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Update on the status of scallops in Scallop Production Area 4 in the Bay of Fundy for 2000

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Abstract

This document presents an update on the stock status of scallops in Scallop Production Area (SPA) 4 on the eastern side of the Bay of Fundy, taking into account the 1999 fishery and the 2000 research survey. Landings in 1999 were 79 t against a TAC of 120 t. The fishing industry had reported that fishing in 1999 was restricted by poor weather and the fishery was extended by one month into January 2000. However, there were few days in January when the weather was good enough for fishing. The 2000 research survey indicated that the abundance of commercial size scallops (shell height $\geq$ 95 mm) has declined from 1999. There were signs in the 2000 survey of better than average recruitment of the 1997 year-class (shell height of 70 to 94 mm) in water less than 90 m depth, for the 2001 fishery. There were also large numbers of 1998 year-class (shell height of 25–50 mm) observed in the survey in both SPA 4 and adjacent SPA 1. While this year-class would not recruit to the fishery until 2002/2003, the location of the year-class could expose it to increased incidental mortality due to fishing activity. Fishing mortality of commercial size scallops in 1999 had decreased from 1998 to about the 1991–99 average. The modified DeLury population model used for the first time in the assessment of the 1998 fishery was used here with new definitions of fully-recruited scallops and recruits. Estimates from this model indicate that a TAC of 120 t in 2000 would result in a fishing mortality of 0.19 on the population of commercial size scallops. A continuation of effort at the recent level of 9000 hours per year would result in an expected removal of not more than 90 t (F = 0.14). Continuation of a full-fledged fishery in SPA 4 in the near-term runs the risk of increasing incidental mortality on the 1998 year-class, thus reducing its potential contribution to the future fishery in this area.

Résumé

Ce document présente une mise à jour de l'état du stock de pétoncles dans la zone de production du pétoncle (ZPP) 4 située du côté est de la baie de Fundy, mise à jour qui tient compte de la pêche de 1999 et du relevé de recherche effectué en 2000. En 1999, les débarquements ont atteint 79 t, alors que le TAC était de 120 t. L'industrie ayant signalé que la pêche de 1999 était limitée par le mauvais temps, la pêche a été prolongée d'un mois, jusqu'en janvier 2000, mais il n'y a eu que peu de jours en janvier pendant lesquels le temps était assez clément pour la pêche. Le relevé de recherche de 2000 a montré que l'abondance des pétoncles de taille commerciale (hauteur de la coquille $\geq$ 95 mm) avait diminué depuis 1999. Le relevé porte à croire que, dans des eaux de profondeur inférieure à 90 m, le recrutement de la classe d'âge de 1997 (hauteur de la coquille allant de 70 à 94 mm) à la pêche de 2001 sera supérieur à la moyenne. On a aussi observé un grand nombre de pétoncles de classe d'âge de 1998 (hauteur de la coquille allant de 25 à 50 mm) dans la ZPP 4 et la ZPP 1 adjacente. Bien que cette classe d'âge ne sera pas recrutée à la pêche avant 2002 ou 2003, sa présence dans un secteur activement pêché pourrait l'exposer à une forte mortalité accessoire. En 1999, la mortalité par pêche de pétoncles de taille commerciale a baissé par rapport à celle de 1998 pour atteindre environ la moyenne pour les années 1991 à 1999. Utilisé pour la première fois dans l'évaluation de la pêche de 1998, le modèle de population DeLury modifié a été appliqué en redéfinissant les pétoncles pleinement recrutés et les recrues. Le modèle

indique que l'atteinte d'un TAC de 120 t en 2000 se traduirait par une mortalité par pêche de 0,19 pour la population de pétoncles de taille commerciale. Si le niveau récent d'effort de pêche de 9 000 heures par année était maintenu, les captures ne devraient pas dépasser 90 t ($F = 0,14$). La poursuite à court terme d'une pêche complète dans la ZPP 4 risquerait d'accroître la mortalité accessoire de la classe d'âge de 1998, réduisant ainsi sa contribution éventuelle à la pêche future dans cette zone.

Introduction

The 1999 stock assessment for scallops in Scallop Production Area 4 (SPA 4, Fig. 1) was unable to provide catch advice for the 2000 fishery (Smith et al. 1999). The modified DeLury population model (Collie and Sissenwine 1983, Conser 1995) was used to evaluate the level of fishing mortality and the current status of the stock. Smith et al. (1999) reported that while the model seemed to capture a plausible trend for the population abundance over time, estimates of total population numbers and biomass appeared to be too large, especially given the results from a companion Lesley analysis presented in the same report.

While the estimates of fishing mortality from the two analyses differed in magnitude they both indicated that fishing mortality had been increasing since 1996. Research survey estimates of recruitment showed a decline in 1999 from 1998 and estimates from the DeLury model showed that current levels of recruitment would not balance the losses due to natural mortality alone and therefore the population was in decline. However, estimates of population biomass from the DeLury model were considered to be too high and therefore, we had no idea what proportion of the population was being removed by the fishery. As a result, TAC advice for the 2000 fishery, scheduled to open 1 October, was not given in the stock status report (DFO 1999) to allow time to conduct further research into the model and the data that it uses.

In the time following the publication of Smith et al. (1999), a relational database was constructed for the research survey data and changes have been made to the data as a result of improved editing procedures. In addition, the calculation of the distance covered by each tow has been revised which has also resulted in changes to the data.

The lack of information on the spatial variability of meat weight-at-shell height during the fishing season was identified as a possible problem with the DeLury model analysis. Industry offered one of their vessels to conduct a survey of SPA 4 early in 2000 to collect the necessary information on meat weights. The initial analyses of the data from this survey and comparison with meat weight/shell height data from the June research surveys is presented here.

Information on the 1999 fishery is presented here along with estimates from the June 2000 research survey. We also present the recalculated 1991–1999 research survey series, accounting for the changes due to improved editing and new tow distances. Thereafter, we have re-evaluated and updated each of the data series used in the previous application of the DeLury model.

The Fishery

The 1999 fishing season in SPA 4 had been originally set from 1 October to 31 December[1] with a meat count restriction of 45 meats per 500 g and shell height minimum of 95 mm. A total of 55 of the 99 vessels licensed to fish in this area participated in the the 1999 fishery. While not all of the licensed vessels fished in 1999, quota transfers between vessels did occur which resulted in all of the quota being available for fishing. The TAC was set at 120 t but only 76.7 t had been landed by 31 December. The fishing industry reported that poor

[1]Except for an area 1 mile from shore which was closed to scallop fishing due to the lobster fishery.

weather had restricted the opportunity to fish and an extension of the season to 31 January 2000 was granted by the department. However, there were few days in January when the weather was good enough for fishing and only an additional 2.2 t was landed.

