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PRELIMINARY ANALYSES OF DATA COLLECTED DURING EXPERIMENTAL PHASES OF THE 1994/95 AND 1995/96 ANTARCTIC CRAB FISHING SEASONS

G. Watters
NOAA Fisheries
Southwest Fisheries Science Center
US AMLR Program, PO Box 271
San Diego, Ca. 92038, USA

Current address:
Inter-American Tropical Tuna Commission
8604 La Jolla Shores Drive
La Jolla, Ca. 92037, USA

Abstract

Data collected on board the FV *American Champion* during Phases 1 and 2 of the experimental crab fishery were analysed using generalised additive models and depletion estimators. Results from the generalised additive models show that the density of fishable *Paralomis spinosissima* is highest off the northern coast of South Georgia and at depths of about 100 to 300 fathoms. The Phase 1 results suggest that it would not be appropriate to extrapolate local estimates of abundance to the whole of Subarea 48.3 solely on the basis of depth-specific seabed area; extrapolations must consider location. Linear models fitted to catch per unit effort (CPUE) and cumulative catch data from the Phase 2 depletion experiments did not have significant negative slopes. The insignificant regressions were probably a result of small catches, inter-haul variability in CPUE, and crab movement and suggested that depletion estimators will not be appropriate tools for estimating local abundances of *P. spinosissima*. It was not possible to determine whether depletion estimators can be used to estimate crab abundance when larger areas are considered and larger catches are taken. Approximately 6 000 crabs were tagged and released during Phase 2. Four of the tagged crabs were recovered, and these crabs were at liberty for about one to five weeks. The recaptured crabs had minimum movement rates of 0.08 to 0.25 n miles/day. Mark–recapture estimates of standing stock and density were made for the area around Phase 2's third depletion square. The assumptions of the mark–recapture model were probably violated, but attempts were made to account for biased sampling of recaptured crabs and the movement of crabs away from their release sites. Density estimates from the mark–recapture data were in the order of 50 000 to 100 000 legal-sized male crabs/n mile^2, and there was a lot of uncertainty associated with these estimates. In general, the experimental harvest regime was successful. The regime provided important information about crab distribution and facilitated evaluation of local depletion estimators for use in stock assessment, but the CCAMLR Working Group on Fish Stock Assessment (WG-FSA) may wish to re-evaluate the design of Phase 2 and consider the implementation of a wide-scale, intensive tagging study.

Résumé

Les données collectées à bord du navire de pêche *American Champion* pendant les phases 1 et 2 de la pêche expérimentale de crabes ont été analysées par des modèles "extensibles" généralisés et des paramètres d'estimation par l'épuisement. Les résultats des modèles extensibles généralisés indiquent que c'est au large de la côte nord de la Géorgie du Sud et à des profondeurs de 100 à 300 brasses que la densité des concentrations exploitables de *Paralomis spinosissima* est le plus élevée. Les résultats de la phase 1 laissent entendre qu'il ne conviendrait pas d'extrapoler les estimations locales d'abondance à l'ensemble de la sous-zone 48.3 simplement en se fondant sur l'aire de fond marin en fonction de la profondeur; les extrapolations doivent tenir compte de l'emplacement. Les modèles linéaires ajustés à la capture par unité d'effort (CPUE) et aux données de captures cumulées des expériences d'épuisement de la phase 2 n'ont pas donné de pentes nettement négatives. Les régressions insignifiantes résultent probablement de la faible importance des captures, de la variabilité de la CPUE d'un relevé de casiers à un autre, et du déplacement des crabes et suggèrent que les paramètres d'estimation par l'épuisement ne seront pas adéquats pour estimer l'abondance locale de *P. spinosissima*. Il n'a pas été possible de déterminer si les paramètres d'estimation par l'épuisement peuvent servir à estimer l'abondance des crabes lorsque l'on étudie des secteurs plus étendus et que les captures sont plus importantes. Quelque 6 000 crabes ont été marqués puis relâchés pendant la phase 2. Quatre d'entre eux ont été recapturés une à cinq semaines plus tard. Leurs taux de déplacement minimum étaient de 0,08 à 0,25 milles/jour. Les estimations du stock permanent et de la densité à partir de la recapture d'individus marqués ont été effectuées dans la région située autour de la troisième case d'épuisement de la phase 2. Les hypothèses du modèle de recapture des marques se sont probablement révélées fausses, mais on a tenté de tenir compte d'une part, du fait que l'échantillonnage des crabes recapturés présente un biais et d'autre part, du déplacement des crabes lorsqu'ils quittent le site où ils sont relâchés. Les estimations de densité provenant des données de recapture des marques étaient de l'ordre de 50 000 à 100 000 crabes mâles de taille légale/mille^2 mais, à ces estimations était associée une incertitude importante. En général, le régime d'exploitation expérimental s'est révélé une réussite. En effet, il a fourni des informations importantes sur la répartition des crabes et a facilité l'évaluation des paramètres d'estimation locale par l'épuisement qui seront utilisés dans l'évaluation des stocks. Toutefois le Groupe de travail de la CCAMLR chargé de l'évaluation des stocks de poissons (WG-FSA) souhaitera peut-être réévaluer la conception de la phase 2 et envisager la mise en place d'une étude de marquage intensif sur une grande échelle.

Резюме

Данные, собранные с борта промыслового судна *American Champion* в ходе этапов 1 и 2 экспериментального промысла крабов, были проанализированы с помощью обобщенных аддитивных моделей и определителей истощения. Согласно результатам, полученным при использовании обобщенных аддитивных моделей, наивысшая плотность пригодного для промысла *Paralomis spinosissima* имеется в районе северного побережья Южной Георгии на глубине около 100 - 300 морских саженей. Результаты Этапа 1 говорят о том, что было бы нецелесообразным экстраполировать локальные оценки численности на весь Подрайон 48.3 с учетом только площади морского дна конкретной глубины; такие экстраполяции должны учитывать и географическое местоположение. Линейные модели, подогнанные к данным улова на единицу усилия (CPUE) и кумулятивным данным по уловам, полученным в результате экспериментов по истощению в ходе Этапа 2, не характеризовались существенными отрицательными наклонами. Эта небольшая регрессия вероятно имела место из-за небольших уловов, изменчивости в CPUE от траления к тралению и перемещения крабов, и говорит о том, что определители истощения не являются эффективными методами определения локальной численности *P. spinosissima*. Возможность использования определителей истощения для оценки численности крабов при рассмотрении более крупных районов и получении более крупных уловов определить не удалось. В ходе Этапа 2 было помечено и выпущено около 6000 крабов. Четыре помеченных краба было выловлено вторично, и эти крабы были на свободе от одной до пяти недель. Минимальная скорость перемещения этих особей равнялась 0,08 - 0,25 морской мили в день. С помощью данных по повторно отловленным помеченным крабам были сделаны оценки биомассы запаса и плотности в районе вокруг третьего квадрата истощения в рамках Этапа 2. Предположения модели отлова помеченных крабов скорее всего были нарушены, однако были сделаны попытки скорректировать ошибки, сделанные при выборке повторно отловленных крабов, и учесть фактор перемещения крабов от мест их высвобождения. Оценки плотности, полученные с помощью данных по повторно отловленным помеченным особям, составили около 50 000 - 100 000 самцов разрешенного к вылову размера на квадратную морскую милю, и эти оценки окружала большая степень неопределенности. В общем, экспериментальный режим промысла оказался успешным. В результате его применения была получена важная информация о распределении крабов и была сделана оценка эффективности определителей локального истощения для использования при оценке запаса. Тем не менее Рабочая группа АНТКОМа по оценке рыбных запасов (WG-FSA) может счесть необходимым пересмотреть схему Этапа 2 и изучить возможность проведения широкомасштабного и интенсивного исследования по мечению.

