas of an SSRU that had not been fished. There are errors inherent in this assumption; toothfish may not be present in similar densities across an SSRU, between areas that were fished and those that were not fished. If toothfish are present in lower densities in unfished areas, and particularly if this was a reason for vessels not fishing there, the resultant estimates of potential biomass will be upwardly biased. On the other hand, areas may have been left unfished due to operational issues, such as the presence of sea-ice which may have precluded vessels from fishing in one part of an SSRU.

Determination of fished depth boundaries was undertaken through examination of fishery catch data. Area size estimates were obtained using GEBCO data (available from http://topex.ucsd.edu/cgi-bin/get_data.cgi) and the area.map() function from the maps library in R (www.R-project.org), which was used to estimate the surface area bounded by the determined depth intervals. A cross-validation exercise comparing the area size estimates from the Ross Sea reported here with those reported in Dunn et al. (2005) showed the two methods produced area size estimates that differ by approximately 20% overall (with estimates from R being higher). However, there was a clear correlation between the two results. Since only the ratio of area sizes is used in equation (2), a difference in absolute values between the area size estimates reported here and those reported by other methods will not affect the results, provided relative area sizes are consistent.

For the depletion analyses, an estimate of the local area being fished is required. In each depletion area, this was represented by the spatial coverage of CPUE datapoints (see Appendix 2).

Mark–recapture data

There were so few tag-returns from the area that a reliable stock assessment of the resource was not possible. Instead, the expected number of tag-returns from a given biomass estimate was calculated by modifying the Lincoln-Petersen tagging estimator (Seber, 2002):

$$\hat{R} = \frac{0.9 n_t . e^{-0.13 l} s_r}{B} \tag{6}$$

where R is the number of tag returns from fish tagged in year y_1 and recaptured in year y_2, n_t is the number of tags released in year y_1, l is the time at liberty (in year integers, i.e. $y_2 - y_1$), s_r is the tonnage of fish scanned (i.e. the catch) in year y_2 and B

Table 1: Summary of fishing effort in Divisions 58.4.1 and 58.4.2. Fishing years extend from 1 December of the previous year to 30 November of the named year.

Division		2003	2004	2005	2006	2007	2008
58.4.1	Number of vessels:	0	0	7	6	4	6
	Hooks set (thousands):	0	0	3024	2109	4025	3035
58.4.2	Number of vessels:	1	1	4	3	3	3
	Hooks set (thousands):	606	216	1373	796	885	986

is the estimate of biomass. This equation assumes a tag-induced mortality of 0.10 and natural mortality of 0.13 (Hillary et al., 2006; SC-CAMLR, 2007).

Results

Distribution of fishing effort and CPUE in Divisions 58.4.1 and 58.4.2

Prior to the start of the experiment in 2006 there had been some fishing in East Antarctica, although only in Division 58.4.2. A total of 17 separate vessels registered to seven CCAMLR Members (Australia, Chile, Republic of Korea, Namibia, New Zealand, Spain and Uruguay) fished during the experiment (Table 1). These vessels did not all fish at the same time or place, nor did individual vessels necessarily fish over a number of years.

A map of the area showing the SSRUs and a summary of catch and CPUE is shown in Figure 1. In the west, in SSRU 5842A, catches and catch rates were relatively low, gradually rising in SSRUs 5842C and D to be highest off the mouth of Prydz Bay (SSRU 5842E). Although there has been no fishing in SSRU 5841B, the area immediately adjacent to it, SSRU 5841Cw, has provided some of the highest catch rates but low catch quantities. There is a clear distinction between the eastern and western parts of SSRU 5841C, with the area of highest catch and most persistence in the fishery being SSRU 5841Ce. This fishing area appears to extend over the wide extension of the 2 000 m contour at 100°E, into SSRU 5841D which has been closed for the last three years.

Dissostichus eleginoides have only been recorded from this eastern side of SSRU 5841C, the northern part of SSRU 5841E and the western part of SSRU 5841G. No *D. eleginoides* have been reported from Division 58.4.2. These fish could be a southern extension of the BANZARE Bank population, but are so few, they will not be discussed further in this paper.

Biological characteristics of *D. mawsoni* in Divisions 58.4.1 and 58.4.2

Biological data collected by observers from 27 110 fish caught between 2003 and 2007 from sets between 500 and 2 500 m depth (13 061 fish from Division 58.4.2 and 14 049 from Division 58.4.1) were analysed to explore distributional patterns in size and maturity structure across the shelf.

Areas west of SSRU 5841C (except SSRU 5842A) illustrated bimodality in length frequency even in the deeper depth bands (Figure 2), whilst in SSRU 5841C and areas east of this, bimodality was rarely observed and then only in the shallower depths. There is a hint in the data from SSRU 5841C that bimodality in the length frequencies persists at least into the west of that area, but it is clear that very few young animals are present at any of the depths sampled in Division 58.4.1.

A very similar pattern is apparent in the analysis of maturity stages of animals (Figure 3). At all depths juvenile stage I animals are more abundant in the west than the east, with a higher proportion of later maturity stage animals (particularly stages II and III) in the east. It is somewhat surprising that there are any animals in stage V in this fishery (December to March), since it would be expected that, like other toothfish populations, spawning would be in late winter. Nevertheless, the proportion of immature animals at all depths is clearly at a maximum in SSRUs 5842C and D, dropping to a slightly lower level off Prydz Bay (SSRU 5842E) and reaching a minimum in SSRU 5841Ce before gradually rising again as the Ross Sea is approached.

This pattern could, of course, be a result of an increasingly shallow distribution of juvenile animals in the east of the two areas, such that they are simply not sampled at depths below the legal limit (500 m) in Division 58.4.1. The most plausible explanation, however, is that there is a population of juveniles in the west that is not present in the east, and that once again there appears to be a significant shift in population structure around SSRU 5841C.

There are also changes around SSRU 5841C in the by-catch composition and rate (Figure 4). While not of immediate importance from an assessment point of view, this does confirm changes in community structure and productivity.

Estimation of area-specific population biomass

Area size estimates

The comparative CPUE method assumes a constant q between the Ross Sea and the study area, as well as comparable availability, i.e. a comparable behaviour and distribution of *D. mawsoni* in the two areas. This assumption is supported by the similarity of distributions of raw CPUE data for Divisions 58.4.1 and 58.4.2 for all years and vessels (Figure 5) and the similarity of the length-frequency distributions from the three fisheries, which have medians at about 140 cm (SC-CAMLR, 2008). The distributions of CPUE values for each SSRU within Divisions 58.4.1 and 58.4.2 are shown in Figure 6. These were used to delimit the fished areas, which are presented in Table 2.

Catch rate comparison

The linear regression standardisation was only applied to data from within the depth bounds illustrated in Figure 6. Results are illustrated in Figure 7, with the standardised CPUE values given in Table 3. A full list of coefficients and their standard errors is given in Appendix 1. Biomass estimates for each SSRU are given in Table 3.

Local depletions

Local area depletions were only occasionally observed across SSRUs. Out of a total of 52 potential combinations of SSRU[1] and fishing season, 11 significant depletions were observed in four SSRUs. Detailed results of the complete regressions, alongside figures, are given in Appendix 2. Table 4 presents the results, including the bootstrap analysis estimates of lower and upper 95% confidence intervals.

Mark–recapture data

Tagging positions have not been consistent in all areas between years, because of the nature of the exploratory fishery, but significant numbers of animals have been tagged in a few areas for there to be an expectation that the tagging rates may be useful in assessments (Table 5). Although a large number of tags have been released by other nations in the area (2 113 *D. mawsoni* tags released), the majority of releases have been reported by Spain (1 330 *D. mawsoni* tags released). Very few recoveries have been reported, and most of these have been within-season recoveries.

Three tags have been recaptured by Spanish vessels in the season following that in which they were tagged. One fish tagged in the west of SSRU 5841C in 2006 was recaptured 3 km distant after 391 days at liberty. One tagged in the east of SSRU 5841C in 2007 was recaptured 147 km east in SSRU 5841D after 419 days at liberty and another tagged in the east of SSRU 5841C in 2007 was recaptured 1 691 km east in SSRU 5841G after 391 days at liberty; it is interesting that both of these fish had moved east after being released in SSRU 5841Ce.

Comparison of results

The results from all analyses are summarised in Table 5. Although there is evidence in some SSRUs, particularly SSRU 5841E, of depletion over the period of the experiment, for the purposes of a single estimate from the depletion calculations all the depletion estimates in Table 4 were averaged so as to be as equivalent to the comparative CPUE analysis as possible. For SSRU 5841G, the depletion results were not included when estimating the expected tag returns, sustainable yield and tag rate, as this biomass estimate was unusually high (relative to the CPUE comparison result and estimates from other areas).

In addition, a catch limit assuming a long-term sustainable exploitation rate of 5% of vulnerable biomass is estimated. This figure is based on experience with the Ross Sea fishery, for which CCAMLR (SC-CAMLR, 2007) calculated a long-term yield (2 700 tonnes) which was 5% of initial vulnerable biomass and 3.8% of initial spawning biomass. This is appropriate to a toothfish fishery in the early stages of exploitation, such as in Divisions 58.4.1 and 58.4.2 (B_{2007}/B_0 for the Ross Sea is estimated to be 82%). For a fishery close to its target level this ratio would be lower. For instance, in the *D. eleginoides* fishery at South Georgia, where B_{2007}/B_0 is 60%, sustainable yield under the CCAMLR decision rules is now 4.5% of initial vulnerable biomass and 3.5% of initial spawning biomass (Hillary et al., 2006; SC-CAMLR, 2007).

[1] SSRUs 5841C, E, G and 5842E were split into two for this analysis.

Table 2: Estimates of fished area for each SSRU in CCAMLR Divisions 58.4.2 and 58.4.1. Maximum and minimum depths are illustrated in Figure 6. Depths are given in m and areas sizes in km^2.