Scallop Production Area 4 Landings (metric tons meats)

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999[2]
Total	678.7	318.4	244.2	162.7	94.8	71.2	116.1	103	78.9
Kg/h	28.55	18.75	14.73	11.84	10.60	8.89	12.81	9.41	8.91
TAC							100	120	120

[2] Preliminary data.

Landings have remained low in recent years after the fishing down of the large 1984 and 1985 year-classes in the late 1980's and early 1990's (Fig. 2, Table 1). Fishing effort has declined in the last two years and remains low compared to most of the previous years (Fig. 3, Table 1). Note that while the Inside Zone portion of SPA 4 was closed in 1995, fishing continued in the 6 to 8 mile portion of the zone. Catch rates continued to decline from 1997 with the 1999 catch rate being the lowest in the recent series as well as for the historic series which includes the fishery in the Inside Zone (Fig. 4, Table 1).

In 1998, the fishery was mainly concentrated in the deeper waters off Gulliver's Head and Centreville where previous research surveys had shown to be areas of high density but low meat yield (Figs. 5 and 6). In 1999, the fishery generally concentrated in the more traditional areas off Digby Gut and Delaps Cove where meat yields are generally higher (Figs. 7 and 8).

Currently the only information on size composition of the catch comes from fishermen voluntarily allowing departmental contractors to sample their catch. While blending of different size meats does occur, it appears from the samples collected that the regulated meat count of 45/500 g was being respected (Table 2). However, few vessels participate in the meat weight sampling program and therefore sampling intensity is quite low. In addition, the samples do not represent catches over the entire area of SPA 4 and samples of catches in the deeper water are not usually obtained (Figs. 9 and 10). In 2000, an industry-based system for collecting meat weight samples has been put into place which will result in higher sampling intensities and more spatial coverage where the catches have been taken.

Research Surveys

Annual stock surveys are conducted every June in SPA 4 to monitor stock abundance and detect incoming recruitment. Since 1991, the stratified random design has been used with strata defined to correspond to historical patterns of fishing effort and named according to adjacent landmarks (Fig. 11).

Surveys are conducted using the research vessel **J.L. Hart**. The four-gang dredge gear configuration has remained unchanged throughout the survey series (Kenchington et al. 1997). Each year, two of the four dredges were lined with 38 mm polypropylene stretch mesh. Catches in the lined gear were used to estimate the abundance of scallops with shell height less than 80 mm while the catches from the unlined gear were used to estimate the abundance of scallops with shell heights greater than or equal to 80 mm. Catches of scallops with shell heights less than 40 mm are thought to give qualitative indications of abundance only, due to uncertainties about catchability of the small animals.

New survey series

All catches from the survey are prorated to the expected catch of a seven-gang Digby gear rig and numbers are standardized to a standard tow distance of 800 m. Changes made in 1998 to the software to download position from the **J.L. Hart's** navigation equipment for each tow to three decimal point accuracy indicated that the previously used two-decimal point tow distance data resulted in the tow distance being overestimated. An analysis of tow distance data resulted in the development of conversion factors which has allowed us to recalculate the tow distances from surveys conducted prior to 1998 in terms of three-decimal point accuracy (see appendix).

Previously, the survey data had been managed as a series of spreadsheet files. This format was cumbersome with respect to access and editing and was not Y2K compliant. A relational database using ORACLE was developed for these data and in addition, data collected in the earlier series (1981–1990) of research surveys in this area. The earlier series differed in design and vessels used and will need more investigation before the results can be used for the assessment of SPA 4. Data collected in the surveys of the other SPA's in the Bay of Fundy are also included in this database.

For the most part, editing of the new database resulted in the reassignment of a number of tows to a different stratum than they were previously assigned to. While this does not change the actual catch associated with the tow, a change in stratum membership will affect the strata means and the overall stratified mean.

The editing and tow distance recalculation changes did not result in substantial differences between the old and new survey series (Fig. 12). The very slight differences between old and new estimates in 1994 and 1995 are due to the coincidental increase in stratified mean numbers due to tow distance with an almost equal decrease due to reassignment of tows to strata.

Update for 2000 survey

Estimates from the June 2000 survey of mean number per tow for three major shell height groups are presented in Table 3. Large numbers of small scallops were found in most of the strata. While the mean number per tow for the 55 to 79 mm and the 80+ mm scallops represent a slight increase over last year, the mean number per tow for the less than 55 mm represents the largest value yet seen since this survey series started in 1991 (Fig. 13).

Spatial plots for scallops less than 80 mm shell height show the recruitment to be in both SPA 4 and 1, starting at about 4 miles from the Nova Scotia shore (Fig. 14). In SPA 4, these areas correspond to the shallower areas (less than 90 m or 50 fm as indicated on the figures) where the higher yield fully-recruited scallops are found (Fig. 15). Scallops in these areas of SPA 4 exhibit higher yields than those in water deeper than 90 m. While the presence of strong recruitment for the next few years in areas where scallops exhibit higher yields is a positive sign, there is also the risk of higher mortality of the smaller scallops due to fishing activity in the area.

Estimates of stratified total numbers for the two depth areas identified as being important for growth differences by Smith et al. (1999) are presented in Fig. 16. Trends are presented separately for the two shell height ranges previously used to characterize fully-recruited (80+ mm) and recruits (55–79 mm), respectively. The decline in fully-recruited numbers observed in the 1999 survey for the deeper water continued in 2000 while there were increases for both size classes in the shallow water.

However, the most significant observation from the June 2000 survey was the large increase for scallops in the less than 55 mm shell height size class (Fig. 17). The major part of this increase in SPA 4 occurred in areas with depths less than 90 m of depth. Shell height histograms (Figs. 18 and 19) identify the mode for this large recruitment to be in the 25 to 50 mm range which roughly corresponds to two-year olds (1998 year-class). The mode is at the same shell height range in the deeper waters (Fig. 20, 21) but the numbers there are less than half of those observed in the shallower waters.

In 1999, the fishing industry expressed concern that the recent increase in distribution of the branching bryozoan (*Flustra foliacea*), commonly referred to as lemon weed may be affecting our survey estimates. The spread of lemon weed has been documented by Fuller et al. (1998), Magee et al. (1999) and Smith et al. (1999). In 2000, there appeared to be a slight decrease in the number of tows in which lemon weed was found (Fig. 22). Smith et al. (1999) compared survey tows made in the presence/absence of lemon weed and found no difference between the trends measured from these tows.