Resumen

Los datos recopilados a bordo del BI *American Champion* durante las fases 1 y 2 de la pesquería experimental de centollas fueron analizados mediante modelos aditivos generalizados e indicadores de reducción. Los resultados de los modelos aditivos generalizados muestran que la densidad de la población de *Paralomis spinosissima* explotable es mayor frente a la costa norte de Georgia del Sur y a profundidades cercanas a las 100 – 300 brazas. Los resultados de la fase 1 indican que no es apropiado proyectar las estimaciones locales de abundancia a la totalidad de la Subárea 48.3 sobre la base de la profundidad específica del área de lecho marino; al hacer las extrapolaciones se debe considerar además la situación geográfica. Los modelos lineales ajustados a los datos de captura por unidad de esfuerzo (CPUE) y a la captura acumulada de los experimentos de reducción de la fase 2 no mostraron pendientes negativas de importancia. Las regresiones insignificantes probablemente fueron el resultado de capturas más bien pequeñas, de variaciones del CPUE entre los lances y del desplazamiento de las centollas, lo cual sugiere que los indicadores de reducción no son herramientas útiles para estimar la abundancia local de *P. spinosissima*. No fue posible determinar si los indicadores de reducción pueden utilizarse para estimar la abundancia de centollas cuando se consideran zonas más extensas y capturas más abundantes. Se marcaron y liberaron unas 6 000 centollas durante la fase 2. Se recuperaron cuatro centollas marcadas que permanecieron en libertad entre una y cinco semanas. Las centollas recobradas se desplazaron a una velocidad mínima de 0.08 a 0.25 millas náuticas por día. De los estudios de marcado y recuperación de marcas se hicieron estimaciones de la biomasa instantánea y de la densidad del área alrededor del tercer cuadrado de reducción en la fase 2. Probablemente se quebrantaron las suposiciones del modelo de marcado-recaptura, pero se hicieron esfuerzos por tomar en cuenta el muestreo sesgado de las centollas recapturadas y el desplazamiento de ellas desde del lugar donde fueron liberadas. Las estimaciones de densidad de los experimentos de marcado-recaptura fueron del orden de 50 000 a 100 000 centollas macho de tamaño legal por milla náutica al cuadrado, con una gran incertidumbre asociada a estas estimaciones. En términos generales, se consideró que el régimen de pesca experimental fue exitoso. Si bien este régimen proporcionó información importante sobre la distribución de las centollas y ayudó en la evaluación de los indicadores de la reducción local para su uso en la evaluación del stock, es posible que el Grupo de Trabajo para la Evaluación de Peces de la CCRVMA (WG-FSA) considere apropiado revisar nuevamente el diseño de la fase 2 y la puesta en marcha de un estudio intensivo de marcado a gran escala.

Keywords: abundance estimates, crab, experimental fishery, *Paralomis spinosissima*, preliminary analyses, tagging experiments, CCAMLR

INTRODUCTION

The Commission has adopted an experimental harvest regime (EHR) for the crab fishery in Subarea 48.3. The EHR was initially adopted for a period of three fishing seasons (split-years 1993/94 to 1995/96) (CCAMLR, 1993) and has been extended (in a slightly revised format) for another three fishing seasons (to the 1997/98 split-year) (CCAMLR, 1995). The current EHR, to which all vessels participating in the Antarctic crab fishery must adhere, is set out in CCAMLR Conservation Measure 90/XIV.

Conservation Measure 90/XIV outlines the three phases of the EHR. Phase 1 requires crab fishing vessels to distribute their fishing effort over a wide area. Phase 1 should be undertaken at the beginning of the first season in which a vessel participates in the crab fishery; this phase is designed to provide an understanding of the spatial differences in the densities of Antarctic crabs (SC-CAMLR, 1993). Phase 2 should take place at the beginning of the second season in which a vessel participates in the crab fishery. In Phase 2, the fishermen select three small areas of approximately 26 n miles^2 and concentrate their fishing effort in each of these squares. Phase 2 is designed to determine whether depletion estimators can be used to estimate local abundances of Antarctic crabs and to provide information about crab movement (SC-CAMLR, 1993). Phase 3 of the EHR should be undertaken at the end of each vessel's second season of participation in the Antarctic crab fishery. During this phase the fishermen must return to the three squares they occupied during Phase 2 and re-concentrate effort in these squares. Phase 3 is designed to provide information about recovery/recruitment rates after depletion events (SC-CAMLR, 1993).

The FV *American Champion* is the only vessel which has participated in the EHR. The *American Champion* entered the Antarctic crab fishery in September, 1995 and initiated Phase 1 at this time. The vessel was fishing during the 1995 CCAMLR meeting, and initiated Phase 2 of the EHR immediately following the end of this meeting (when the vessel's second season of participation in the fishery began). This paper provides results from preliminary analyses of data collected during Phases 1 and 2 of the EHR. The *American Champion* left the Antarctic crab fishery at the end of January, 1996 to participate in Subarea 48.3's fishery for *Dissostichus eleginoides*. The *American Champion* has not returned to the crab fishery and did not conduct Phase 3 of the EHR, so there are no results presented for this phase.

The *American Champion* used square-shaped, steel-framed pots to fish for the target species, *Paralomis spinosissima*. The pots were fished on longlines, and 40 pots were usually attached to each line. Pots were spaced approximately 100 fathoms apart, so individual longlines were generally about 6.5 km long. The *American Champion* carried approximately 550 pots to the fishing grounds; each pot measured approximately 2.4 m x 2.4 m x 0.9 m and had two entrance tunnels measuring approximately 22.9 x 91.4 cm. The pots were mostly covered with 8.9 cm (stretch measure) mesh, but the two entrance tunnels were covered with 7.6 cm mesh (smaller mesh was used on the tunnels to make it easier for crabs to enter the pot). The pots were baited with frozen herring and the carcasses of various fishes caught as by-catch. Haul-specific soak times (measured as start haul time - start set time) varied between 25.5 and 305.3 hours. Soak times which were greater than about 72 hours were generally associated with strings that had been left on the fishing grounds while the *American Champion* returned to port. All soak times were probably sufficient to saturate the gear.

The data analysed in this paper were provided by scientific observers. There were usually two or three observers on the *American Champion* during the entire period in which the vessel participated in the Antarctic crab fishery. All of the analyses presented in this paper were conducted on data relating to legal-sized (minimum carapace width = 102 mm as specified in Conservation Measure 91/XIV) male *P. spinosissima*; catch rates (CPUE) are expressed in numbers of legal-sized males per pot. Additional data were collected on females, sub-legal males, and *Paralomis formosa*, and analyses of these data are currently in progress.

PRELIMINARY RESULTS AND DISCUSSION

Phase 1

The *American Champion* hauled 97 strings of gear while conducting Phase 1 of the EHR; summary statistics on data collected from these hauls are provided in Table 1. The vessel initiated Phase 1 on 31 August, 1995 and finished the phase on 29 September, 1995. In general, the vessel expended most of its fishing effort off the northern coast of South Georgia, but at least one haul was made in each of the 0.5° x 1.0° squares identified in Conservation Measure 90/XIV (see Figure 1). Haul-specific CPUE varied between 0.0 and 53.9 legal-sized males per pot, and the distribution of catch rates was positively skewed (see differences between mean and median CPUEs in Table 1).

Since the *American Champion*'s longlines measured about 6.5 km, each string of gear could potentially cover a wide range of depths. The start depth and end depth of each string was recorded in fathoms and two covariates were used to describe the depth of each string: 'mid-depth' and 'gradient'. Mid-depth was calculated as (start depth + end depth)/2, and gradient was calculated as max(start depth, end depth) - min(start depth, end depth). Both depth measures were expressed in fathoms. During Phase 1, strings were set at mid-depths ranging from 49.5 to 456.0 fathoms (approximately 91–834 m), and gradients ranged from 0 to 294 fathoms (approximately 0–538 m) (Table 1).