Area	Min. depth	Max. depth	Fished area size
5842A	950	1 850	24 149
5842C	950	1 750	5 999
5842D	650	1 650	8 909
5842E	850	1 850	12 680
5841C	650	1 950	29 731
5841D	1 150	1 450	9 509
5841E	1 050	1 950	18 776
5841F	1 350	1 450	935
5841G	550	2 150	30 945
5841H*	950/1 550	1 050/1 650	2 093
Ross Sea	500	2 000	592 984

* Discontinuous distribution (see Figure 6)

Table 3: Standardised CPUE values and biomass estimates from each SSRU, using data from vessels that had fished in both Divisions 58.4.1 and 58.4.2 and the Ross Sea. CPUE values are given in kg/hook and biomass values in tonnes. Confidence intervals were calculated using the standard error of the Ross Sea biomass (SC-CAMLR, 2007) and the standard error of the SSRU standardised CPUE (see 'Methods').

Area	Nominal CPUE	Standardised CPUE	Standard error	Median biomass	Lower 95% CI	Upper 95% CI
5842A	0.0770	0.0529	0.0058	477	340	651
5842C	0.0651	0.0776	0.0116	174	114	247
5842E	0.1846	0.1561	0.0128	739	553	974
5841C	0.0920	0.1761	0.0178	1 955	1 419	2 636
5841E	0.0880	0.1233	0.0223	865	527	1 275
5841G	0.1063	0.0883	0.0103	1 020	719	1 392
Ross Sea	0.3436	0.2634	-	58 320	46 700	75 010

Table 4: Biomass estimates (in tonnes) for each SSRU in which a seasonal depletion was observed. The *maximum biomass* refers to estimates made using the total area size.

SSRU	Depletion area	CCAMLR season	Estimated biomass		
			Median	Lower 95%	Upper 95%
5842A	5842A	2006/07	208	170	297
5842A	5842A	2007/08	1 391	1 216	1 713
5842C	5842C	2002/03	40	30	82
5842E	5842E	2002/03	2 122	1 798	3 281
5842E	5842E	2006/07	1 263	788	5 369
5842E	5842E	2007/08	838	679	1 319
5841C	5841Ce	2004/05	1 837	1 668	2 107
5841C	5841Ce	2005/06	1 900	1 691	2 257
5841C	5841Ce	2006/07	683	533	1 154
5841E	5841E	2004/05	1 382	975	3 021
5841G	5841G	2006/07	15 334	10 619	38 654

Table 5: Summary of estimates of biomass and catch limits, together with the discrepancy between expected and observed tag returns. Note that although two tags are assumed to have been recovered from SSRU 5841Ce, in reality one was recovered to the very western side of SSRU 5841D by the Spanish research fishery. For estimated confidence intervals of biomass estimates, please see previous tables. TOA – *Dissostichus mawsoni*.

SSRU	58.4.2			58.4.1		
	A	C	E	C	E	G
Catch limit (tonnes)	260	260	260	200	200	200
TOA catches (tonnes)						
2005	62	15	48	182	154	143
2006	4	4		250	22	152
2007	58		65	170	193	188
2008	54		125	177	15	197
TOA released (numbers)						
2005	227	42	59	132	100	208
2006	6	4	125	277	79	111
2007	162		86	217	609	436
Tags recovered (numbers)						
Tag 2006, recover 2007	0	0	0	1	0	0
Tag 2006, recover 2008	0	0	0	1	0	0
Tag 2007, recover 2008	0	0	0	2	0	1
Median biomass from CPUE comparison (tonnes)	477	174	739	1 955	865	1 020
Median biomass from local depletion (average of all estimates in Table 4) (tonnes)	800	40	1 408	1 473	1 382	15 334
Estimated biomass (average of two methods) (tonnes)	639	107	1 074	1 714	1 124	1 020*
Expected returns 2007 (numbers)	0	0	6	22	11	16
Expected returns 2008 (numbers)	11	0	8	18	6	67
Median annual sustainable yield derived from CPUE comparison (tonnes)	24	9	37	98	43	51
Median annual sustainable yield derived from local depletion (tonnes)	40	2	70	74	69	767

* For SSRU 5841G only the median biomass from CPUE comparison was used.

Discussion

The analyses appear to confirm that Divisions 58.4.1 and 58.4.2 contain different types of toothfish distribution and density. In the west there is a high proportion of juveniles in the catch, but densities are very low. Densities increase to the east of Division 58.4.2, particularly in SSRU 5842E off Prydz Bay. There is a sharp discontinuity in SSRU 5841C, with biological data suggesting that its western half is more similar to SSRU 5842E, whilst a sharp drop in CPUE in the east of SSRU 5841C suggests that this population is more similar to others further east in Division 58.4.1. As one continues east in Division 58.4.1, CPUE again rises as the Ross Sea is approached.

The discontinuity at about 100°E is consistent with other indicators of the biogeography of the region (S. Nicol, pers. comm.). It is associated with an oceanographic gyre set up by the rapid northwards movement of the Antarctic Circumpolar Current (ACC) at this point, away from its close continental position to the north of Prydz Bay and from the east-flowing slope current (Bindoff et al., 2000). Clearly, also, this area is associated with an extension of the slope northwards to create a relatively wide platform (Bruce Rise), across SSRU 5841Ce and the western part of SSRU 5841D, at the right depth for toothfish habitat.

It therefore seems plausible to postulate that there are two stocks of *D. mawsoni* across Divisions 58.4.1 and 58.4.2, with the stock to the west being centred on Prydz Bay having significant juvenile areas in the west (SSRUs 5842C and D; perhaps resulting from spawning in the westerly coastal current in SSRUs 5842E and 5841B) and extending to the western side of SSRU 5841C; and a second population, comprising mostly adults, extending from the eastern side of SSRUs 5841C to 5841H.

Since in Division 58.4.1 immature animals appear to increase in abundance only in the extreme east, it is tempting to suggest that this population is simply an adult extension of the Ross Sea population of *D. mawsoni*. Although it is assumed here that this is not the case – and that the assessed biomass and estimated yields should be applied to SSRUs in Division 58.4.1 – if the eastern population is an extension of the Ross Sea *D. mawsoni* stock, it should be included in the assessment of that stock and not be subject to a separate assessment and catch limits.

The exact relationship between the east and west sides of SSRU 5841C is not entirely clear. There is a possibility that the western side of SSRU 5841C should be considered part of the Division 58.4.2 population rather than the Division 58.4.1 population. In any case, it is evident that there is considerable mixing between the two populations in this area. Spawning behaviour, larval drift and juvenile distribution patterns in the area remain largely unknown. In other areas toothfish are known to spawn in late winter (Agnew, 2004; Hanchet et al., 2008). Since both commercial fishing and research surveys take place in summer in Divisions 58.4.1 and 58.4.2 they are unlikely to encounter spawning or larval toothfish. For instance, the Australian BROKE survey (January–March 1996) found no larval toothfish in the shelf waters of Division 58.4.1, including over Bruce Rise (Hoddell et al., 2000).

Both methods of biomass estimation contain assumptions and potential bias and error. For the comparative CPUE analysis, it is believed that the assumptions of constant (or comparable) q and availability are met, but it is still necessary to apply the resultant estimate of density to the entire habitat area within an SSRU even when fishing has been concentrated in one part of it. If it is the case that the density in the wider habitat area is lower than in the assessed area, the estimate of biomass would be biased upwards. This bias is difficult to control for, since it involves an extrapolation to areas for which there are no data. Some of this bias has been corrected for by limiting the potential habitat in an SSRU to the depth zones in which fish were actually found (Figure 6), and that which therefore might approximate most closely the potential habitat for exploitable biomass. A more correct experimental approach would be to require a truly random fishing plan by the fleet.

The problem of the effective habitat area in an SSRU is also encountered when raising the estimates derived from depletion analysis to the whole SSRU, and has the same solutions as described above. However, a further source of error is introduced in the case of depletion analyses: depletions usually take place over areas of smaller spatial scale than that over which exploratory fishing has taken place, and such areas may need to be isolated from the main dataset in order to identify depletions in space and time (see 'Methods'). Available knowledge about toothfish populations in the Southern Ocean from previous studies (e.g. McKinlay et al., 2008) indicates that relatively small areas of (presumably favourable) habitat seem to support high densities of toothfish. Through exploratory fishing, the fleet identifies and targets these hotspot areas in order to maximise catches, and will often fish hard enough to force a local depletion, whereas it may not be economically feasible to fish sufficiently hard to generate a depletion in the low densities seen in other areas.

This could be corrected for by examining the relationship between within-hotspot CPUE and outside-hotspot CPUE, and by examining the data for even smaller-scale depletions. Such an assessment could lead to spatial (including by depth) and temporal stratification of fishing grounds for the purposes of extrapolating biomass estimates from concentrated regions of fishing (i.e. depletion areas) to total fishable area but probably requires more data than are currently available. Agnew and Pearce (2004) have previously been able to correct for this bias by deriving a relationship between initial CPUE and toothfish density in depletion events, and then applying this to all fished areas irrespective of whether they resulted in a depletion or not. Unfortunately, although this relationship does exist within the current depletion dataset, fishing has not been extensive enough in Divisions 58.4.1 and 58.4.2, and there are not enough depletion events, to allow this in the present analysis.

Despite all the uncertainty surrounding the biomass estimates, there is some consistency across the results given in Tables 3 and 4. In particular, it is encouraging to see similar results for the CPUE comparison and local depletion methods (Figure 8). The exception is SSRU 5841G, for which the depletion result was unusually high. This appears to be due to the relatively large difference between the local area size (representing the spatial coverage of CPUE data points) and fished area (Table 2; Appendix 2, Figure 2.2(k)). Note that the CPUE comparison method suggests a rather higher biomass estimate in SSRU 5841C primarily because of the high CPUE in the western area, which has not yet demonstrated a CPUE decline.