Meat weight/shell height relationship

Measurements of meat weight and shell height have only been collected for the current survey series (starting in 1991) since 1996. The standard analysis of meat weight (w_i), shell height (H_i) data postulates a relationship of,

$$w_i = \alpha H_i^{\beta}, \tag{1}$$

which is usually treated as a linear relationship in the log scale,

$$\log(w_i) = log(\alpha) + \beta \log(H_i). \tag{2}$$

Previous analyses of these data (e.g. Kenchington et al. 1997, Smith et al. 1999, Smith et al. in press) have all investigated the effects of depth upon this relationship in a number of different ways. In this study, we plotted the partial residuals from a model of the form

$$\log(w_i) = log(\alpha) + \beta_1 \log(H_i) + \beta_2 \log(\text{depth}), \tag{3}$$

to identify the relationship between depth and $\log(w_i)$ (Fig. 23). Depths have not been corrected for tides in these analyses. All of the plots suggest a piecewise relationship with log(depth) where there is only a relationship for depths greater than 90 m,

$$\log(w_i) = log(\alpha) + \beta_1 \log(H_i) + \beta_2 \log(\text{depth}|\text{depth} > 90), \tag{4}$$

where,

$$(\text{depth}|\text{depth} > 90) = \begin{cases} \text{depth} & \text{if depth} > 90 \\ 0 & \text{otherwise.} \end{cases}$$

This analysis will need to be refined once tide-corrected depths have been entered into the new survey database. The ANOVA results indicate that the piecewise relationships are all significant fits to the data (Table 4).

Included in this table is the fit for the data collected with the assistance of the F/V **Nova Delight** (owner: M. Longmire) on the 24 and 25th of February, 2000. Meat weight/shell height data were collected from the SPA 4 area using a grid pattern. The sample grid along with average meat weights for shell heights ranging from 80 to 89 mm and 110 to 119 mm are presented in Figs. 24 and 25, respectively. Previous studies of meat weight/shell height relationships outside of the period covered by the June survey (Roddick et al. 1994) had been confined to the shallower waters of the Digby Gut area. The data collected in February 2000 represents a wider range of depths and areas.

The parameter estimates for the piecewise models for all years are presented in Table 5. While the results appear to be similar over all the years, these analyses are to be considered preliminary until depths have been corrected for tides. It may be possible to use the predictions such as those in Table 6 to predict meat weights[3] over during the fishing season. The next step in this analysis will be to relate, at least for 1999/2000 data, meat weight-at-shell height in each area from the survey with the same area later in the year. This may help fill in for areas missed from the commercial samples such as happened during 1998.

Population Model

Background and previous implementation

Smith et al. (1999) used the modified DeLury model (Collie and Sissenwine 1983, Conser 1995) to characterize the dynamics of the scallop population in SPA 4. This model relates the numbers of fully-recruited scallops in the population in year t, to those in year $t-1$ as,

$$N_t = (N_{t-1} + R_{t-1}) \times \exp(-M) - C_{t-1} \times \exp((tc - ts - 1) \times M). \quad (5)$$

The terms in the model are defined as follows,

N_t, N_{t-1}	=	Population numbers of fully recruited scallops in year t and $t-1$, respectively.
R_{t-1}	=	Population numbers of scallops in year $t-1$ expected to become fully-recruited in year t.
C_{t-1}	=	Numbers of scallops caught by the commercial fishery.
t_c	=	Time of the year when the fishery starts expressed as number of months/12.
t_s	=	Time of the year when the survey occurs expressed as number of months/12.
M	=	Natural mortality rate.

Fishing mortality is estimated from this model as,

[3] Predictions were corrected for bias due to exponential term (see Gavaris 1980).

$$\widehat{F}_{t-1} = \log_e \left[\frac{N_{t-1} + R_{t-1}}{N_t}\right] - M. \tag{6}$$

None of the above quantities are measured directly and have to be estimated. Conser (1995) suggested estimating the N_{t-1} and R_{t-1} from survey data as,

$$\begin{aligned} n_{t-1} &= q_n N_{t-1} \\ r_{t-1} &= q_r R_{t-1}, \end{aligned} \tag{7}$$

where q_n and q_r are catchability coefficients for the survey gear and hence n_{t-1} and r_{t-1} are the expected values for the survey estimates. Therefore the model in equation 5 becomes

$$n_t = \left(n_{t-1} + \frac{r_{t-1}}{s_r}\right) \times \exp\left(-M + \varepsilon_t\right) - q_n C_{t-1} \exp\left((tc - ts - 1) \times M + \varepsilon_t\right), \tag{8}$$

and $s_r = q_r/q_n$. The ε_t term represents the random variation associated with the model and is usually referred to as process error.

Once the catchability coefficients have been estimated then population numbers in equation 5 can be estimated from survey population numbers in equation 8.

Update of DeLury model for new survey data

The quantities in equation 8 were defined as follows in Smith et al. (1999):

n_t	=	total numbers of scallops with shell height 80 mm and greater from survey in year t.
r_{t-1}	=	total numbers of scallops with shell height 55 to 79 mm from survey in year $t-1$.
C_{t-1}	=	the total meat weight landed divided by the average meat weight from samples of the commercial catches.
M	=	assumed to be 0.1 for fully recruited and pre-recruits.
$q_n = q_r$	=	assumed that the catchability of scallops to the lined gear and unlined gear to be equal.

Survey estimates were calculated separately for areas shallower and deeper than 90 m to reflect the differing growth characteristics discussed in Smith et al. (in press) but both estimates were combined to get n_t and r_{t-1}.

In addition to process error for the model, measurement error has been assumed for the survey quantities,

$$n'_t = n_t \exp\left(\eta_t\right), \quad t = 1, \ldots, T. \tag{9}$$

$$r'_t = r_t \exp\left(\delta_t\right), \quad t = 1, \ldots, T-1. \tag{10}$$

All error terms (ε_t, η_t and δ_t) are assumed to be normally distributed with mean 0 and non-zero variances (i.e., σ^2_ε, σ^2_η and σ^2_δ). Parameter estimates are obtained for the n_t, r_t and q_n by minimizing the following nonlinear least squares objective function.

$$S(\Theta) = \lambda_\varepsilon \sum_{t=2}^{T} \varepsilon_t^2 + \lambda_\eta \sum_{t=1}^{T} \eta_t^2 + \lambda_\delta \sum_{t=1}^{T-1} \delta_t^2 \tag{11}$$

The λ terms are weights which allow one to fit the model emphasizing a closer fit to the model or to the survey data. In Smith et al. (1999) we set $\lambda_\varepsilon = 2$ and $\lambda_\eta = \lambda_\delta = 1$ to emphasize the fit to the model in equation 8.