Pairwise, bivariate scatter plots of haul-specific string identification number, location (identified by the squares drawn in Figure 1), CPUE, mid-depth, and gradient are presented in Figure 2. This figure illustrates a number of important results. String identification number was correlated with both location and CPUE. In general, the *American Champion* began Phase 1 at the southern end of South Georgia and moved north and west as the phase progressed; as the vessel moved along the eastern and northern coasts of the island, CPUE first decreased and

Table 1: Summary statistics for data collected from hauls made by the FV *American Champion* during Phase 1 of the experimental crab fishery. The location of each square is identified in Figure 1. CPUE is in numbers of legal-sized males per pot. Mid-depth is calculated as (start depth + end depth)/2 and expressed in fathoms. Gradient is calculated as max(start depth, end depth) - min(start depth, end depth) and expressed in fathoms.

Square	No. of Sets	CPUE				Mid-depth				Gradient			
		Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max
A	4	15.4	22.2	28.4	53.9	205.0	240.0	267.9	386.5	20.0	85.0	88.3	163.0
B	19	10.8	17.4	19.3	40.8	162.0	259.5	248.3	340.0	44.0	101.0	107.6	263.0
C	16	0.1	11.3	14.2	36.6	68.5	198.8	202.2	333.5	11.0	54.5	57.6	141.0
D	14	0.0	6.4	8.4	25.2	85.0	221.5	236.3	438.5	11.0	57.5	75.0	294.0
E	1			6.35				158.5				67.0	
F	1			0.6				146.5				3.0	
G	7	0.1	2.1	2.5	7.3	101.0	128.0	162.0	277.0	9.0	20.0	71.1	253.0
H	7	0.0	0.0	0.3	2.0	49.5	71.0	86.1	173.5	3.0	10.0	17.7	66.0
I	5	0.0	0.0	1.9	9.2	179.0	381.0	329.3	456.0	14.0	96.0	83.8	145.0
J	3	4.1	4.1	5.8	9.2	265.5	298.5	291.8	311.5	53.0	109.0	150.3	289.0
K	14	0.0	3.2	5.5	23.8	63.0	97.0	118.0	257.5	0.0	13.5	19.1	99.0
L	6	1.4	6.5	7.4	17.2	53.5	96.0	97.8	149.0	3.0	11.0	22.3	80.0

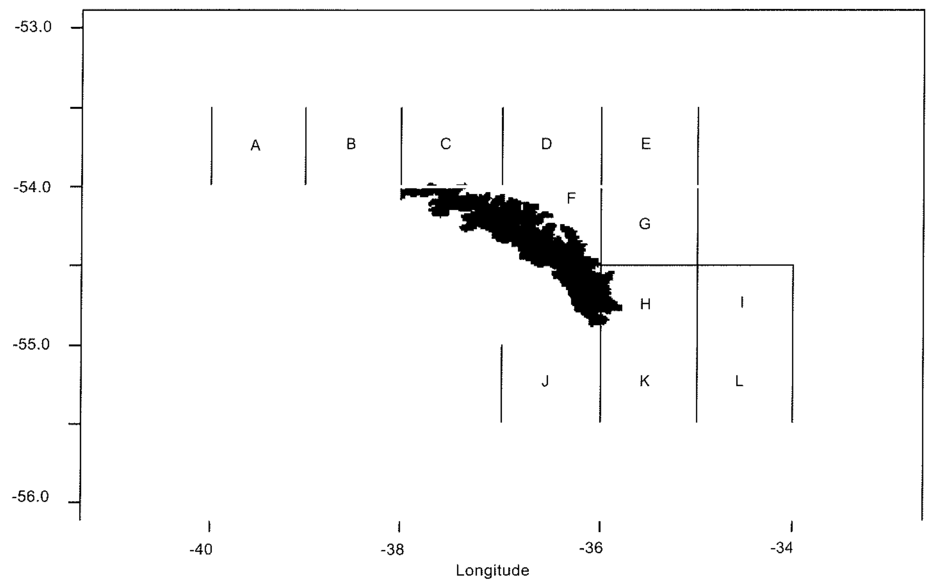

Figure 1: Squares designated for distribution of fishing effort during Phase 1 of Conservation Measure 90/XIV; the letters are used to identify each square.

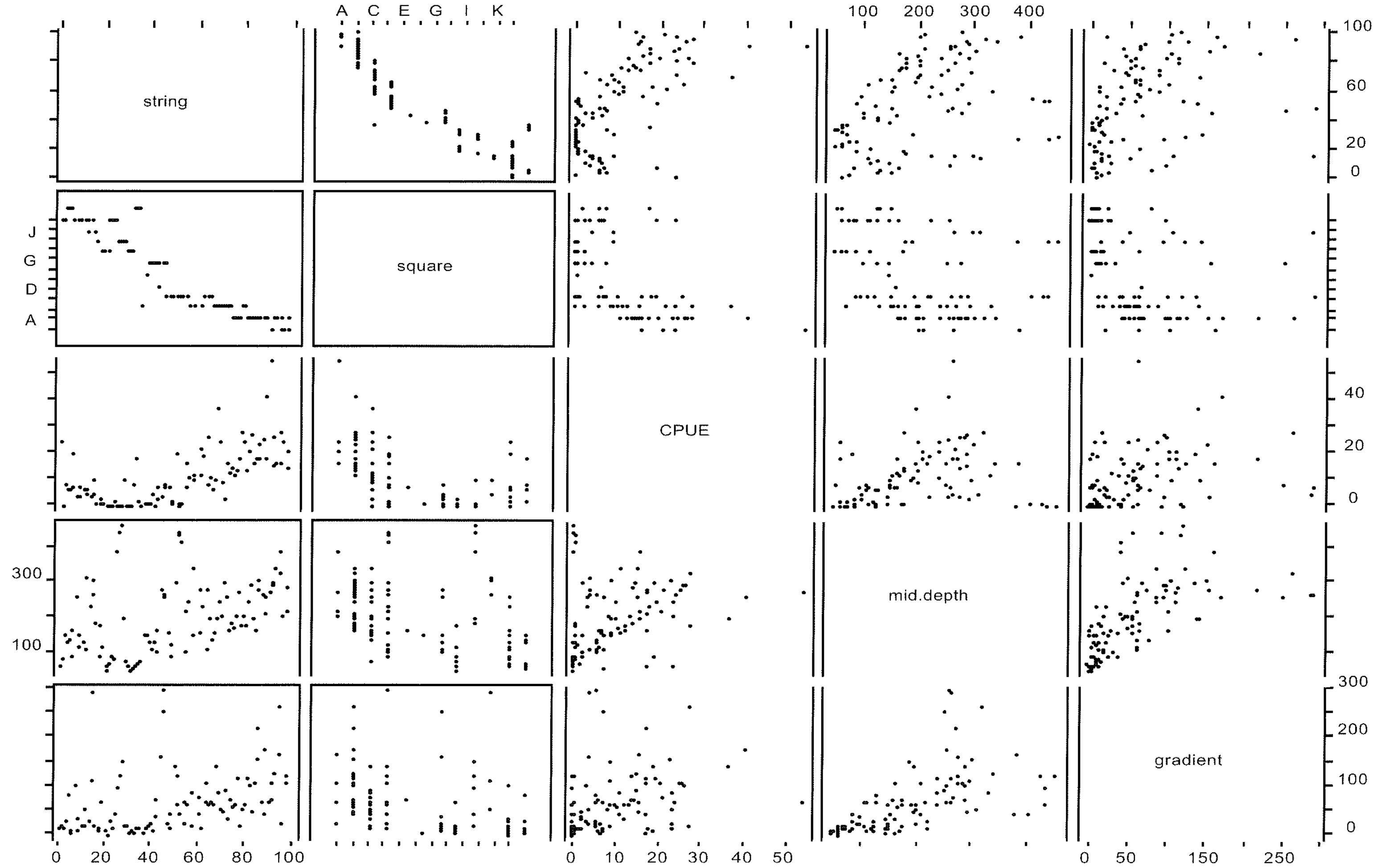

Figure 2: Pairwise scatter plots of haul-specific data collected during Phase 1 of the experimental crab fishery. The units for CPUE, mid-depth, and gradient are the same as given in Table 1.

then increased. CPUE was related to mid-depth, with the lowest catch rates being obtained on the shallowest and deepest hauls and intermediate to high CPUEs being obtained on hauls made at intermediate depths. Mid-depth and gradient were positively correlated. This correlation occurred because shallow sets were made on the continental shelf (where there is a weak bathymetric gradient) and deep sets were made on the continental slope (where, by definition, there is a strong bathymetric gradient).