The relative scarcity of recaptures (particularly in SSRU 5841C) is puzzling, and the observed recapture rates would suggest much higher vulnerable biomass than has been estimated. Clearly, lower detection rates, higher tag mortalities, lower encounter rates, higher stock abundance and the lack of inclusion of illegal, unreported and unregulated (IUU) catch would all reduce the number of tags that one would expect to see in the legal fishery, but it is not possible, as yet, to determine which of these factors is/are to blame for the apparent discrepancy.

Given the experience that the fleet has now gained in mark–recapture research in the Ross Sea, there is no reason to expect that tag-mortality and observation rates are lower than in the Ross Sea. Unfortunately, the fleet that has generated the largest amount of data in the Ross Sea, and for which reasonable estimates of observation rates are available from that area, has not fished in Divisions 58.4.1 or 58.4.2. Although tagging effort and recoveries in Divisions 58.4.1 and 58.4.2 have been dominated by Spain, some tags have been recovered by vessels from other nations, but the possibility of low and variable observation rates in different fleets is a possible explanation for the low recoveries.

Another explanation could be that there is simply very little overlap between tagging positions and subsequent fishing areas. There is apparent localisation of the fishing so it could also be the case that, from one year to the next, the fish are tagged in one small area, which is not fished as much in the subsequent year and, given their slow apparent movement, the tagged fish are not present as much in the area fished in the following year, thereby decreasing their chances of recapture. Such localised fishing activity needs to be addressed, as it can significantly bias any tagging-related abundance estimates, as it would be assumed that the tagged fish are mixed into the population. However, note the case of SSRU 5841Ce, where fishing in three consecutive years was virtually in the same place each year (Appendix 2, Figures 2.1(g, h and i)).

Fish could also be moving out of the tagged area. This is a distinct possibility, as the recovery of SSRU 5841C tags in SSRUs 5841D and G showed in 2008. For this to be a serious explanation in SSRU 5841G however, a large number of fish would need to be moving into and out of the area each year, which is a rather implausible behaviour for toothfish. Nevertheless, analysis of the tag data would certainly benefit from estimates of the movement rate for toothfish. These could be used to calculate the probability of tagged fished leaving the (localised) area of exploitation, adjusting expected returns in a similar manner to the probability of tag mortality or shedding.

The calculations of sustainable yield presented here, based on an exploitation rate of 5%, suggest appropriate catches significantly lower than the current precautionary catch limits for the six SSRUs presented in Table 5. Although a sustainable catch is not estimated above for all the six other SSRUs, where CPUE data are available from limited exploratory fishing in these areas (Figure 1) they suggest population densities similar to those from adjacent assessed SSRUs. This suggests, in turn, that a sustainable catch for Divisions 58.4.1 and 58.4.2 combined would be a maximum of twice the combined catch limits from Table 5, i.e. about 520 tonnes rather than the 1 380 tonnes at present.

CCAMLR (SC-CAMLR, 2007) estimated 98, 197, 86, 192 and 197 tonnes of IUU catch in each of the years 2003–2007 respectively for Division 58.4.2, and 597 and 612 tonnes for Division 58.4.1 in 2006 and 2007 respectively, figures which exceed the estimated sustainable catch limit in most cases. Yet in only one SSRU (5841E) is a convincing CPUE decline apparent over time (2005–2008) (Figure 1). This could be because, as reported, IUU fishing has mostly taken place in closed SSRUs (where, by and large, IUU vessels were observed), or it could indicate that these calculations are under-estimates of the available biomass.

These results suggest that the precautionary catch in these SSRUs should be revised[2]. The very low recapture rates and the apparently rapid movement of some of the tagged fish in Division 58.4.1 suggest that CCAMLR should not wait for tagging data to yield sensible results before acting to adjust catch limits in Divisions 58.4.1 and 58.4.2. A reduction in catch limit should be accompanied by more innovative exploratory research, in particular to develop an understanding of the relative density of toothfish over the whole fishable area within an SSRU. This could be developed, for instance, by requiring commercial vessels to undertake some stratified random research hauls in an SSRU prior to them undertaking commercial fishing.

Acknowledgements

We would like to acknowledge all CCAMLR data owners for making available to us data from the Ross Sea and Divisions 58.4.1 and 58.4.2 for use in this analysis. The paper benefited significantly from comments provided by J. McKinlay and G. Pilling.

[2] Note that at CCAMLR-XXVII the SSRU catch limits were revised by rounding up all the catch estimates derived from comparative CPUE analyses given in Table 5.

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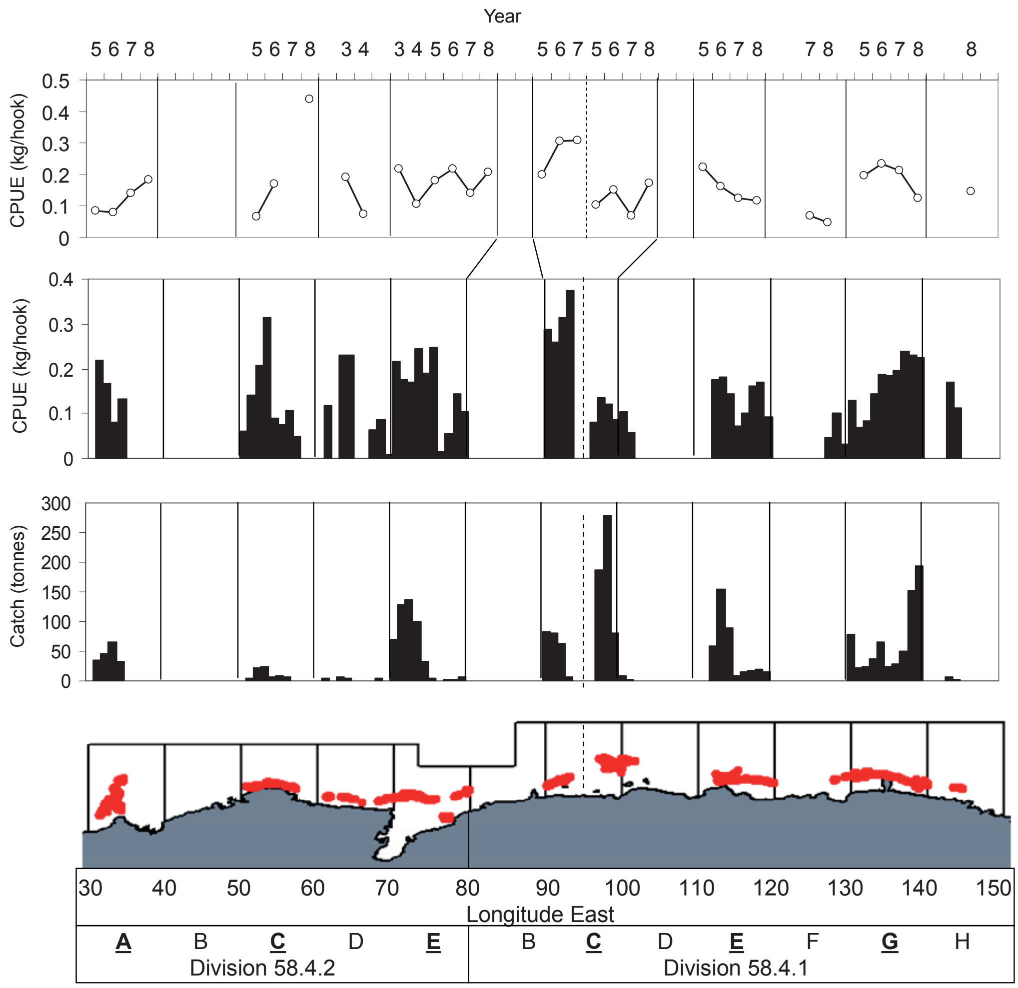

Figure 1: Fishing patterns during the experiment. Bottom panel: spatial distribution of effort, with SSRUs marked and labelled; <u>bold</u> labels indicate SSRUs open to fishing during the experiment. Middle two panels: total catch and average CPUE of *Dissostichus mawsoni* over the entire duration of fishing (2003–2008), arranged spatially so that each bar is the CPUE for a degree of longitude. Top panel: CPUE trends by year, arranged in panels corresponding to each SSRU (year label 5 = 2005 etc.). Two points are not plotted in the top panel for convenience: there was a very small catch in SSRU 5842C in 2003 (16 tonnes, CPUE = 0.105 kg/hook); and in SSRU 5841D in 2008 (10 tonnes, CPUE = 0.096 kg/hook). SSRU 5841C is separated into two sub-SSRUs, east and west, by the dashed line, and the other vertical lines indicate 10° of longitude.