The fully recruited meat weight biomass was estimated as

$$\widehat{B}_{n,t} = \hat{n}_t \bar{w}_t / \hat{q}_n \tag{12}$$

where $\bar{w}_t$ is the average meat weight for fully recruited scallops.

We have updated the analysis presented in Smith et al. (1999) to take into account the new survey series and then again with the additional data from the 1999 commercial fishery and the June 2000 survey (Table 7). The results for the 1991 to 1999 data are not very different from those presented in Smith et al. (1999) and the problems noted there with the estimates from this model still exist. That is, why did the fishery have difficulty meeting their quota of 120 t in 1998 and 1999 when the fully recruited biomass was estimated to be 1398 and and 1057 t, respectively. Addition of the 1999 fishery and 2000 survey data only appears to make the situation even more puzzling with population biomasses for 1998 and 1999 estimated even higher at 1820 and 1328 t, respectively.

While the model is estimating the biomass in 1998 to be the second largest in the series, the commercial catch rate was one of the lowest (see page 5).

Possible sources of problems with the model and the data used in it are discussed below.

1. Removals from the population by the fishery were measured as annual catches in the model but the survey measures population size as of June. While the commercial fishery has been restricted to the fall since 1997, landings were made all year round in the early part of the landing series. In fact in 1991, 57 percent of the annual catch was taken prior to the survey. Action: Recalculate landings for survey year (June in year t to May in year $t+1$).

2. Recruits and fully-recruited scallops in the model were defined by the same ranges of shell heights over the whole time series over all depth ranges. This approach may not adequately reflect the spatial heterogeneity of growth discussed in Smith et al. (1999) and Smith et al. (in press). In addition, constant shell height ranges would not reflect changes in regulations concerning minimum shell height or meat count. Action: Reconsider shell size definition of recruit and fully-recruited animals.

3. The number of scallops caught by the commercial fishery was estimated by dividing the landed weight by the average meat weight obtained from meat weight samples from the commercial fishery (Table 2). The population biomass of meats was estimated from the model by multiplying the estimated numbers in the population by this same average meat weight (equation 12). Sampling intensity for these meat weights has been quite low and only a few vessels have been supplying samples. While the new industry sponsored meat sampling program should provide more samples and wider coverage,

this program only started for the Full Bay fleet in 2000. Average meat weights are available from the June survey representing the spatial variability in meat weight-at-size. However, these weights probably do not represent conditions during the fishery. Roddick et al. (1994) reported that meat weights in the Digby Gut area increased by as much as 23 percent between June and the fall. Action: As a preliminary step, compare meat weights-at-shell height from June 1996–2000 surveys to the Industry survey in February 2000 to determine spatial distribution of meat weights.

4. Natural mortality is assumed to be equal to 0.1 and constant over all of the years in the analysis. Caddy (1973) estimated that on some kinds of substrate as many scallops were killed or lethally damaged by fishing gear as were caught in the gear. The number of clappers (dead paired shells), recorded during the surveys, may reflect this natural or incidental gear mortality. Clappers have been used in the past to estimate natural mortality rates (Dickie 1955, Merrill and Posgay 1964, Kenchington et al. 1995). Action: Look at clapper-based mortality estimates to see if there are any patterns/trends and evaluate constant mortality assumption.

New implementation of DeLury model

Commercial landings were determined for the survey year as defined above (Table 8). Landings for 1997 to the present have not changed from the previous series because the fishery has been confined to the fall since 1997.

Based on the range of meat weights observed in commercial samples for 1991 to 1995 (Table 9), we determined that minimum shell height would at most be 80 mm and was probably less in some years. While it would probably be more realistic to use a selectivity curve such as given by Worms and Lanteigne (1986) than assume knife-edged recruitment as done here, incorporating such a selectivity curve(s) will be left for further investigation. Since 1996, the regulated minimum shell height has varied from 95 to 100 mm and minimum meat weights appeared to have increased as well (Table 2). Therefore, the fully-recruited population from the survey given in Table 8 has been defined as scallops with shell heights greater than or equal 80 mm during the period 1991–1995 and all scallops with shell heights greater than or equal to 95 mm for 1996 to the present.

Recruits are those scallops in year t which will grow large enough to be considered fully-recruited in year $t + 1$. Smith et al. (in press) developed growth models in which growth varied with depth (Fig. 26). From these models, we determined that for the period 1991 to 1994, recruits would be scallops with shell heights 55–79 mm and 65–79 mm for depths less than or equal to 90 m and greater than 90 m, respectively. For the period 1995 to 2000, recruits are defined as scallops with shell heights 70–94 mm and 85–94 mm for the shallow and deeper depths, respectively. Trends for fully-recruited and recruits by depth range are presented in Fig. 27. Confidence intervals for both recruit and fully-recruited scallops in each depth zone have been calculated using the percentile bootstrap method (Smith 1997) and are presented in Table 10. The limits are roughly $\pm$ 50 percent for recruits and $\pm$ 20 to 30 percent for fully-recruited.

Catch numbers were based on survey-year landings and average meat weights from samples of the commercial catch based on the survey year. Finally, commercial catch rates were also recalculated for the survey year.

Three forms of the modified DeLury model were fit to the data in Table 8 by setting different values for the weighting factors (λ's) in equation 11. All λ's were set to sum to 1.0 as recommended in NFSC (1997). The settings used were,

1. $\lambda_\varepsilon = \lambda_\eta = \lambda_\delta = 1/3$, that is, all sources of information are weighted equally.

2. $\lambda_\varepsilon = 0.75$, $\lambda_\eta = \lambda_\delta = 0.125$ which emphasizes the fit of the fishery model in equation 5 by minimizing the process error.

3. $\lambda_\eta = 0.75$, $\lambda_\varepsilon = \lambda_\delta = 0.125$, which emphasizes the fit to the survey estimates of fully-recruited scallops by minimizing the measurement error η in equation 9.

With the survey year beginning in June being used for this analysis, t_s was set equal 0. The index t_c was set 4/12 (October) because 50 percent or more (in recent years all) of the catch is taken in the fall.

The trends for the observed survey estimate of fully-recruited scallops and the fishery model estimate (equation 8) are very similar until 1998–1999 in the first form of the model (Fig. 28). The survey estimates suggest a large decline in population numbers from the 1998 to the 1999 survey which may have been due to the fishery, increased natural mortality or both. The fishery model estimates has difficulty with the decline in the survey estimates given that the catch in 1998 was lower than in 1997 and recruitment in 1998 for the 1999 fishery was the second highest in the series (Table 8). Note that most of this recruitment was in depths greater than 90 m (Fig. 27). For this model, population numbers in 2000 are at the lowest in the series with the potential of strong recruitment for the 2001 fishery (Fig. 29). Fishing mortality in 1998 was as high or higher than estimated for 1991 and even the relatively low landings of 1999 represent a mortality of 0.18.