Generalised additive models (GAMs) were used to model the data illustrated in Figure 2 and provide information on area- and depth-specific variation in the catch rates of legal-sized, male *P. spinosissima*. Since the catch rates from Phase 1 were not strictly positive (i.e. 10 out of 97 hauls had CPUE = 0), two different GAMs were applied to the data. One GAM was used to predict the probability of a positive CPUE and another GAM was used to predict the expected value of CPUE for positive hauls. The two GAMs were fitted and evaluated according to various techniques outlined in Hastie and Tibshirani (1990), Chambers and Hastie (1993), and Statistical Sciences (1995).

The first GAM modelled the probability of obtaining a positive CPUE by assuming that the presence or absence of legal-sized males in a single haul was the long-run outcome of the sum of numerous, independent Bernoulli trials where individual crabs were either captured or not captured (i.e. the model assumed a binomial error structure). In this context, the log-odds of obtaining a positive CPUE was modelled as a linear function of location (as designated by each square) and of smooth fits to mid-depth, and gradient:

$$\ln\left(\frac{\Pr(CPUE > 0|\mathbf{x})}{1-\Pr(CPUE > 0|\mathbf{x})}\right) = \alpha + \boldsymbol{b}\cdot\mathbf{area} + f(mid-depth) + f(gradient) + f(soak). \quad (1)$$

area was a matrix of column vectors denoting location according to a treatment contrast coding scheme, and ***b*** was a vector of coefficients for the effects of location. The variable *area* was a factor with three levels determined by where each string of gear was hauled (see Figure 1): Northern (hauls made in Squares A–D), Central (hauls made in Squares E–H), or Southern (hauls made in Squares I–L). The smooth terms in equation 1 (the *f*s) were modelled with smoothing splines. Significant terms in equation 1 were identified by a stepwise modelling procedure which used Akaike's Information Criterion as an objective function and included both forward and backward selection processes. The smoothing splines were parameterised with four degrees of freedom (*df*) during the stepwise procedure. The *df* of a smoothing spline can be adjusted and used as a smoothing parameter; higher *df*s provide less smoothing and greater local flexibility (Hastie and Tibshirani, 1990). After the stepwise procedure, any smooth terms which were retained in equation 1 were reparameterised with 3 *df*. The 3 *df* model was compared to the 4 *df* model with a χ^2 deviance test (Hastie and Tibshirani 1990). If the test was not significant at $\alpha = 0.05$, the 3 *df* model was adopted in favour of the 4 *df* model. A χ^2 deviance test was also performed to determine whether a 2 *df* model (a linear model) was more parsimonious than the 3 (or 4) *df* model. This latter test was also conducted at $\alpha = 0.05$.

The second GAM modelled the conditional expectation of a positive CPUE by assuming that the effects of area, mid-depth, and gradient were multiplicative and could be linearised by log-transformation:

$$\ln\left(CPUE_{\text{positive}}\right) = \alpha + \boldsymbol{b}\cdot\mathbf{area} + f(mid-depth) + f(gradient) + f(soak). \quad (2)$$

Equation 2 was fitted by assuming that the error distribution for a model of positive CPUEs was gamma; this assumption implies that the variance of CPUE is proportional to the mean CPUE squared (this is a model in which the coefficient of variation is constant). The significant terms in equation 2 were selected by a stepwise technique similar to that used for equation 1, and appropriate *df*s for the smooth terms (again modelled with smoothing splines) were also identified as per equation 1. The adequacy of the gamma-error assumption was addressed by a visual check of the residuals from the fitted model; heteroscedastic residuals on the raw (not log-transformed) CPUE scale were interpreted as an indication that the assumption was reasonable.

Mid-depth was significant in equation 1 (χ^2-test, $p < 0.05$), but area and gradient were not significant ($p > 0.05$). The final model for predicting the probability of obtaining a positive

CPUE was given by

$$\ln\left(\frac{\hat{\Pr}(CPUE > 0|\mathbf{x})}{1-\hat{\Pr}(CPUE > 0|\mathbf{x})}\right) = \hat{\alpha} + \hat{f}(mid - depth), \quad (3)$$

where the smooth term for mid-depth had 3 *df*. The smooth term for mid-depth was significantly different from a simple linear term ($p < 0.05$).

Predictions from equation 3 are illustrated in the middle panel of Figure 3. The binomial-error model predicted that the probability of obtaining a positive CPUE would decline dramatically at depths of less than about 100 fathoms and depths of more than about 300 fathoms. Sets made between about 100 and 300 fathoms (approximately 180–550 m) had an excellent chance of obtaining a positive CPUE ($\hat{\Pr}$ (CPUE > 0)≈1). The predicted probability of obtaining a positive CPUE declined more rapidly in shallow water than it did in deep water.

Area and mid-depth were significant in equation 2 (χ^2-test, $p < 0.05$), but gradient was not significant ($p > 0.05$). The final model for predicting the conditional expectation of positive CPUEs was given by

$$\ln(CPUE_{\text{positive}}) = \hat{\alpha} + \hat{\boldsymbol{b}} \cdot \mathbf{area} + \hat{f}(mid - depth). \quad (4)$$

The smooth term for mid-depth had 3 *df* and was significantly different from a simple linear term ($p < 0.05$). A visual check of residuals (on the raw CPUE scale) from equation 4 confirmed that the gamma-error model was appropriate for modelling the positive CPUEs; these residuals were heteroscedastic.

Predictions from equation 4 are illustrated in the upper three panels of Figure 3. In general, the gamma-error model predicted that the relationship between CPUE and mid-depth was dome-shaped with a peak between about 200 and 300 fathoms and low values in shallower or deeper water. The gamma-error model also predicted that between about 200 and 300 fathoms, catch rates are highest in the Northern area and lowest in the Central area. Catch rates in the Southern area were predicted to fall between those of the Northern and Central areas.

It should be noted that the smooth fit to mid-depth was sensitive to four hauls which obtained high catch rates from shallow locations in the Southern area (Figure 3, upper-left panel). These four points caused the fits to bend upwards at shallow depths (Figure 3, upper three panels). While these four points were definitely outside the trends defined by the bulk of the data, they have been checked and do not appear to be erroneous.

Predictions made by the gamma-error model were adjusted to account for the results of the binomial-error model and develop a composite picture of area- and depth-specific differences in CPUE. The adjusted predictions were estimated by multiplying the depth-specific expectations from the gamma-error model by depth-specific probabilities from the binomial-error model. The adjusted predictions are plotted in the lower three panels of Figure 3. For most of the depths sampled during Phase 1, the adjustment affected neither the shape of the relationship between CPUE and mid-depth nor the relative differences between area-specific CPUEs. However, the adjustment did remove the gamma-error model's tendency to predict increases in CPUE when hauls are made shallower than about 100 fathoms (Figure 3, bottom three panels).

Assuming that CPUE can be used as a proxy for the density of legal-sized male *P. spinosissima*, a number of interesting points can be raised from the results presented in Figure 3. First, although CPUE was generally predicted to decrease in shallow water, it is possible to find dense concentrations of legal-sized male crabs on the continental shelf. One might speculate that local crab densities in waters shallower than about 150 m are related to habitat. Six of the ten hauls that had zero catch rates were located high on the continental shelf where the bottom topography was relatively featureless. In contrast, the four shallow hauls that were made in the Southern area but had relatively high CPUEs (see Figure 3, upper-left panel) were near major bathymetric features like submarine canyons.