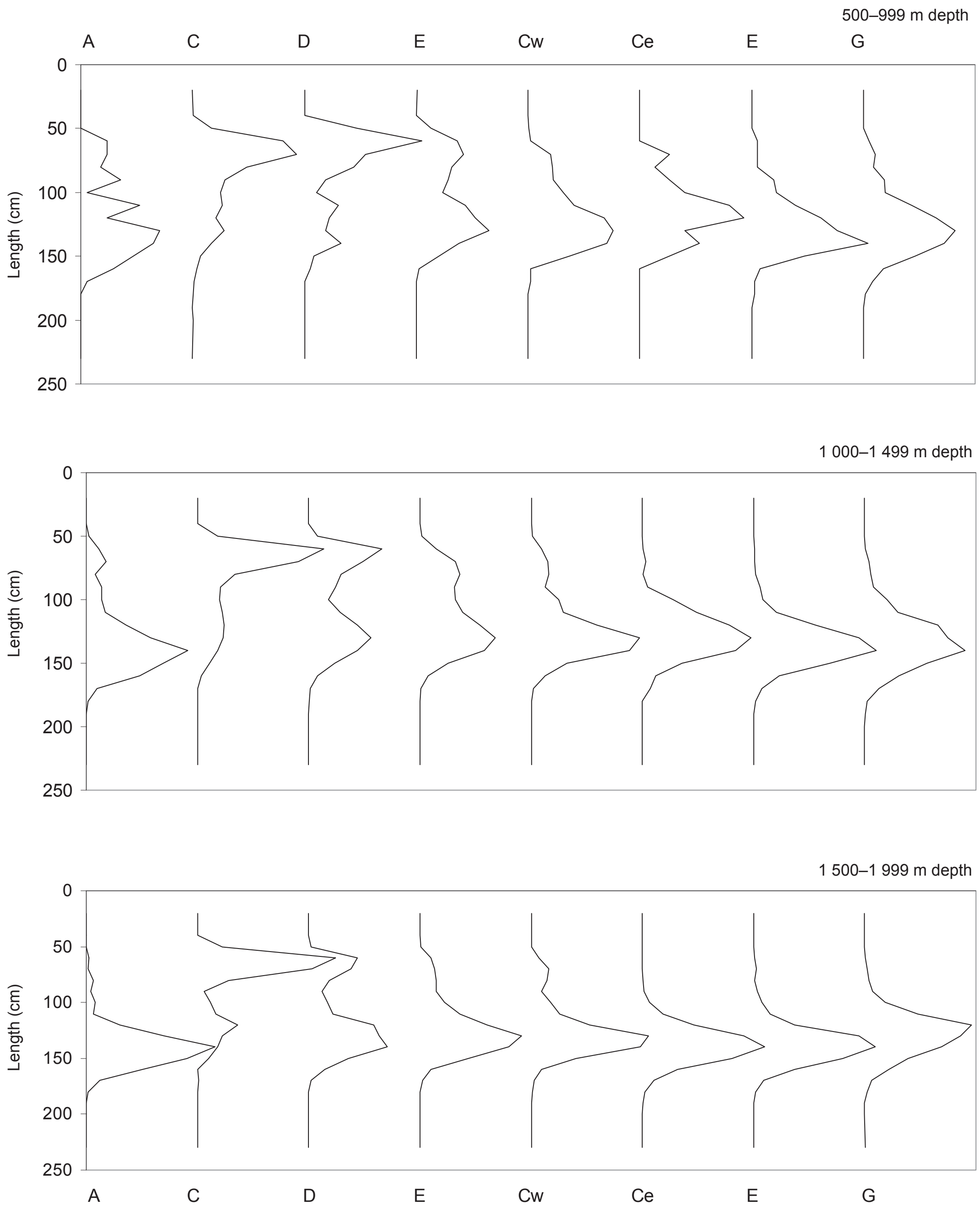

Figure 2: Proportional length frequencies for *Dissostichus mawsoni* from different depths (500–999, 1 000–1 499 and 1 500–1 999 m) in subareas of Divisions 58.4.2 (left, A–E) and 58.4.1 (right, Cw–G). Data for 2003–2007 are pooled. Sample sizes were, for each SSRU from left to right: 500–999 m: 68, 1 070, 145, 605, 329, 30, 161, 448; 1 000–1 499 m: 1 440, 955, 527, 3 720, 847, 612, 1 778, 1 009; 1 500–1 999 m: 603, 268, 327, 3 289, 901, 5 555, 1 528, 652; 2 000–2 499 m: 243 animals, not shown). X-axis scales are the same for all SSRUs.

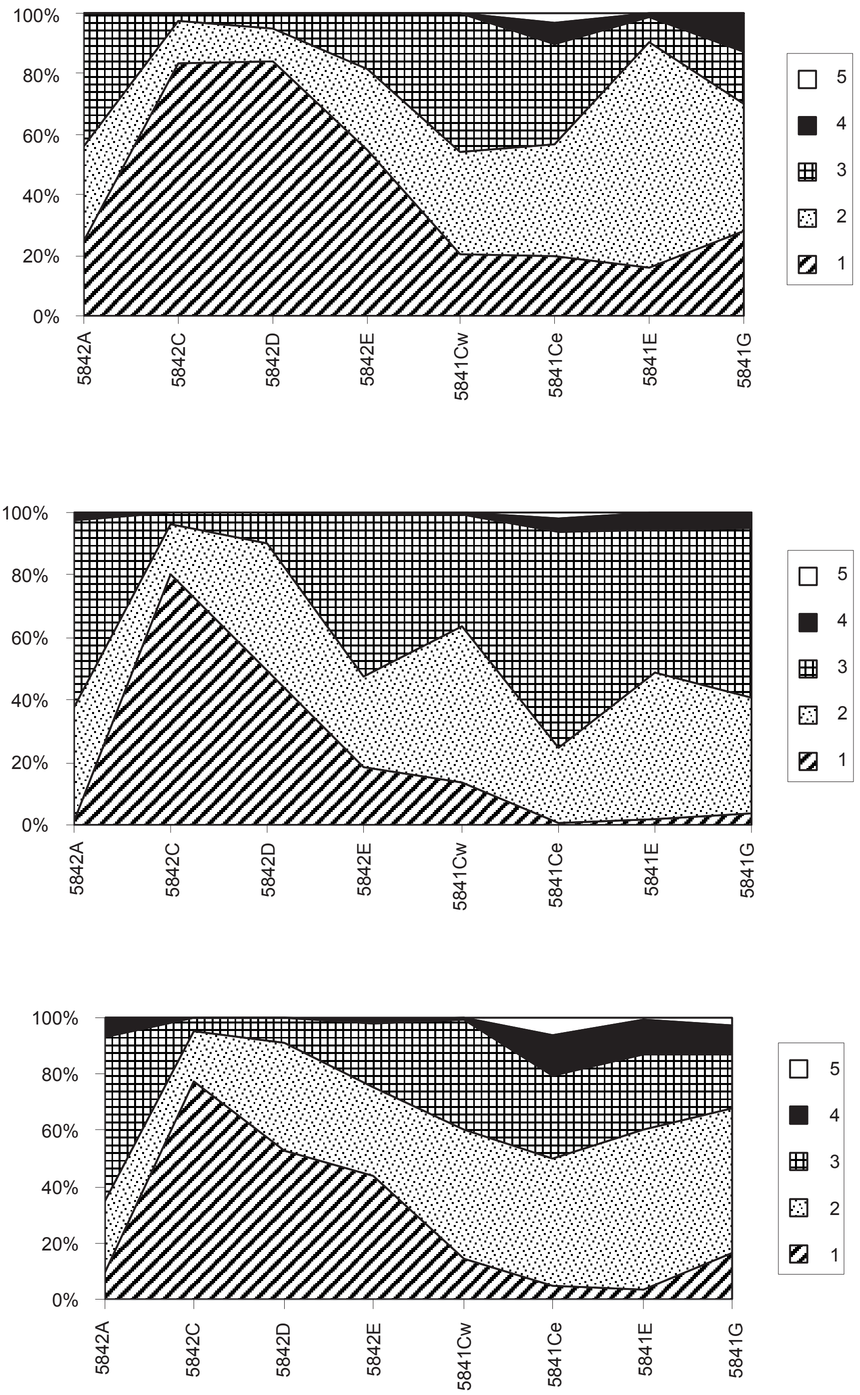

Figure 3: Maturity stage (label at right of figure) at depths of 500–999 m (top), 1 000–1 499 m (middle) and 1 500–1 999 m (bottom). Data from all years pooled. Sample sizes were respectively: 500–999 m: 48, 918, 120, 515, 326, 30, 161, 334; 1 000–1 499 m: 1 246, 771, 384, 3 145, 834, 612, 1 657, 843; 1 500–1 999 m: 579, 195, 270, 2 844, 895, 5 582, 1 376, 1 127.

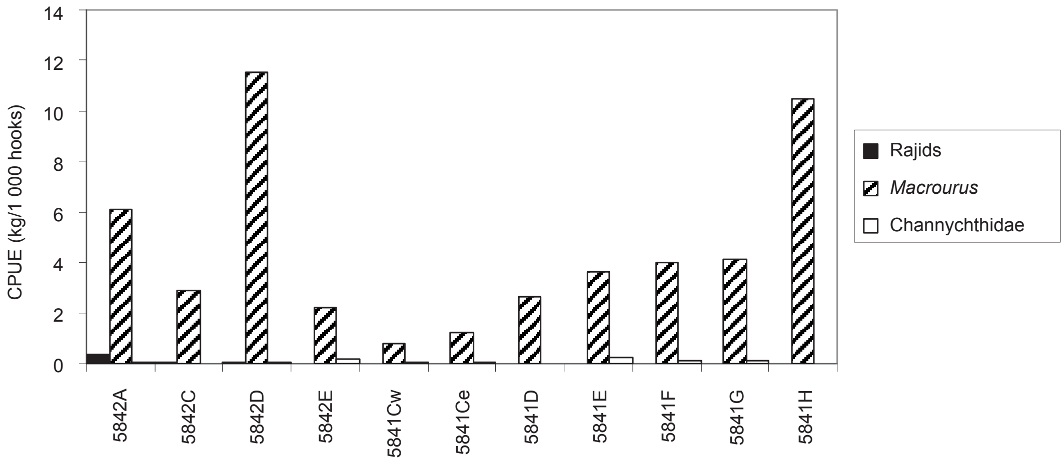

Figure 4: By-catch CPUE. Data for all years 2003–2007 combined. As can clearly be seen, *Macrourus* spp. is by far the most caught by-catch species.