In the second model the fit to the fishery model in equation 7 was emphasized with the result that the model estimates deviate greatly from the survey estimates in 1998 and especially in 1999 (Fig. 30). Population estimates indicate that numbers in 2000 are at about the fourth lowest in the series and fishing mortality has been below 0.2 since 1994 (Fig. 31).

Emphasis on minimizing the error for the survey estimates of fully-recruited scallops results in a very close fit of the model estimates to the observed survey estimates (Fig. 32). The model incorporates the decline from 1998 to 1999 by estimating the fishing mortality to be in excess of 0.5 and the current population level as the lowest in the series (Fig. 33).

The fishing mortality estimates from each form of the model are presented below with the process error model providing the more optimistic view and the survey error model the more pessimistic view for 1998. Estimates from the first and third model are similar in 1999.

	Fishing Mortality								
Model	1991	1992	1993	1994	1995	1996	1997	1998	1999
1) equal weights	0.30	0.21	0.22	0.18	0.10	0.08	0.19	0.35	0.18
2) process error	0.28	0.24	0.22	0.26	0.09	0.09	0.17	0.18	0.13
3) Survey error	0.34	0.14	0.30	0.06	0.15	0.05	0.13	0.52	0.17

All three fits of the model have identified a major inconsistency between the survey estimates of recruits and fully-recruited in 1998 and fully-recruited in 1999, and the landings in 1998. As noted above most of the recruitment observed in the 1998 survey occurred at depths greater than 90 m. Smith et al. (1999) also noted that a large part of the effort of the commercial fishery in 1998 was in the same area as this recruitment (see Figs. 5 and 6). However, average meat weights from the commercial samples in 1998 are the largest in the series and therefore do not reflect fishing in deeper water or on recruiting scallops (Table 8). As a result the estimate of the number of scallops in the catch are estimated to be too low to account for the decline observed in the survey.

In fact, the meat weight samples from 1998 do not come from any of the catches in the deeper water and therefore probably overestimate the average meat weight for the entire commercial catch (Fig. 9). This was less of a problem in 1999 because, while the locations of commercial meat weight samples were still mainly from catches at depths less than 90 m (Fig. 10) more of the effort and catch were from these areas as well (Fig. 7 and 8).

Comparison of the population biomass estimates of meats from the model (equal λ's) to the commercial catch rate presents another confirmation of something being wrong with the 1998 estimate of meat weight and numbers of scallops caught (Fig. 34). The decline in catch rate for 1998 does not support there being an increase in biomass that same year.

As noted earlier, there were no meat weight samples taken during the 1991 to 1995 surveys. For this report, the average meat weights for these surveys was estimated using the observed shell heights and depths from each survey and the model for 1996. Average meat weights for fully-recruited scallops from the survey series were compared with the commercial average meat weights from Table 8 in Fig. 35. The most striking difference between the two data sets is the increasing divergence after 1996. Part of this increase may be expected given the implementation of stricter meat weight restrictions. However, the large increase in 1998 when the June survey shows an overall decrease due to the large recruitment of scallops in the deeper water, does not make sense.

Finally, a comparison of biomass of meats estimated from the survey and the commercial catch per unit effort shows that these two indices track each other very closely further suggesting that the biomass estimates for 1997 to 1999 from the model are too high (Fig. 36).

Clapper trends

Stratified total estimates for clappers were calculated for the two depth zones used for the live scallops over all years. Estimates were made separately for recruits and fully-recruits as per Fig. 27. These estimates are presented as proportions of the total survey catch in Fig. 37. The die-off of the early 1990's is quite plainly reflected in both depth zones in this figure. In addition, it appears that the proportion of clappers is greater and more variable in the deeper water with an increasing trend since 1998. This increase was more pronounced for the fully-recruited scallops.

Estimates of the instantaneous rate of natural mortality, M, has been calculated from clappers by Dickie (1955) and Merrill and Posgay (1964) by using the formula,

$$a = 1 - \exp(-(C/t)(1/L) \times 365),$$

where a is the annual rate of natural mortality, C is the number of clappers in the survey, t is the average time in days required for the shells to separate, L is the number of live scallops in the survey and 365 is the number of days in the year. The exponent of equation 13 is equal to M and can be written as,

$$M = (C/L) \times (365/t) \,. \tag{13}$$

Estimates for t for scallops in SPA 4 are not available. Dickie (1955) used results from tank experiments to estimate t to be on average 50 days for scallops with shell heights less than 96 mm and 100 days for shell heights between 96 and 155 mm in his analysis of mortality rates for the Digby area. On the other hand, Merrill and Posgay (1964) determined that based on the general condition of the ligament, the shell, the kinds and degree of fouling on the shell and the position of the latest ring with respect to the shell edge of clappers caught on Georges Bank, the average time that clappers persisted was 33 weeks. Finally, Kenchington et al. (1995) assumed that t equaled one year for their estimates of M for a VPA analysis of the scallop data in the Digby area.

Mortality rates were calculated separately for fully-recruited and recruits for both the deep and shallow water areas from the clapper data in Fig. 37 and the live scallop estimates in Fig. 27 using equation 13. The rates for the deep and shallow water areas were combined by weighting the individual mortality rates by the population estimates in Fig. 27 (Fig. 38). The assumed constant mortality of 0.1 is also indicated on Fig. 38.

The impact of varying the natural mortality in the modified DeLury model is illustrated below by comparing population biomass estimates from the equal λ case.

Natural Mortality	t	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
$M = 0.1$		1706	1153	985	634	613	701	807	1095	851	757
Varying	365 d	1493	974	838	548	519	593	697	946	742	647
Varying	33 w	1751	1131	983	646	618	695	818	1118	874	745

We have used one year and 33 weeks for estimates of t in equation 13. Assuming that clappers persist on average for 33 weeks and using the mortality estimates from Fig. 38 does not result in appreciable differences in biomass estimates from those assuming a constant M. Biomass estimates from assuming that t equals one year are lower than for the other two cases.