Dense concentrations of legal-sized male *P. spinosissima* are also likely to be difficult to find in deep water, but the decrease in CPUE for hauls made on the lower portion of the continental slope may have resulted from a combination of factors. It seems likely that the density of legal-sized male *P. spinosissima* actually decreases beyond depths of about 550 m; data presented in Watters (1994) show that mean crab size decreases with increasing depth and suggest an onshore, ontogenetic migration. It is also possible, however, that the gear was not fishing effectively

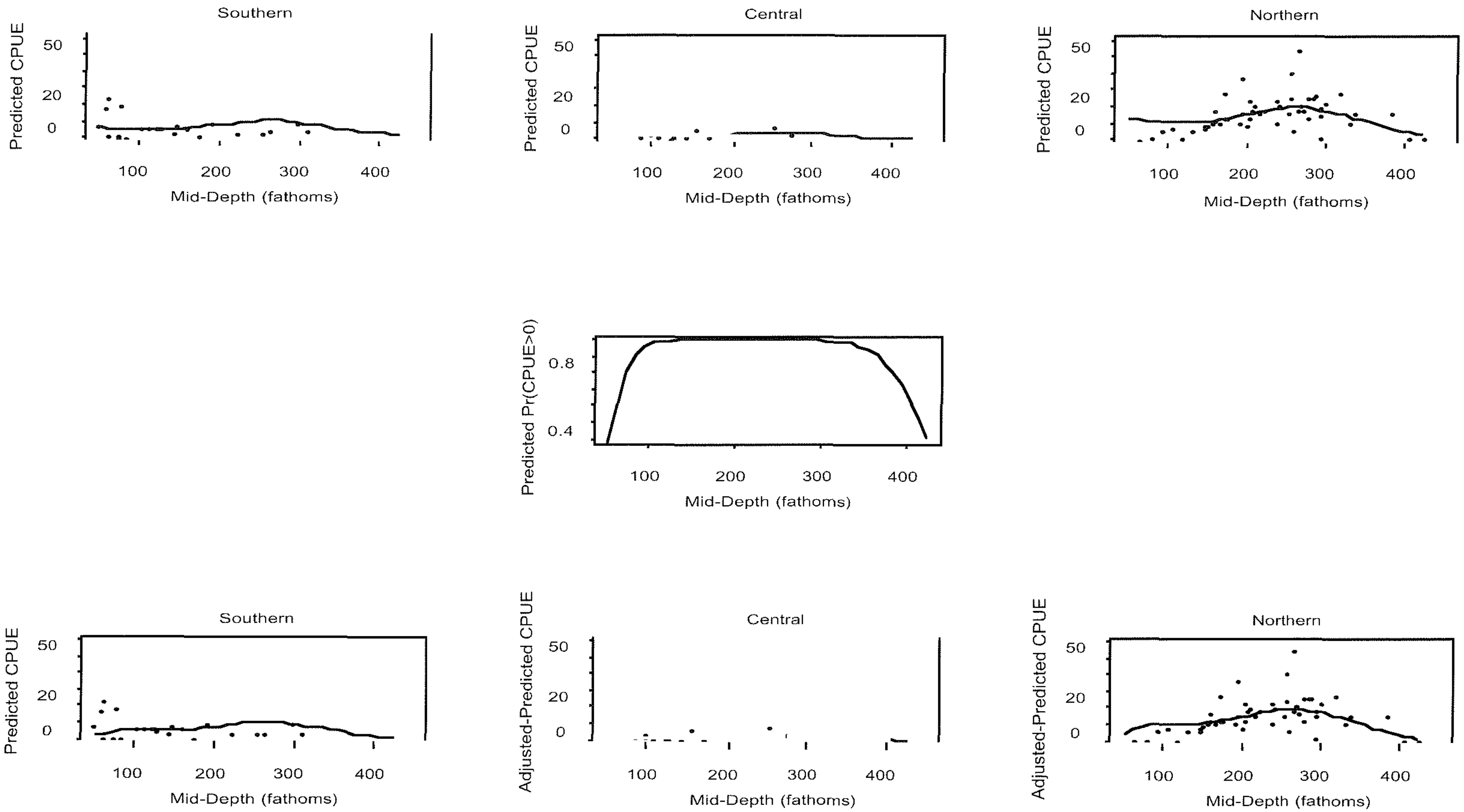

Figure 3: Results of fitting generalised additive models (GAMs) to CPUE data collected during Phase 1 of the experimental crab fishery. See the text and Figure 1 to identify the boundaries of the Southern, Central, and Northern areas. The upper three panels illustrate the fit of the GAM with gamma errors and log-link to the positive CPUE data. The middle panel shows the trend in predicted probability that CPUE is greater than zero. The lower three panels illustrate how the predicted CPUEs from the gamma model are adjusted for the relative absence of positive CPUEs at shallow and deep depths.

at depths greater than about 550 m. Since mid-depth and gradient were strongly correlated (see Figure 2), the deeper hauls were also made on steeper grounds and it seems possible that crab pots may be less effective if the bottom is steeply sloped because the gear may not land on the bottom correctly. Personal communications with the skipper and mates of the *American Champion* confirm that it is more difficult to set and haul gear on extremely steep grounds, but the fishermen also felt that such grounds were productive.

It is difficult to say why depth-specific CPUEs were observed (and predicted) to be higher in the Northern area than in either the Central or Southern areas. As previously noted, CPUE was strongly correlated with string identification number so it is possible that the area-specific trends in CPUE were influenced by fishermen gaining experience. However, since the *American Champion* fished over a wide depth range in all three areas, it seems more likely that area-specific differences in CPUE reflect actual differences in crab densities. Also, personal observations suggest that, when making decisions about how to fish their gear, the fishermen relied much more upon experiences from Alaskan and Russian crab fisheries than they did upon limited prior experience at South Georgia. Unfortunately, there are no data available which might be used to attribute certain biological or physical factors to increases in crab density along the northern coast of South Georgia.

If the area-specific differences in CPUE mirror area-specific differences in the densities of legal-sized male crabs, the results of Phase 1 suggest that localised estimates of crab standing stock should not be extrapolated to the remainder of Subarea 48.3 solely on the basis of seabed area. At the very least, seabed area extrapolations of localised standing stock estimates should be modified to account for the fact that crab densities are probably low along the eastern coast of the island and at depths of less than about 150 m.

Phase 2

The *American Champion* initiated Phase 2 of the EHR on 2 November, 1995 and finished the phase on 20 November, 1995. During this period, the vessel hauled 79 strings of gear which were set in three squares located off the northwestern tip of South Georgia (see Figure 4, upper-left panel). The hauls were distributed near the western and eastern boundaries of Squares 1 and 2 but were more evenly distributed throughout Square 3 (Figure 4, upper-right panel). In general, hauls in Square 3 had higher CPUEs, shallower mid-depths, and gentler gradients than hauls in Squares 1 and 2 (Table 2).

As a simple consistency check, the CPUEs obtained during Phase 2 were compared to predictions made by the GAMs used to standardise the CPUEs from Phase 1 (i.e. equations 3 and 4). Most of the hauls made during Phase 2 were set within the range of depths (about 100–300 fathoms) at which, from the binomial-error GAM (equation 3), the predicted probabilities of obtaining positive CPUEs were approximately equal to 1.0 (see Figure 3, middle panel). Consistent with such predictions, all of the hauls made during Phase 2 had CPUE > 0. Noting that all of the Phase 2 hauls were made in the Northern area and plugging in the minimum and maximum mid-depths fished in each depletion square, the gamma-error GAM (equation 4) predicted that expected CPUEs should be approximately within the range [2, 18] in square 1, [16, 20] in square 2, and [10, 11] in square 3. The mean CPUE actually obtained from square 1 fell within the range predicted by equation 4, but this was not true for the mean CPUEs actually obtained from squares 2 and 3 (compare the mean CPUEs listed in Table 2 to the ranges listed above). Despite these differences between predicted and actual values, the CPUEs obtained during Phase 2 were, in fact, similar to those obtained from square A during Phase 1 of the EHR. During Phase 1, CPUEs in square A (the region where all three depletion experiments were conducted) fell in the approximate range [15, 54] (Table 1).