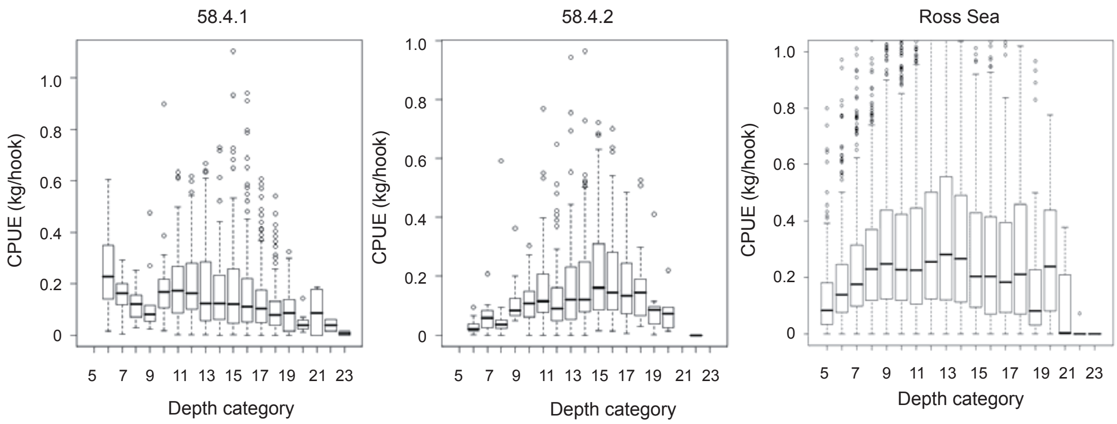

Figure 5: Distribution of CPUE values by 100 m depth category in CCAMLR Divisions 58.4.1, 58.4.2 and, for comparison, the Ross Sea, over all years.

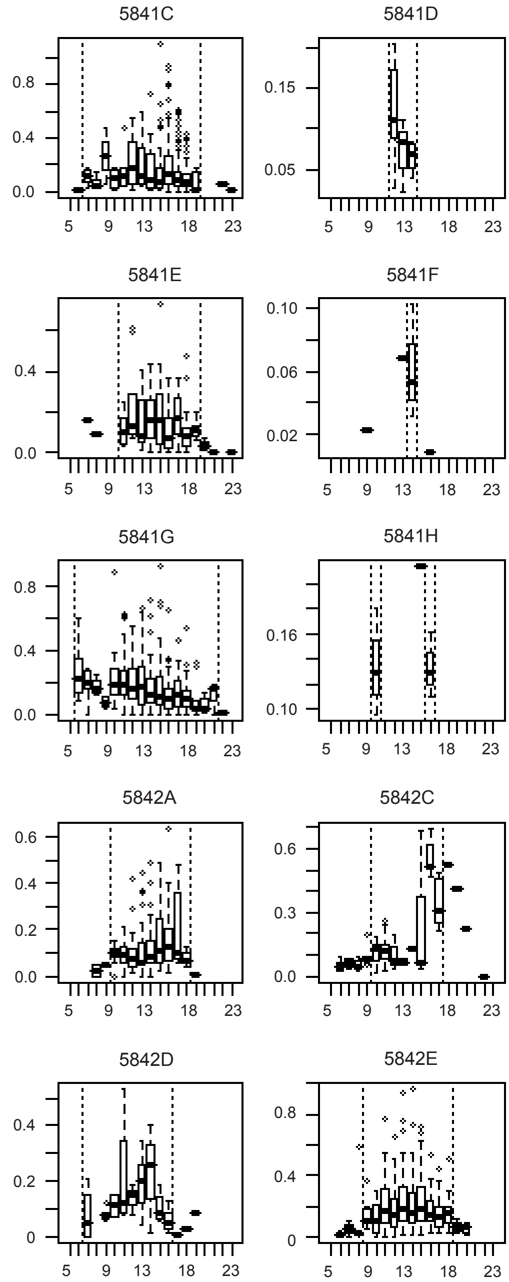

Figure 6: Distribution of CPUE values by 100 m depth category for fished SSRUs within Divisions 58.4.1 and 58.4.2. Axis labels are the same as for Figure 5. Vertical dotted lines indicate depths between which the size of the fished area within each SSRU was estimated.

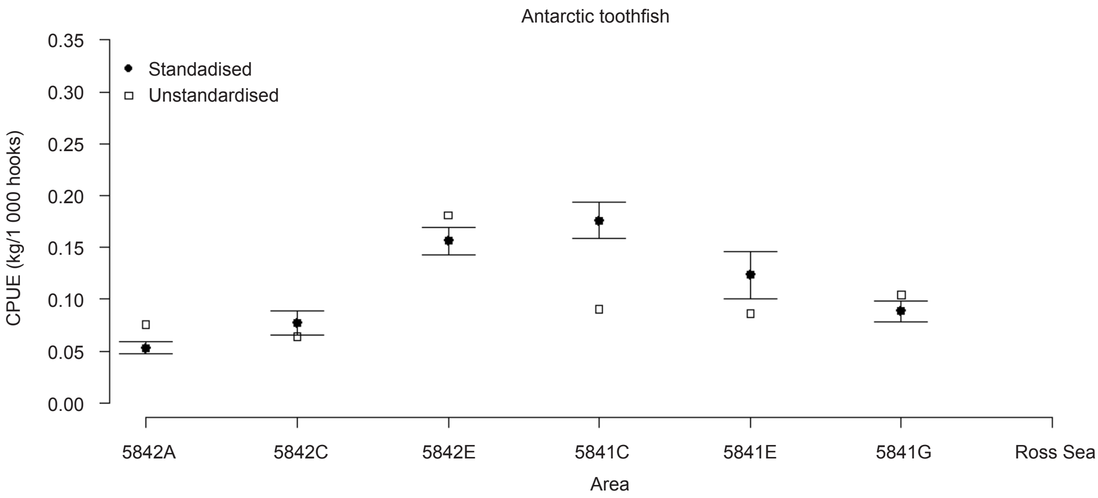

Figure 7: CPUE (kg/hook) values from each SSRU, using data from vessels that had fished in both Divisions 58.4.1 and 58.4.2 and the Ross Sea. Standard error bars are shown. Unstandardised CPUE values have been renormalised to the same scale.

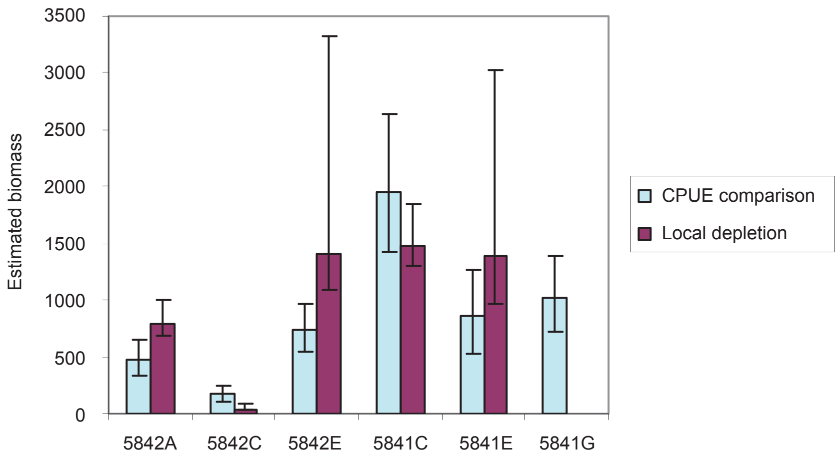

Figure 8: Results of the CPUE comparison and local depletion methods. Depletion results for SSRU 5841G have been excluded (see text).

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Tableau 1.1: Coefficients de régression et erreurs standard fondés sur les données fournies par les navires pêchant tant dans les divisions 58.4.1 et 58.4.2 qu'en mer de Ross. na – non applicable.

Tableau 1.2: Tableau ANOVA de régression appliqué aux données fournies par les navires pêchant tant dans les divisions 58.4.1 et 58.4.2 qu'en mer de Ross. na – non applicable.

Tableau 2.1: Résultats détaillés de l'analyse d'épuisement, utilisant toutes les données. La surface de zone locale correspond à la couverture spatiale des points de données de CPUE. Les estimations de biomasse sont en tonnes. La biomasse maximale correspond à l'estimation fondée sur la surface totale de l'ensemble des zones. Toutes les régressions sont significatives avec $p < 0{,}01$.

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Figure 1: Tendances de la pêche pendant l'expérience. Cadre du bas : répartition spatiale de l'effort de pêche, les SSRU étant délimitées et nommées ; les noms en gras indiquent les SSRU ouvertes à la pêche pendant l'expérience. Deux cadres du milieu : capture totale et CPUE moyenne de *Dissostichus mawsoni* pendant toute la durée de la pêche (2003–2008), disposées spatialement de manière à ce que chaque barre représente la CPUE d'un degré de longitude. Cadre du haut : tendances de la CPUE par année, disposées dans des cadres correspondant à chaque SSRU (année 5 = 2005, etc.). Dans le cadre du haut, deux points ne sont pas représentés pour des raisons de commodité : il s'agissait de captures très faibles – dans la SSRU 5842C en 2003 (16 tonnes, CPUE = 0,105 kg/hameçon) et dans la SSRU 5841D en 2008 (10 tonnes, CPUE = 0,096 kg/hameçon). La SSRU 5841C est divisée en deux sous-SSRU, est et ouest, par la ligne en tirets, et les autres lignes verticales indiquent 10° de longitude.

Figure 2: Fréquences de longueurs proportionnelles de *Dissostichus mawsoni* de diverses profondeurs (500–999, 1 000–1 499 et 1 500–1 999 m) dans des sous-secteurs des divisions 58.4.2 (à gauche, A–E) et 58.4.1 (à droite, Cw–G). Les données de 2003–2007 sont agrégées. Taille des échantillons, pour chaque SSRU de gauche à droite : 500–999 m : 68, 1 070, 145, 605, 329, 30, 161, 448 ; 1 000–1 499 m : 1 440, 955, 527, 3 720, 847, 612, 1 778, 1 009 ; 1 500–1 999 m : 603, 268, 327, 3 289, 901, 5 555, 1 528, 652 ; 2 000–2 499 m : 243 animaux, non indiqué). L'échelle en abscisse est la même pour toutes les SSRU.

Figure 3: Stade de maturité (légende à droite de la figure) à des profondeurs de 500–999 m (haut), 1 000–1 499 m (milieu) et 1 500–1 999 m (bas). Les données de toutes les années sont agrégées. Taille respective des échantillons : 500–999 m : 48, 918, 120, 515, 326, 30, 161, 334 ; 1 000–1 499 m : 1 246, 771, 384, 3 145, 834, 612, 1 657, 843 ; 1 500–1 999 m : 579, 195, 270, 2 844, 895, 5 582, 1 376, 1 127.