Discussion

A number of changes have been made to the data used in the fit of the modified DeLury model to the research survey data. These changes have resulted in lower biomass estimates than those given in Smith et al. (1999) and therefore may be considered more realistic in that sense. However, the estimated population size from the model in equation 8 suggests a very different population trajectory from the survey estimates for the years 1997 to 2000. Both the commercial catch rate (Fig. 34) and the average meat weights from the survey (Fig. 35) suggest that the commercial meat weights sampled in 1998 provided an overestimate of the actual average meat weight of the landings. Consequently the number of scallops landed in 1998 based on this average meat weight and used in the model was an underestimate of the actual numbers landed. The difference between commercial and survey average meat weights varied between 15 and 22 percent for the years 1996, 1997 and 1999. Given all things equal, this may suggest that the actual average meat weight for 1998 may lay somewhere in this range of 17.5 to 18.5 g. If the decline in catch rate from 1997 to 1998 was to be attributed to a decrease in meat weight alone, then a value of $0.74 \times 19.9 = 14.7$ g may be used for 1998. In fact this latter decline may be greater given that the survey estimates suggest an increase in population numbers from 1997 to 1998.

Natural mortality as estimated from the catch of clappers in the survey appears to have been varying over time and in particular, for depths greater than 90 m, it may have increased over the last two years. Unfortunately we do not have a definitive estimate of how long the dead paired shells will stay together in SPA 4.

As a compromise we have fit the model assuming an average meat weight of 17.5 for 1998, constant M of 0.1 and equal λ's for the objective function in equation 11. The smaller average meat weight for 1998 does not appear to have had an appreciable effect on the results in comparison to the previous fit of the model (compare Fig. 39 to Fig. 28). The numbers landed would have to increase even more to offset the effect of the large recruitment observed in 1998 (Figs. 27 and 40). Conditional non-parametric bootstrap confidence intervals (percentile limits) were calculated for the estimated population numbers (Figs. 41) and the estimated fishing mortality (Figs. 42). The limits around the estimated population numbers were less than 20 percent. Estimates of fishing mortality were less precise than this.

This version of the model predicts that there will be 30.5 million fully recruited scallops in 2000 with an estimated 22.1 millions recruits for 2001. In order to estimate the biomass of meats for 2000 we need to estimate an average meat weight for the planned fishery in the fall of 2000. As a conservative estimate, we increased the survey average mean weight of 19.59 g by 15 percent to give 22.5 g for the average meat weight in the 2000 fishery. This results in an estimated meats biomass of 686 t for 2000. Using this average meat weight then, the previously set TAC of 120 t implies that 5.3 million scallops would be landed and the fishing mortality on the fully-recruited population alone would be

$$\log\left(\frac{30.5}{(30.5-5.3)\times\exp(-0.1)}\right) - 0.1 = 0.19. \tag{14}$$

However, the large recruitment expected in 2001 would offset the effects of the fishery and result in an increase of the fully-recruited population to 43 million in June 2001.

If we assume that the q for fishing gear is the same as that estimated for the survey gear, then the predicted catch rate for the biomass estimated above would be 9.8 kg/h assuming the whole area is fishable. A TAC of 120 t would require over 12000 hours of fishing effort. In the last two years, effort has averaged 9000 hours suggesting a total catch of about 88 t would be realized if all things stayed the same.

However, the two-year olds (Fig. 43) observed in the survey were found to be widespread throughout the areas commonly fished between 4 to 8 miles from the Nova Scotia coast (e.g., Fig. 7 and also the location of the fully-recruited scallops from the survey in Fig. 44). Consequently, increased incidental mortality on these pre-recruits as well as the recruits for 2001 (Fig. 45) due to fishing activity can be expected which would diminish prospects for the near future. Any measures designed to restrict fishing in areas where the pre-recruits are located will have to be accompanied by reductions in the TAC.

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References

Caddy, J. F. 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. Journal of the Fisheries Research Board of Canada. **30**: 173–180.

Collie, J. S. and Sissenwine, M. P. 1983. Estimating population size from relative abundance data measured with error. Canadian Journal of Fisheries and Aquatic Science. **40**: 1871–1879.

Conser, R. J. 1995. A modified DeLury modelling framework for data-limited assessments: bridging the gap between surplus production and age-structured models. Working paper, ICES Working Group on Methods of Fish Stock Assessment, NMFS, Northeast Fisheries Center, Woods Hole, MA 02543.

DFO.1999. Scallop production areas in the Bay of Fundy. DFO Science Stock Status Report. C3-56.

Dickie, L. M. 1955. Fluctuations in the abundance of the giant scallop *Placopecten magellanicus* (Gmelin), in the Digby area of the Bay of Fundy. Journal of the Fisheries Research Board of Canada. **12**: 797–857.

Fuller, S., Kenchington, E. L., Davis, D. and Butler, M. 1998. Associated fauna of commercial scallop grounds in the lower Bay of Fundy. Marine issues committee special publication 2, Ecology Action Centre, Ecology Action Centre, Suite 31, 1568 Argyle Street, Halifax, Nova Scotia.

Gavaris, S. 1980. Use of a multiplicative model to estimate catch rate and effort from commercial data. Canadian Journal of Fisheries and Aquatic Science. **37**: 2272–2275.

Jamieson, G. S. 1982. A system for precise determination of tow distance and tow path in offshore resource surveys. Canadian Technical Report of Fisheries and Aquatic Sciences. **1035**: iv+34 pp.

Kenchington, E., Lundy, M. and Smith, S. 1997. Bay of Fundy scallop stock assessment: Areas 2, 3, 4, 5, 7.. Canadian Stock Assessment Secretariat Research Document. **97/63**: 98 pp.

Kenchington, E., Roddick, D. L. and Lundy, M. J. 1995. Bay of Fundy scallop analytical stock assessment and data review 1981–1994: Digby grounds. DFO Atlantic Fisheries Research Document. **95/10**: 70 pp.

Magee, S., Kenchington, E., Roddick, D. L., Davis, D. and Butler, M. 1999. Diversity and distribution of associated fauna of commercial scallop grounds in the lower Bay of Fundy. Canadian Technical Report of Fisheries and Aquatic Sciences. **2285**: iv+73 pp.

Merrill, A. S. and Posgay, J. A. 1964. Estimating the natural mortality rate of the sea scallop *(Placopecten magellanicus)*. ICNAF Research Bulletin **1**: 88–106.

NFSC 1997. Report of the 23rd Northeast Regional Stock Assessment Workshop (23rd SAW): Stock Assessment Review Committee (SARC) consensus summary of assessments. Northeast Fisheries Science Center, National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026. Reference Document **97-05**: 191 pp.

Roddick, D. L., Lundy, M. J. and Kenchington, E. L. R. 1994. Yield per recruit analysis and minimum meat weight recommendations for the Bay of Fundy scallop fishery. DFO Atlantic Fisheries Research Document. **94/58**: 15 pp.