Phase 2 was designed to assess whether depletion estimators could be used to provide local estimates of crab abundance (see SC-CAMLR, 1993), so Leslie's method (as given in Ricker, 1975) was used to estimate the pre-fishing standing stock in each of the three squares identified in Figure 4. The method involved fitting straight lines to time-ordered, haul-specific CPUE and cumulative catch data:

$$CPUE_{s,i} = qN_{s,0} + qK_{s,i} = \alpha_s + \beta_s K_{s,i}. \qquad (5)$$

$K_{s,i}$ is the cumulative catch in square s up to and including the ith haul; q is the catchability coefficient; and $N_{s,0}$ is the pre-fishing abundance

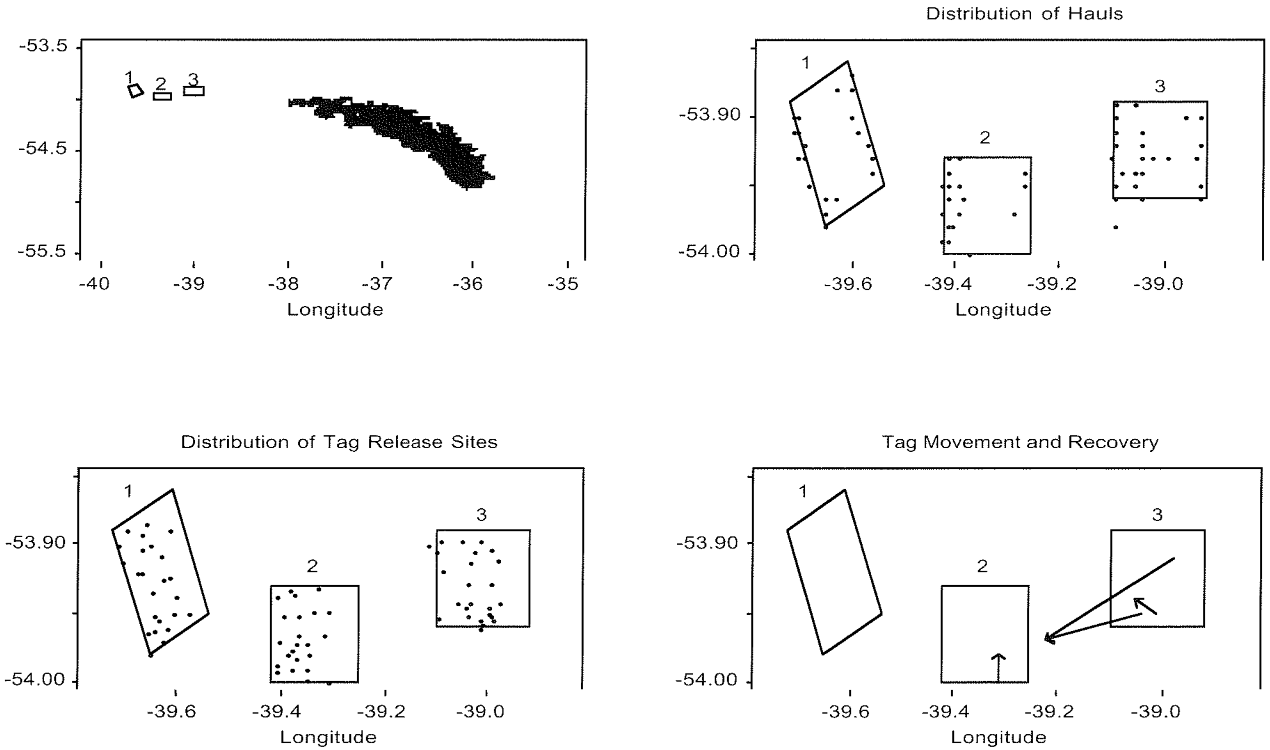

Figure 4: Spatial distributions of fishing and tagging effort expended during the FV *American Champion*'s participation in Phase 2 of the experimental crab fishery. Arrows in the lower-right panel point from a recaptured crab's release location to its recapture location.

Table 2: Summary statistics for data collected from hauls made by the FV *American Champion* during Phase 2 of the experimental crab fishery. CPUE, mid-depth, and gradient are expressed in the same units as the results presented in Table 1.

Square	No. of Sets	CPUE				Mid-depth				Gradient			
		Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max
1	24	7.6	15.2	16.3	27.7	220.5	271.0	273.8	459.5	19.0	66.5	74.3	141.0
2	20	7.7	22.0	26.2	58.0	208.5	230.0	231.4	252.0	31.0	66.0	57.9	93.0
3	35	13.1	42.8	41.9	77.9	88.5	98.0	96.5	105.5	4.0	23.0	22.0	38.0

Table 3: Results of fitting Leslie models to CPUE and cumulative catch data collected during the FV *American Champion*'s conduct of the three depletion experiments in Phase 2 of the experimental crab fishery.

	Square 1	Square 2	Square 3
Intercept	14.2999	38.4544	35.4948
Slope	0.0003	-0.0009	0.0002
R^2	0.0542	0.1900	0.0596
Residual *df*	22	18	33
p	0.2735	0.0547	0.1575

in square *s*. It was assumed that the crabs did not suffer natural mortality during the course of each depletion experiment. Given the short time period of each depletion experiment (approximately one week each), this assumption seems reasonable. Equation 5 also requires the assumption that CPUE is proportional to abundance (with proportionality constant q), and, in principle, any proportional index of abundance can be substituted for $CPUE_{s,i}$. In this regard, one might be tempted to standardise the Phase 2 CPUEs with the GAMs developed from Phase 1 of the EHR, and then use this standardised index of abundance as the response variable in equation 5. Such an approach does not, however, seem appropriate because the standardised CPUEs would not be dependent on the cumulative catch (recall that the GAMs only included area and depth effects). A better approach would be to standardise the Phase 3 CPUE trends and fit the depletion models in one step; this might be a promising topic for future work.

Equation 5 was fitted to each depletion experiment's raw CPUE and cumulative catch data, and the parameters α_s and β_s were estimated by least squares. None of the depletion experiments resulted in a significant depletion event ($p > 0.05$ for each test of H_0: $\beta_s = 0$), but the result for square 2 was marginal ($p = 0.0547$) (Table 3). Models fitted to the data from Squares 1 and 3 actually had positive slopes (Table 3). The results of the three depletion experiments are illustrated in Figure 5. The absence of significant depletion effects prevented estimation of pre-fishing standing stocks ($N_{s,0}$). Note that fitting equation 5 by least squares assumes that CPUE has constant variance. While this feature is not consistent with the gamma-error GAM used to analyse CPUEs from Phase 1 (this GAM was developed under the assumption that CPUE has constant coefficient of variation), the residuals from fitting equation 5 by least squares were not heteroscedastic. It may be worthwhile to orient future work towards identifying the most appropriate error structure for modelling crab CPUEs (e.g. constant variance, variance proportional to mean CPUE, or variance proportional to mean CPUE squared).