Figure 4: CPUE des captures accessoires. Données de toutes les années 2003–2007 combinées. Il est évident que *Macrourus* spp. constitue de loin les espèces les plus souvent capturées.

Figure 5: Distribution des valeurs de CPUE par catégorie de 100 m de profondeur des divisions 58.4.1, 58.4.2 et, à titre de comparaison, celles de la mer de Ross, pour toutes les années.

Figure 6: Distribution des valeurs de CPUE par catégorie de 100 m de profondeur des SSRU des divisions 58.4.1 et 58.4.2. Les légendes des axes sont les mêmes que celles de la figure 5. Les lignes verticales en pointillés indiquent les profondeurs entre lesquelles la surface de fond marin exploitable a été estimée pour chaque SSRU.

Figure 7: Valeurs de CPUE (kg/hameçon) de chaque SSRU, tirées des données des navires ayant pêché tant dans les divisions 58.4.1 et 58.4.2 qu'en mer de Ross. Les barres d'erreur standard sont présentées. Les valeurs de CPUE non standard ont été renormalisées à la même échelle.

Figure 8: Résultats de la comparaison de CPUE et des méthodes d'épuisement local. Les résultats de l'épuisement de la SSRU 5841G ont été exclus (voir texte).

Figure 2.1: Épuisement (à gauche), zone d'épuisement (à droite, en noir) et zone exploitable (à droite, en gris clair). Les zones en gris foncé correspondent au continent antarctique. (a) SSRU 5842A 2006/07 ; (b) SSRU 5842A

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Рис. 4: CPUE прилова. Данные за все годы (2003–2007 гг.) вместе. Четко видно, что чаще всего как прилов ловятся виды *Macrourus*.

Рис. 5: Распределение значений CPUE по 100-метровым классам глубины на участках АНТКОМ 58.4.1, 58.4.2 и, для сравнения, в море Росса по всем годам.

Рис. 6: Распределение значений CPUE по 100-метровым классам глубины для облавливаемых SSRU на участках 58.4.1 и 58.4.2. Обозначения осей такие же, как на рис. 5. Вертикальными пунктирными линиями показаны глубины, между которыми рассчитывался размер облавливаемой площади в каждой SSRU.

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Рис. 8: Результаты сравнения CPUE и методов локального истощения. Исключены результаты истощения для SSRU 5841G (см. текст).

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Tabla 4: Estimaciones de biomasa (en toneladas) para cada UIPE donde se observó una reducción estacional. La *biomasa máxima* se refiere a estimaciones que utilizaron el tamaño de toda el área.

Tabla 5: Resumen de las estimaciones de biomasa y límites de captura, y diferencia entre el número previsto y el número observado de marcas recuperadas. Nótese que a pesar de que se supone que dos marcas fueron recuperadas en la UIPE 5841Ce, en realidad una fue recuperada en el extremo occidental de la UIPE 5841D por la pesquería de investigación española. Los intervalos de confianza calculados para las estimaciones de biomasa aparecen en las tablas anteriores. TOA – *Dissostichus mawsoni*.

Tabla 1.1: Coeficientes de regresión y error típico utilizando datos de los barcos que operaron tanto en las Divisiones 58.4.1 y 58.4.2 como en el Mar de Ross. na – no corresponde.

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APPENDIX 1

Linear regression coefficients, diagnostics and ANOVA tables

The linear regression model applied to log-transformed catch rate vector I, can be specified as:

$$\ln(I+\delta) = X\beta + \varepsilon \tag{1.1}$$

where β is the vector of coefficients, X is the design matrix and ε is a vector of normally distributed error terms. To allow for zero CPUE values, a constant δ was added to each record (Butterworth, 1996). A small value of 10% of the mean CPUE was chosen as the minimum value that did not substantially upset underlying assumptions of normality in the distribution of $\ln(I+\delta)$.

Assuming (for purposes of illustration relevant to this analysis) two discrete covariates β^A and β^Y (corresponding to area and fishing year respectively), with n^A and n^Y levels for each, and n^i data points, the design matrix can be written as:

$$X = \begin{bmatrix} 1 & x_{1,1} & \cdots & x_{1,n^A} & x_{1,n^A+1} & \cdots & x_{1,n^A+n^Y} \\ 1 & x_{2,1} & \cdots & x_{2,n^A} & x_{2,n^A+1} & \cdots & x_{2,n^A+n^Y} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n^i,1} & \cdots & x_{n^i,n^A} & x_{n^i,n^A+1} & \cdots & x_{n^i,n^A+n^Y} \end{bmatrix}. \tag{1.2}$$

Here $x_{i,j}$ are binary values indicating whether the coefficient for factor level j, β_j, should be applied to obtain the predicted value for record i. For a particular record equation (7) can be written as:

$$\ln(I_i+\delta) = \beta^0 + \sum_{j=1}^{n^A} x_{ij}^A \beta_j^A + \sum_{j=1}^{n^Y} x_{ij}^Y \beta_j^Y + \varepsilon_i \tag{1.3}$$

where β^0 is the intercept term, and x^A and x^Y are the observed binary data for area and year respectively.

After setting sum to zero contrasts in R (using options(contrasts = c("contr.sum", "contr.poly"))) coefficients were estimated using the code:

```
lm(log(CPUE_TOA+delta)~area+vessel+fyear+month+hook_code+soak_time_cat+depth_
cat,data=data)
```

where TOA = *D. mawsoni*.

If one is interested in the effect on I of a single factor level β_1^A (corresponding to the effect of area 1), it is possible to take the expectation over a subset of the data k, which contains all data entries for which $x_{i1}^A = 1$ (i.e. all records from area 1). Then:

$$E_{i\in k}\left[\ln(I_i+\delta)\right] = \beta^0 + \beta_1^A + \sum_{j=1}^{n^Y} p_j^Y \beta_j^Y \tag{1.4}$$

where p is the proportion of records in k that correspond to year factor level j. The expected effect of factor level β_1^A therefore amounts to the β_1^A coefficient plus a weighted average of β_j^Y coefficient values. Since $\sum_j \beta_j = 0$, orthogonality of the data (so that p_j is equal for all j) would mean that:

$$E_{i\in k}\left[\ln(I_i+\delta)\right] = \beta^0 + \beta_1^A. \tag{1.5}$$

The analysis makes use of this equation to extract the desired effects. Because the data are clearly not orthogonal, this amounts to an implicit re-weighting that gives equal weight to all other factor levels, despite unequal sampling. The CPUE estimate for each area level j is therefore:

$$\hat{I}_j = \exp\left(\beta^0 + \beta_1^A\right) - \delta. \tag{1.6}$$

The delta method is used to obtain standard errors for $\hat{I}$. Thus the standard error π for factor level j is:

$$\hat{\pi}_j = \sqrt{\exp\left(2\left(\beta^0 + \beta_1^A\right)\right)\sigma_j^2} \tag{1.7}$$

where σ_j is the regression standard error. Coefficients and factor significance is shown in Tables 1.1 and 1.2.

Table 1.1: Regression coefficients and standard errors using data from vessels fishing in both Divisions 58.4.1 and 58.4.2 and the Ross Sea. na – not applicable.

	Estimate	Std. error	*t*-value	Pr(>|*t*|)	
Intercept	–1.8872	0.0896	–21.06	2.00E-16	***
area1	0.3083	0.0713	4.32	1.60E-05	***
area2	0.0127	0.1103	0.12	9.09E-01	
area3	–0.2463	0.0695	–3.54	4.04E-04	***
area4	–0.6011	0.0877	–6.86	8.77E-12	***
area5	–0.3414	0.1504	–2.27	2.33E-02	*
area6	0.2064	0.0882	2.34	1.93E-02	*
vessel1	2.4309	0.5962	4.08	4.69E-05	***
vessel2	0.2532	0.1215	2.08	3.73E-02	*
vessel3	–0.2678	0.1675	–1.60	1.10E-01	
vessel4	–0.3885	0.1695	–2.29	2.19E-02	*
vessel5	–1.0182	0.1395	–7.30	3.82E-13	***
vessel6	–1.1386	0.1865	–6.11	1.19E-09	***
fyear1	0.0198	0.2041	0.10	9.23E-01	
fyear2	0.4024	0.1073	3.75	1.81E-04	***
fyear3	–0.0938	0.1052	–0.89	3.73E-01	
fyear4	0.4288	0.1039	4.13	3.80E-05	***
fyear5	0.4034	0.1072	3.76	1.72E-04	***
fyear6	–0.2147	0.0972	–2.21	2.72E-02	*
fyear7	0.5695	0.0764	7.45	1.25E-13	***
fyear8	0.5804	0.0838	6.93	5.42E-12	***
fyear9	na	na	na	na	
month1	–0.0754	0.0318	–2.37	1.77E-02	*
month2	–0.1979	0.0486	–4.07	4.88E-05	***
month3	–0.1335	0.0326	–4.10	4.36E-05	***
month4	–0.0079	0.0426	–0.19	8.53E-01	
hook_code1	–0.4767	0.0995	–4.79	1.76E-06	***
hook_code2	0.9796	0.1992	4.92	9.25E-07	***
hook_code3	–0.3473	0.1412	–2.46	1.40E-02	*
hook_code4	1.4171	0.1326	10.69	2.00E-16	***
hook_code5	–0.4833	0.1603	–3.02	2.59E-03	**
soak_time_cat1	–0.6075	0.1358	–4.47	8.01E-06	***
soak_time_cat2	–0.2841	0.0514	–5.53	3.57E-08	***
soak_time_cat3	–0.0492	0.2185	–0.23	8.22E-01	
soak_time_cat4	0.2680	0.2316	1.16	2.47E-01	
soak_time_cat5	–0.0612	0.0495	–1.24	2.16E-01	
soak_time_cat6	–0.0068	0.0507	–0.14	8.93E-01	
soak_time_cat7	0.1618	0.0564	2.87	4.15E-03	**
soak_time_cat8	0.1577	0.0649	2.43	1.51E-02	*
soak_time_cat9	0.2759	0.0768	3.60	3.31E-04	***
soak_time_cat10	0.1708	0.0822	2.08	3.79E-02	*
soak_time_cat11	–0.0106	0.1027	–0.10	9.18E-01	