Smith, S. J. 1997. Bootstrap confidence limits for groundfish trawl survey estimates of mean abundance. Canadian Journal of Fisheries and Aquatic Science. **54**: 616–630.

Smith, S. J., Kenchington, E. L., Lundy, M. J., Robert, G. and Roddick, D. In Press. Spatially specific growth rates for sea scallops (*Placopecten magellanicus*), *in* G. H. Kruse, A. B. N. Bez, M. Dorn, S. Hills, R. Lipcius, D. Pelletier, C. Roy, S. J. Smith and D. Witherell, eds, Spatial Processes and Management of Marine Populations. University of Alaska Sea Grant, AK-SG-00-04, Fairbanks. (in press).

Smith, S. J., Lundy, M. J. and Claytor, R. 1999. Scallop Production Areas 4 and 5 in the Bay of Fundy: Stock status update for 1999. DFO Canadian Stock Assessment Secretariat Research Document. **99/170**: 51 pp.

Worms, J. and Lanteigne, M. 1986. The selectivity of a sea scallop (*Placopecten magellanicus*) Digby dredge. ICES CM. **k:23**: 25 pp.

Appendix

Calculating tow distance from position data

The distance covered by each tow in the research survey has been calculated from a series of positions recorded at regular intervals during the tow. For the first three years of the survey series used here, position was obtained using a Loran C system on the **J.L. Hart** recorded every 4 seconds on a MacIntosh SE computer. Distance towed was calculated by first using a smoothing algorithm on the recorded positions and then summing up point-to-point distances (Jamieson 1982). In 1994, the Loran C was replaced with a Global Positioning System (GPS) and positions were recorded on a Mac Plus with a HyperCard program. At this point, the smoothing program appears to have been removed from the process and tow distances were calculated as simply the sum of the point-to-point distances. The GPS was replaced with a Differential GPS (DGPS) in 1996. From 1994 to 1997, Latitude and Longitude was recorded in degrees and decimal minutes to two decimal places. From 1998 onwards, the DGPS was set to give three decimal place accuracy. In 1999, we also began to record the track files from the vessel's navigation computer which records position to 6 decimal place.

The complete analyses of these data will be published as a research document in the near future. In the meantime, we give a brief summary of results here with respect to recalculating tow distance. A comparison of point-to-point distances for two and three decimal place positions indicated that the latter resulted in distances 15.27 percent shorter on average than the former. Analysis of track files plots showed that the most accurate estimate of distance towed resulted from smoothing (19 point weighted average) and then summing up smoothed point-to-point distances (as per Jamieson 1982). Using this approach on the three decimal data and then applying this same approach to these same data rounded to two decimal points showed a -0.10 percent difference in the estimated distance towed for the two forms of the data. Therefore all data collected to two decimal point can provide accurate distances if the smoothing then summing estimate was used. For some years, we only had the estimated distance towed and were missing the point-to-point records (for SPA 4 these were 1991, 1992 and 1996). In these cases, a regression equation was developed to predict the distance towed.

Table 1. Commercial catch, effort in hours and catch rate (CPUE) for SPA 4 from 1991 to 1999. Prior to 1991, the catch and related data could only be apportioned to an inside zone, which represents 75 percent of the current area of SPA 4.

Year	CPUE (kg/h)	Effort (h)	Catch (t)
Inside Zone			
1980	44.71	7166	320.4
1981	44.54	9805	436.7
1982	39.86	12288	489.8
1983	27.28	14835	404.7
1984	19.92	15718	313.1
1985	14.47	18853	272.8
1986	11.51	8601	99.0
1987	111.78	1920	214.6
1988	91.44	20791	1901.1
1989	81.80	17785	1454.8
1990	33.46	14372	480.9
SPA 4			
1991	28.55	23772	678.70
1992	18.75	16981	318.40
1993	14.73	16578	244.20
1994	11.84	13699	162.20
1995	10.60	8943	94.80
1996	8.89	8009	71.20
1997	12.81	9063	116.10
1998	9.41	10946	103.00
1999	8.92	8845	78.96

Table 2. Results of the departmental meat weight sampling program in Scallop Production Area 4, 1996–1999.

			Meat Weight (g)				Count	Number of
Year	Month	N	Mean	SD	Min.	Max.	per 500 g.	Vessels
1996	November							
	Less than 6 mile	339	24.36	8.57	6.0	49.7	20.53	5
	6 to 8 mile	992	6.84	1.32	4.0	13.2	73.07	6
	December							
	Less than 6 mile	530	21.33	8.89	5.5	46.8	23.44	7
	6 to 8 mile	54	18.43	6.50	8.6	35.5	27.13	1
1997	October	1168	20.78	5.79	7.1	45.4	24.1	11
	November	193	14.39	4.79	6.3	29.7	34.7	3
1998	September	282	25.24	7.83	8.7	45.9	19.8	6
	October	331	22.92	6.73	7.9	49.2	21.8	5
	November	177	24.29	7.26	11.5	61.3	20.6	4
	December	354	24.40	8.99	15.4	99.0	20.5	5
1999	October	296	24.29	4.84	16.5	44.0	20.9	5
	November	205	21.63	6.36	8.4	49.4	23.1	4
	December	468	22.84	5.95	8.7	49.6	21.9	6
2000	January	442	30.35	9.28	9.7	56.8	16.5	13

Table 3. Estimates from stratified survey for scallops in Scallop Production Area 4, June 2000. Proportion of survey area in each stratum is given in the second column.

			< 55 mm		55 to 79 mm		80+ mm	
Stratum Name	Propn. area in stratum	Number of Tows	Mean number	Standard error	Mean number	Standard error	Mean number	Standard error
Centreville	0.133	13	107.05	34.70	18.08	3.08	86.64	14.95
CV to GH	0.068	9	298.33	115.95	31.38	8.65	77.94	19.23
Gulliver's Head	0.133	20	508.44	127.08	44.88	8.61	59.12	8.36
GH to DG	0.100	7	929.76	375.61	78.19	26.32	52.69	14.63
Digby Gut	0.200	17	484.75	160.78	48.64	13.40	76.72	19.98
DG to DC	0.100	6	606.20	285.85	74.25	43.18	77.73	30.99
Delaps Cove	0.133	6	412.58	221.12	79.97	40.59	145.43	38.69
Parkers Cove	0.133	7	16.77	4.83	19.89	14.46	88.19	3.96
Stratified estimates	1.000	85	409.75	67.06	48.77	8.21	84.17	7.84

Table 4. Analyses of variance for fitting piecewise relationship with depth to model for shell height/meat weight analyses. Scallops in Scallop Production Area 4.