There are a number of ways to explain the insignificance of the three depletion experiments. First, local crab abundance may have been so high that the *American Champion* could not deplete an area of approximately 26 n miles^2 in one week. It is unknown how many crabs would have to be caught out of an area of 26 n miles^2 to detect a declining trend in CPUE. Second, trends in CPUE may have been difficult to detect because there was a great deal of inter-haul variability in CPUE; catch rates varied by more than 50 crabs per pot on successive hauls (Figure 5). As previously mentioned, it might be fruitful to develop a method of standardising CPUEs (i.e. accounting for significant sources of variation in CPUE) and fitting the depletion model in a single analysis. Third, the depletion squares may not have been closed to immigration and emigration. If crab movement is simply random, and immigration balances emigration, equation 5 may still be a valid model. If, however, crabs have directional movement patterns, equation 5 may have to be modified to include immigration and emigration rates. Fourth, catchability may not have been constant during the course of each depletion experiment. A change in catchability could have resulted from fishermen gaining experience and resulting changes in fishing strategy during the course of a depletion experiment. Alternatively, catchability may have changed if some crabs were more vulnerable to fishing than others (e.g. some males were more active and encountered pots more frequently than others), and the more vulnerable crabs were captured early in the depletion experiments.

It is difficult to know which of the four explanations is responsible for the insignificant results of Phase 2; the first three explanations are all likely. The data presented in Figure 5 cannot be used to discount the first explanation (catches were too small to cause depletion events), and,

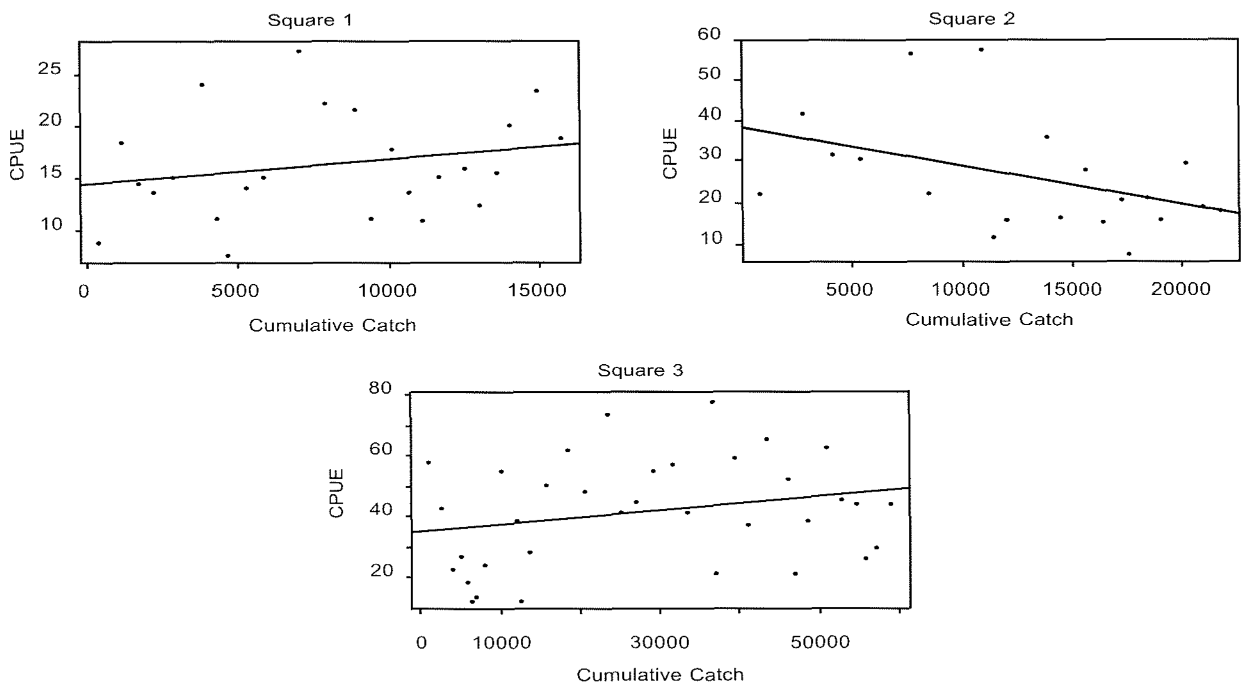

Figure 5: Results of the FV *American Champion*'s Phase 2 depletion experiments.

obviously, these data also support the second explanation (highly variable CPUE). The third explanation (crab movement) is supported by data from a small mark-recapture study (see the following section). There are two reasons why the fourth explanation (nonstationary catchability) is probably not supportable. First, the *American Champion* had been participating in the fishery for about 2 months prior to Phase 2, and it seems likely that the fishermen would have settled into a particular fishing strategy during this period of time. Second, if catchability changes because of differential vulnerability there is often curvature in the cumulative catch–CPUE relationship, and this was obviously not observed (Figure 5).

Although local estimates of standing stock could not be made from the data collected in Phase 2, the depletion experiments provided valuable information; it appears that local depletion estimators will not be appropriate tools for estimating local abundances of *P. spinosissima*. It is important to emphasise that although the depletion experiments did not work on a local scale, Phase 2 did not provide information about the utility of applying depletion estimators on larger temporal and spatial scales. It is not known whether depletion models can provide estimates of crab abundance when larger areas are considered and larger catches are taken.

Tagging Studies Conducted during Phase 2

Approximately 2 000 crabs were tagged and released in each of the three depletion squares (about 6 000 total crabs were tagged and released) occupied by the *American Champion* during Phase 2 of the EHR. The marked crabs were released at 74 locations in groups of about 50 to 100 crabs, and the release sites were distributed throughout each of the three depletion squares (Figure 4, lower-left panel). The tagged crabs were released at depths from 82 to 362 fathoms over the period 4 to 19 November, 1995. Approximately 5 000 crabs were marked with Floy t-bar anchor tags; these tags were inserted into the abdominal musculature. The remaining crabs were marked with spaghetti tags; these tags were also inserted into the abdominal musculature.

Four of the marked crabs were recovered; all four of these crabs were legal-sized males (carapace width > 102 mm) which were collected in the *American Champion*'s processing plant. One of these crabs was released in the second depletion square, and the remaining three crabs were released in the third depletion square. Summary information about the recaptured crabs is provided in Table 4. All four crabs were released near the end of the tagging period; the four crabs were at liberty for about one to five weeks. The crabs were released at depths from

Table 4: Tag recovery information for animals marked during Phase 2 of the experimental crab fishery.

Tag No.	Date Released	Days at Liberty	Release Depth	Recapture Depth	Distance Travelled	Direction Travelled	Min Rate
3872	15 Nov	8	198	205	1.1	N	0.14
4206	16 Nov	30	92	117	2.5	NW	0.08
4128	16 Nov	36	95	156	7.6	SW	0.21
4540	16 Nov	36	82	156	9.0	SW	0.25

82 to 198 fathoms and recovered at depths from 117 to 205 fathoms. All four crabs were recaptured from locations that were deeper than where they were released. The four crabs moved minimum distances of 1.1 to 9.0 n miles while at liberty, and dividing the distances travelled by the days at liberty estimated minimum movement rates to be from 0.08 to 0.25 n miles/day (the distances and rates travelled are minimum estimates because these are straight line distances between release and recapture sites, and the crabs may not have travelled in a linear fashion). Release and recapture positions are plotted in the lower-right panel of Figure 4. The tag recovery data suggest that individual *P. spinosissima* are capable of moving appreciable distances, and it seems likely that crab movement played a role in the insignificance of the Phase 2 depletion experiments. The recapture data indicate that the depletion squares were not closed to immigration and emigration.

The tag recovery data also suggest that individual *P. spinosissima* are capable of directed movements. The two crabs marked with tag numbers 4128 and 4540 (see Table 4) were initially captured in different hauls and released approximately 3 n miles away from each other. Despite being released at different locations, these two crabs were recaptured in the same haul 36 days later (see Figure 4, lower-right panel). It should be noted, however, that the possibility of directed movement in *P. spinosissima* is speculatory, and there is no information about what factors might cue directed movement in this species. Note again, however, that all four recaptures were taken from locations that were deeper than their respective release locations (Table 4).