(continued)

Table 1.1 (continued)

	Estimate	Std. error	t-value	Pr(>|t|)	
depth_cat1	0.1724	0.0484	3.56	3.78E-04	***
depth_cat2	0.1570	0.0494	3.18	1.50E-03	**
depth_cat3	0.2217	0.0427	5.19	2.30E-07	***
depth_cat4	0.2096	0.0431	4.86	1.22E-06	***
depth_cat5	0.2489	0.0454	5.49	4.51E-08	***
depth_cat6	0.2089	0.0528	3.96	7.86E-05	***
depth_cat7	0.1596	0.0580	2.75	5.98E-03	**
depth_cat8	–0.0985	0.0706	–1.39	1.63E-01	
depth_cat9	–0.1398	0.1000	–1.40	1.62E-01	
depth_cat10	–0.2982	0.1393	–2.14	3.24E-02	*
depth_cat11	–0.7754	0.1974	–3.93	8.78E-05	***
depth_cat12	–0.1192	0.0669	–1.78	7.50E-02	
depth_cat13	–0.1161	0.0631	–1.84	6.60E-02	
depth_cat14	0.0403	0.0534	0.76	4.50E-01	

Table 1.2: ANOVA table for regression applied to data from vessels fishing in both Divisions 58.4.1 and 58.4.2 and the Ross Sea. na – not applicable.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
area	6	320.06	53.34	123.28	4.13E-137
vessel	6	327.27	54.55	126.06	6.83E-140
fyear	8	290.32	36.29	83.87	1.54E-123
month	4	36.03	9.01	20.82	6.64E-17
hook_code	5	131.47	26.29	60.77	5.67E-60
soak_time_cat	11	57.26	5.21	12.03	2.48E-22
depth_cat	14	39.12	2.79	6.46	5.73E-13
Residuals	2545	1101.21	0.43	na	na

APPENDIX 2

Results and figures from the depletion analysis

Detailed results of the depletion analysis are shown in Table 2.1 and Figure 2.1. In each figure the depletion plots are shown alongside a map of the area. The total fishable area (between 500 and 2 000 m deep) is shown in light grey. CPUE data points used in the depletion analysis are shown on the map in black.

Table 2.1: Detailed results of the depletion analysis, utilising all the data. The local area size refers to the spatial coverage of the CPUE data points. Biomass estimates are given in tonnes. Maximum biomass refers to the estimate made using the total area sizes. All regressions were significant with $p < 0.01$.

Depletion area	Season	c	m	n	R^2	Local biomass	Local area size (km^2)	SSRU biomass
5842A	2006/07	0.2088	–4.99E-06	49	0.2939	42	4 901	208
5842A	2007/08	0.4982	–1.47E-05	27	0.6242	34	590	1 391
5842C	2002/03	0.1680	–6.71E-06	38	0.2371	25	3 769	40
5842E	2002/03	0.4477	–6.02E-06	62	0.2378	74	443	2 122
5842E	2006/07	0.1917	–1.17E-06	57	0.0737	165	1 615	1 263
5842E	2007/08	0.2548	–6.63E-06	27	0.4264	38	577	838
5841Ce	2004/05	0.2125	–1.48E-06	94	0.3864	144	2 329	1 837
5841Ce	2005/06	0.2904	–1.67E-06	89	0.3556	174	2 712	1 900
5841Ce	2006/07	0.1207	–7.76E-07	141	0.0744	156	6 732	683
5841E	2004/05	0.3140	–1.12E-06	59	0.1378	280	3 835	1 382
5841G	2006/07	0.3793	–1.27E-06	55	0.1134	299	599	15 334

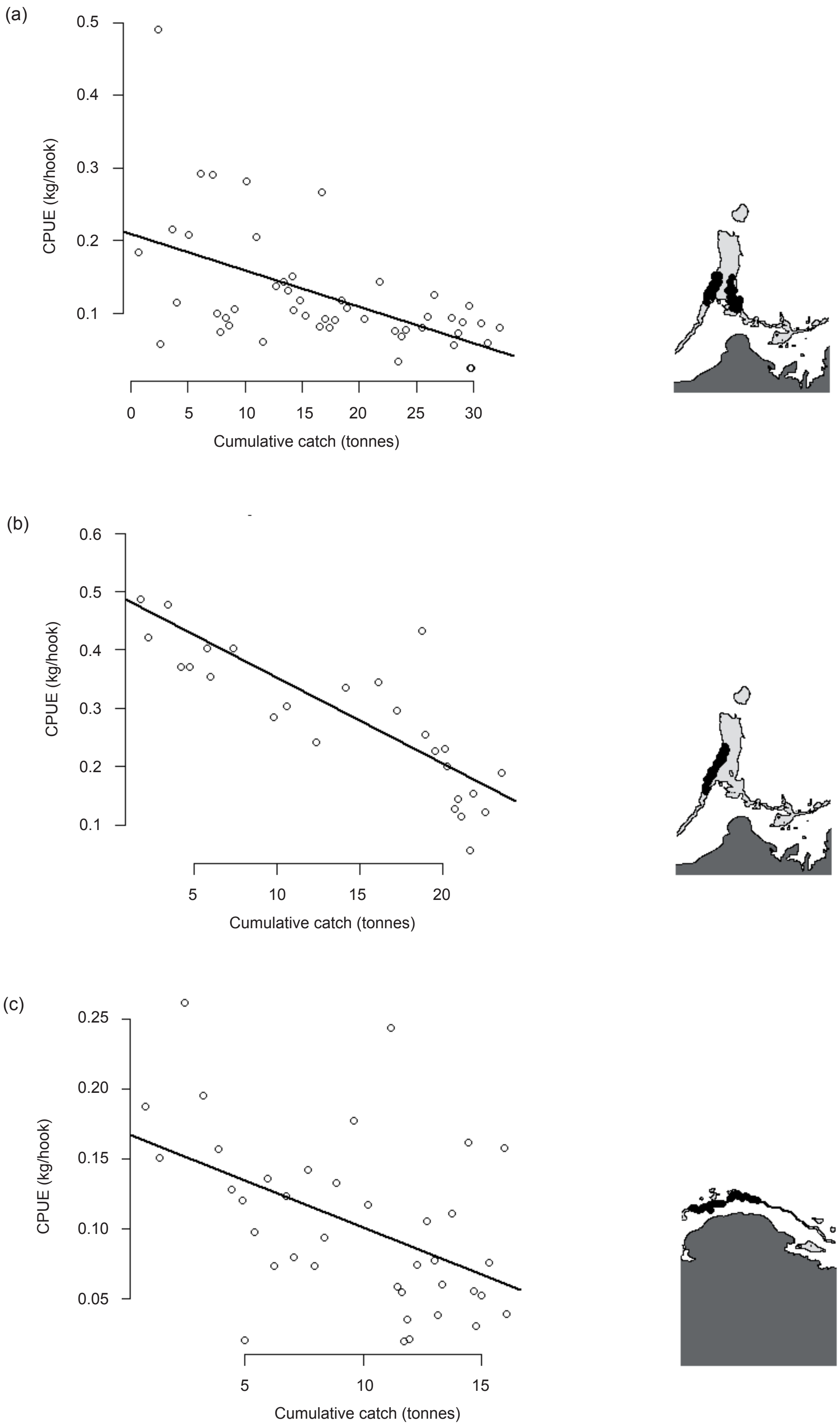


Figure 2.1: Depletion (left), depletion area (right, in black) and fishable area (right, light grey). The dark grey areas are the Antarctic continent. (a) SSRU 5842A 2006/07; (b) SSRU 5842A 2007/08; (c) SSRU 5842C 2002/03.

(continued)