There is no information about discard mortality on sub-legal or female *P. spinosissima* which are returned to the sea under the requirements of Conservation Measure 91/XIV, but the recovery of four marked crabs provides some evidence that not all discarded crabs will die.

The mark-recapture data were used to obtain three estimates of crab density in the area surrounding the third depletion square. Chapman (in Ricker 1975) provided a formula for making an unbiased estimate of population size ($\hat{N}$) from mark-recapture data:

$$\hat{N} = \frac{(M+1)(C+1)}{(R+1)}. \quad (6)$$

M is the number of marked crabs released; C is the total number of crabs caught after the tagged individuals were released; and R is the number of recaptures. The large-sample sampling variance for $\hat{N}$ was also given by Chapman (in Ricker 1975):

$$\text{var}(\hat{N}) = \frac{\hat{N}^2(C-R)}{(C+1)(R+2)}. \quad (7)$$

The density of crabs can be estimated from the results of equation 6:

$$\hat{d} = \frac{\hat{N}}{A}. \quad (8)$$

A is the area over which density is being estimated. The estimator for the variance of $\hat{d}$ is given by

$$\text{var}(\hat{d}) = \frac{\text{var}(\hat{N})}{A^2}, \text{ and} \quad (9)$$

the coefficient of variation for $\hat{d}$ is

$$CV(\hat{d}) = \frac{\sqrt{\text{var}(\hat{d})}}{\hat{d}}. \quad (10)$$

Equations 6 to 10 were used to estimate crab abundance and density, and, where possible, the input values (M, C, R, and A) were adjusted to

Table 5: Inputs and estimates from mark-recapture data collected by the FV *American Champion*. Estimated abundances ($\hat{N}$) are for legal-sized male *P. spinosissima*, and density estimates ($\hat{d}$) are given in crabs per n mile^2.

	Movement Rate (n mile/day)		
	0.08	0.21	0.25
M	810	810	810
C	52615	81183	86724
R	3	3	3
A (n mile^2)	82	290	366
$\hat{N}$	1.1×10^7	1.6×10^7	1.7×10^7
var($\hat{N}$)	2.3×10^{13}	5.4×10^{13}	6.2×10^{13}
$\hat{d}$	1.3×10^5	5.7×10^4	4.8×10^4
var($\hat{d}$)	3.4×10^9	6.4×10^8	4.6×10^8
CV($\hat{d}$)	0.45	0.45	0.45
95% CI for $\hat{d}$	$(5.3 \cdot 10^4, 3.3 \cdot 10^5)$	$(2.3 \cdot 10^4, 1.4 \cdot 10^5)$	$(2.0 \cdot 10^4, 1.2 \cdot 10^5)$

account for possible violations in the assumptions of this mark-recapture estimator (see the following two paragraphs).

At a minimum, equations 6 to 10 require the following assumptions (see Ricker, 1975):

(i) marked crabs suffer the same natural mortality as unmarked crabs;

(ii) marked crabs and unmarked crabs are equally vulnerable to the fishing gear;

(iii) marked crabs do not lose their tags;

(iv) marked crabs mix randomly with unmarked crabs OR the distribution of fishing effort during the recapture period is proportional to the areal distribution of crab numbers;

(v) marked crabs are recognised and reported; and

(vi) recruitment to the catchable population of crabs is negligible during the recapture period (Ricker, 1975).

Data were not available to determine whether or not assumptions 1 to 4 were violated during the *P. spinosissima* tagging study, but assumptions 5 and 6 were probably violated. It seems likely that the fifth assumption was violated because recaptured crabs were only identified in the *American Champion*'s processing plant; thus sub-legal males or females were likely to be thrown overboard without being carefully inspected for tags. The crab movement results provided in Table 4 and illustrated in the lower-right panel of Figure 4 suggest that the study area was not closed to recruitment and that the sixth assumption was also violated.

Input values for equations 6 to 10 are provided in Table 5. An attempt was made to account for assumption 5 by limiting M to the number of legal-sized males released in the third depletion square and limiting R to the number of legal-sized males recaptured from these M releases. An attempt was made to account for assumption 6 by limiting C to catches made within 36 days (the maximum time at liberty from Table 4) of when the final marked crab was released. The variable C was also limited to catches made within the area defined by the intersecting arcs of circles drawn around all of the tag release sites in the third depletion square. The circles were drawn with radii of approximately 3, 7.5, and 9 n miles (radial distances derived from multiplying 36 days at liberty by the movement rates provided in Table 4). Limiting C in these two ways may have accounted for crabs moving away from their release sites, but it was not possible to account for the immigration of crabs into the mark-recapture study area.

Confidence intervals for $\hat{N}$ were approximated by application of the Poisson distribution (see Ricker 1975). The lower and upper 95% confidence bounds for $\hat{N}$ were computed by respectively substituting the values 0.6 and 8.8 for R in equation 6 (these values were taken from Appendix II in Ricker, 1975). The lower and upper 95% confidence bounds for $\hat{d}$ were estimated by substituting the corresponding bounds for $\hat{N}$ into equation 8.

Estimates of standing stock from the mark-recapture data are presented in Table 5. The highest density estimate ($\hat{d}$ = 1.3 x 10^5 for a movement rate of 0.08 n miles/day) was approximately twice as large as the lowest density estimate ($\hat{d}$ = 4.8 x 10^4 for a movement rate of 0.25 n miles/day), but there was a lot of uncertainty associated with all three density estimates (CV = 0.45 for all three movement rates). 95% confidence intervals for $\hat{d}$ generally spanned an order of magnitude (Table 5).

Since assumption 6 (no recruitment to the population of unmarked crabs) was probably violated, the results presented in Table 5 are likely to be overestimates of standing stock (Ricker, 1975). Given this caveat, the following calculation should be considered with caution. Using Table 5's smallest, lower 95% confidence bound for $\hat{d}$ (2.0 x 10^4 crabs/n mile^2) and a mean crab weight of 0.80 kg/crab gives an estimated density of 16 tonnes of fishable *P. spinosissima* per square nautical mile. It is interesting to note that this density estimate is not very different from an estimate previously obtained by the CCAMLR Working Group on Fish Stock Assessment (WG-FSA) (17 tonnes/n mile^2 in SC-CAMLR, 1992) when the Working Group considered the effective fishing area of a string of crab pots. The Working Group extrapolated its previous density estimate to the whole of Subarea 48.3 on the basis of seabed area, but if the mark-recapture density estimate is extrapolated to a larger area it would be important to consider the fact that the tagging study was conducted in an area and over depths where the densest concentrations of *P. spinosissima* are thought to occur (see the results from Phase 1).

GENERAL REMARKS ABOUT THE EHR

The EHR has been successful in providing valuable information to WG-FSA. The aim of Phase 1 was to gather information about the distribution of *P. spinosissima* in relation to depth strata within designated blocks around South Georgia and to determine whether seabed area extrapolations of local density estimates are appropriate estimators of standing stock (SC-CAMLR, 1993). Phase 1 certainly accomplished this objective; if local density estimates are extrapolated, location should be considered as well as depth. The aim of Phase 2 was to determine whether depletion estimators could be used to estimate local densities (SC-CAMLR, 1993), and the results of Phase 2 suggest that this approach is not appropriate for *P. spinosissima*.

Despite these successes, WG-FSA may want to re-evaluate the EHR. Specifically, it may be worthwhile to consider whether a wide-scale, intensive tagging study could be developed to provide information for a crab stock assessment. Such a study may be expensive and require that fishermen be trained to identify and report recaptured tags, but the potential benefits of a tagging study may be greater than attempting to study catch and effort data.

ACKNOWLEDGEMENTS

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nasa. La profundidad media se calcula como (profundidad inicial + profundidad al término)/2 y se expresa en brazas. El gradiente se calcula como (prof. inicial, prof. terminal) máxima - (prof. inicial, prof. terminal) mínima y se expresa en brazas.

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