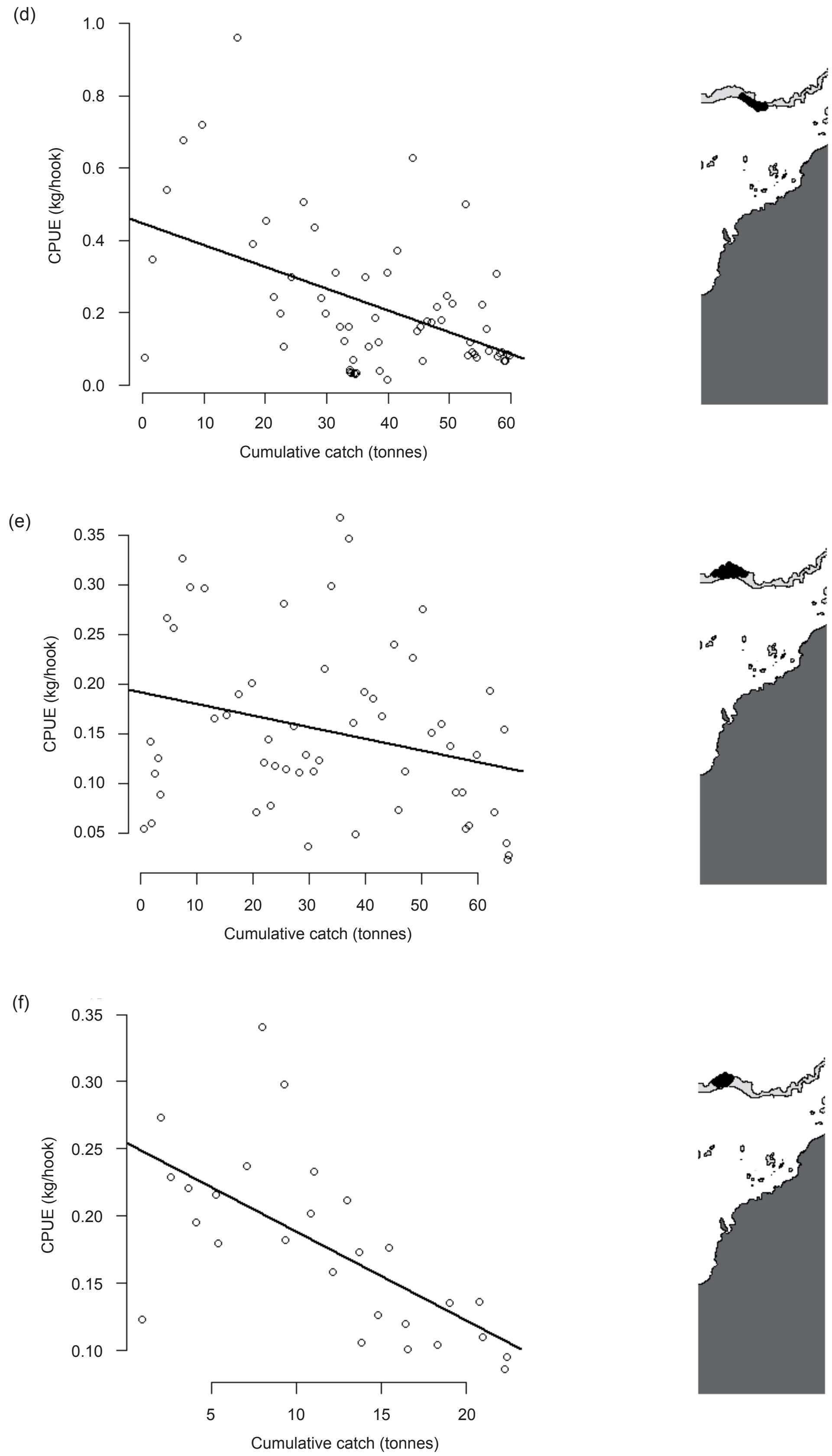


Figure 2.1 (continued): Depletion (left), depletion area (right, in black) and fishable area (right, light grey). The dark grey areas are the Antarctic continent. (d) SSRU 5842E 2002/03; (e) SSRU 5842E 2006/07; (f) SSRU 5842E 2007/08.

(continued)

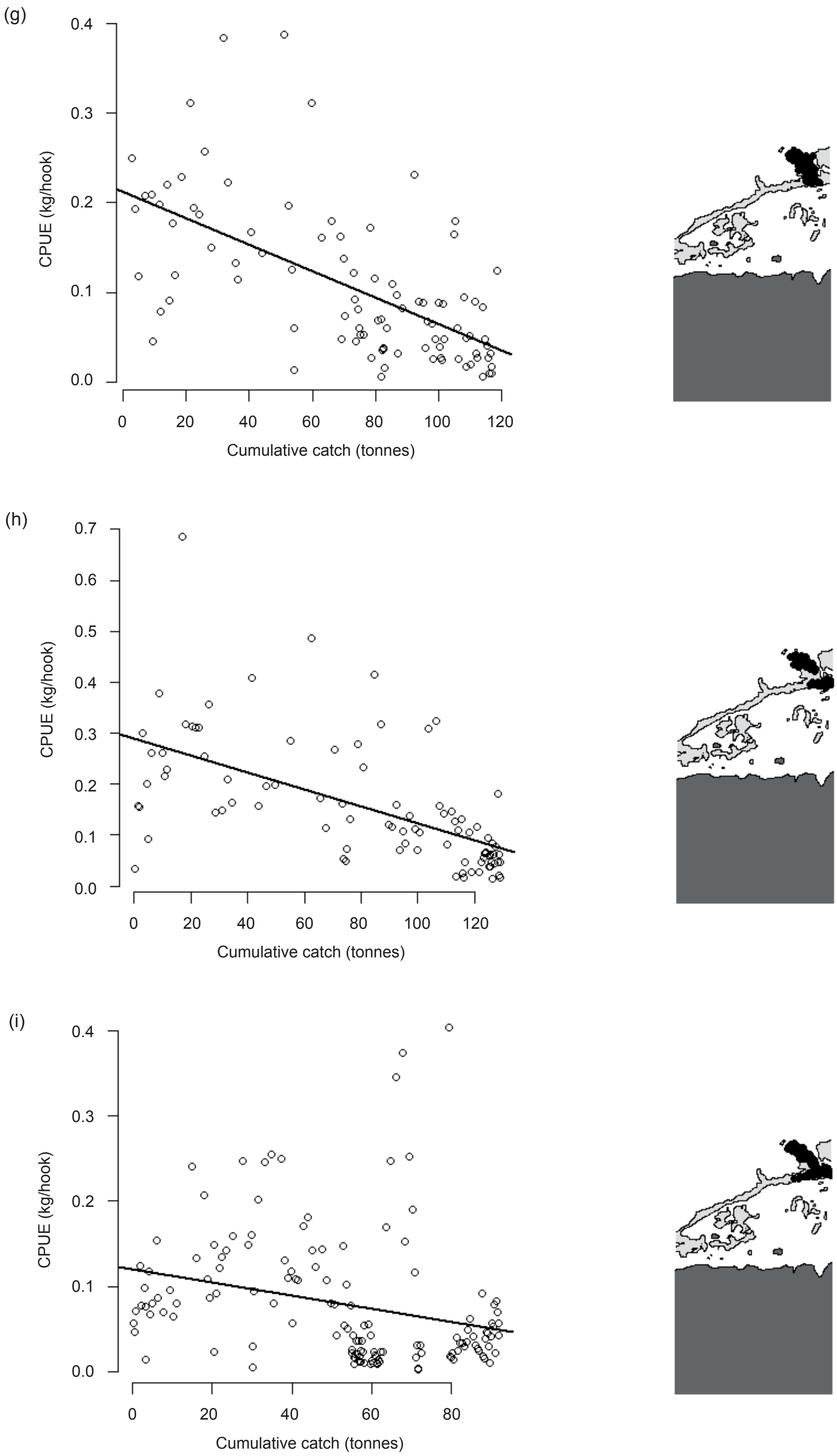
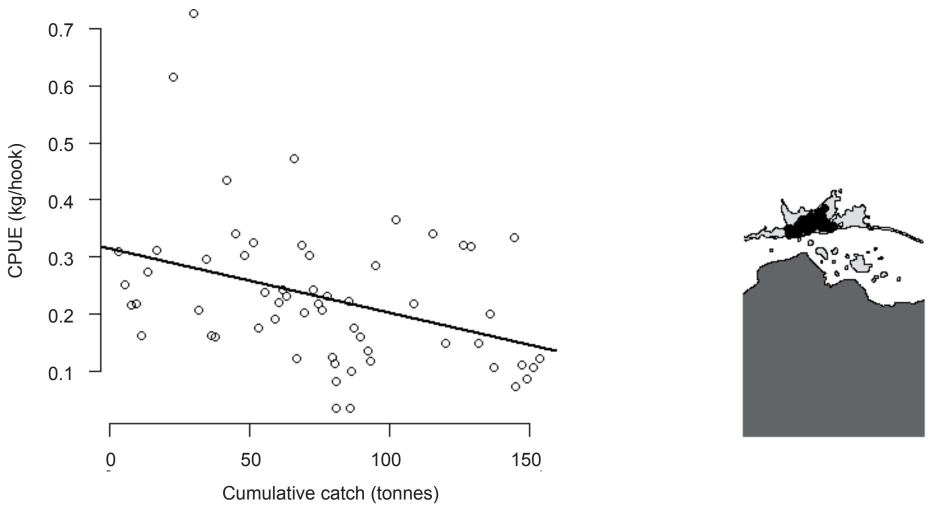


Figure 2.1 (continued): Depletion (left), depletion area (right, in black) and fishable area (right, light grey). The dark grey areas are the Antarctic continent. (g) SSRU 5841Ce 2004/05; (h) SSRU 5841Ce 2005/06; (i) SSRU 5841Ce 2006/07.

(continued)

(j)



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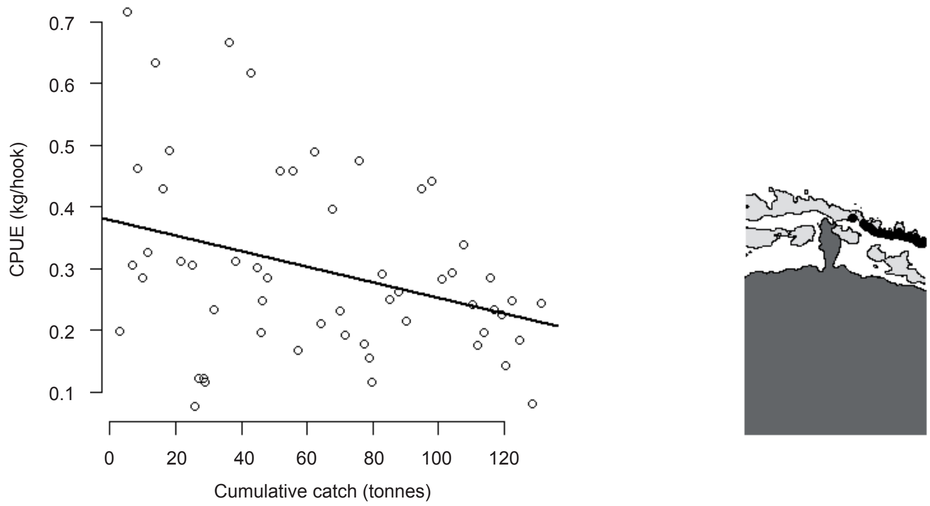

Figure 2.1 (continued): Depletion (left), depletion area (right, in black) and fishable area (right, light grey). The dark grey areas are the Antarctic continent. (j) SSRU 5841E 2004/05; (k) SSRU 5841G 2006/07.