Terms	Residuals DF	RSS	Test DF	Sum of Squares	F Value	Pr(F)
		June, 1996				
log(height)	5002	458.4				
log(height) + log(depth$\|>$ 90m)	5001	265.33	1	193.07	3639.00	0
		June, 1997				
log(height)	7186	222.38				
log(height) + log(depth$\|>$ 90m)	7185	148.13	1	74.25	3601.50	0
		June, 1998				
log(height)	1693	79.59				
log(height) + log(depth$\|>$ 90m)	1692	54.38	1	25.21	784.32	0
		June, 1999				
log(height)	2281	95.95				
log(height) + log(depth$\|>$ 90m)	2280	69.92	1	26.02	848.62	0
		June, 2000				
log(height)	5413	244.78				
log(height) + log(depth$\|>$ 90m)	5412	198.92	1	45.86	1247.60	0
		February, 2000				
log(height)	712	22.02				
log(height) + log(depth$\|>$ 90m)	711	18.94	1	3.09	115.94	0

Table 5. Parameter estimates for shell height/meat weight model with piecewise relationship for depth. Scallops in scallop production area 4.

	Parameter Estimates		
Year	Intercept	log(height)	log(Depth | Depth> 90 M)
1996	−10.50	2.826	−0.1528
1997	−11.02	2.927	−0.0897
1998	−11.62	3.056	−0.1069
1999	−10.89	2.926	−0.0950
2000	−12.23	3.201	−0.0717
Feb.	−13.54	3.519	−0.0618

Table 6. Predicted weights from piecewise regression for selected shell heights and depths. For relationships in depths greater than 90 m, 110 m was chosen as an example. Scallops in Scallop Production Area 4.

	Depth < 90 m				Depth = 110 m			
Year	60 mm	80 mm	100 mm	120 mm	60 mm	80 mm	100 mm	120 mm
1996	3.00	6.78	12.73	21.32	1.90	4.29	8.06	13.49
1997	2.65	6.16	11.84	20.18	2.03	4.71	9.05	15.43
1998	2.49	6.00	11.86	20.71	1.81	4.35	8.61	15.03
1999	3.02	7.00	13.45	22.93	2.27	5.27	10.12	17.25
2000	2.43	6.10	12.47	22.35	1.96	4.92	10.06	18.03
Feb.	2.42	6.66	14.61	27.75	2.01	5.54	12.14	23.06

Table 7. A comparison of model estimates of population biomass and fishing mortality (F_t) for scallops in Scallop Production Area 4. Old data refers to survey data used in previous assessments before development of database. Data from the Oracle database with changes due to editing and change in tow distance is called new data here. The population model used here is form of the modified DeLury used in Smith et al. (1999). Constant natural mortality of 0.1 was assumed throughout.

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
					Old data					
Population Biomass (t)	2358	1497	1151	765	949	987	1212	1432	1088	
F_t	0.30	0.19	0.23	0.19	0.06	0.08	0.10	0.20		
					New data (1991–1999)					
Population Biomass (t)	2275	1427	1102	728	879	931	1170	1398	1057	
F_t	0.31	0.19	0.23	0.20	0.08	0.11	0.13	0.21		
					New data (1991–2000)					
Population Biomass (t)	2590	1632	1266	853	1107	1200	1513	1820	1328	1252
F_t	0.31	0.18	0.21	0.12	0.03	0.05	0.10	0.17	0.05	

Table 8. Quantities used in the re-formulation of the modified DeLury population model for scallops in Scallop Production Area 4. Landings were calculated based on a survey year (from June in year t to May in year $t+1$).

Quantity	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Landings (t)	425.2	282.3	199.8	173.9	50.2	59.8	116.1	103.0	78.9	
Fully recruited (millions)	23.8	15.3	14.3	9.4	10.6	9.0	11.1	13.1	7.9	7.5
Recruits (millions)	1.3	1.7	1.1	1.8	1.6	3.8	4.5	3.9	1.5	6.0
Mean meat weight (g)	19.2	18.3	19.2	15.8	17.1	20.4	19.9	25.5	23.5	
Catch numbers (millions)	22.1	15.4	10.4	11.0	2.9	4.1	5.8	4.0	3.4	
Catch rate (kg/h)	24.3	16.5	14.2	10.8	8.0	8.6	12.8	9.4	8.9	

Table 9. Results of the departmental meat weight sampling program in Scallop Production Area 4, 1991–1996 by survey year (from June in year t to May in year $t+1$).

Survey	Meat weight (g)				Count
Year	Mean	Minimum	Maximum	SD	per 500 g.
1991	19.21	2.11	57.03	10.15	26.0
1992	18.31	2.30	79.50	9.77	27.3
1993	19.20	3.20	57.40	8.52	26.0
1994	15.75	4.10	63.50	8.06	31.7
1995	17.09	3.60	45.10	8.68	29.3
1996	14.71	3.60	49.70	9.55	34.0

Table 10. Bootstrap confidence intervals (95 percent) for survey population estimates of recruits and fully recruited scallops in Scallop Production Area 4.

a) Depth $\leq$ 90 m

	Recruits			Fully-recruited		
Year	Total no.s	Lower	Upper	Total no.s	Lower	Upper
1991	0.51	0.30	0.75	16.85	10.23	17.09
1992	1.17	0.57	1.73	8.81	6.97	9.75
1993	0.65	0.34	0.95	9.86	8.07	11.68
1994	1.27	0.58	2.08	5.62	4.50	6.43
1995	2.45	1.45	3.47	7.05	5.05	8.66
1996	3.00	2.03	3.70	6.48	4.68	7.86
1997	3.11	2.40	3.85	7.52	6.10	9.01
1998	0.58	0.37	0.80	7.41	6.09	8.98
1999	0.53	0.29	0.76	5.41	4.49	6.31
2000	5.65	3.06	8.54	5.32	4.57	6.26

	Recruits			Fully-recruited		
Year	Total no.s	Lower	Upper	Total no.s	Lower	Upper
1991	0.32	0.18	0.47	7.39	5.46	8.73
1992	0.57	0.40	0.75	6.51	4.45	8.70
1993	0.43	0.23	0.76	4.46	3.52	5.37
1994	0.53	0.26	0.85	3.83	2.45	5.20
1995	0.71	0.47	0.95	3.58	2.94	4.21
1996	0.84	0.40	1.29	2.50	2.14	2.81
1997	1.37	1.05	1.71	3.63	2.97	4.33
1998	3.29	1.93	4.92	5.64	3.90	7.84
1999	0.49	0.32	0.68	2.60	2.11	3.10
2000	0.33	0.23	0.44	2.21	1.74	2.80

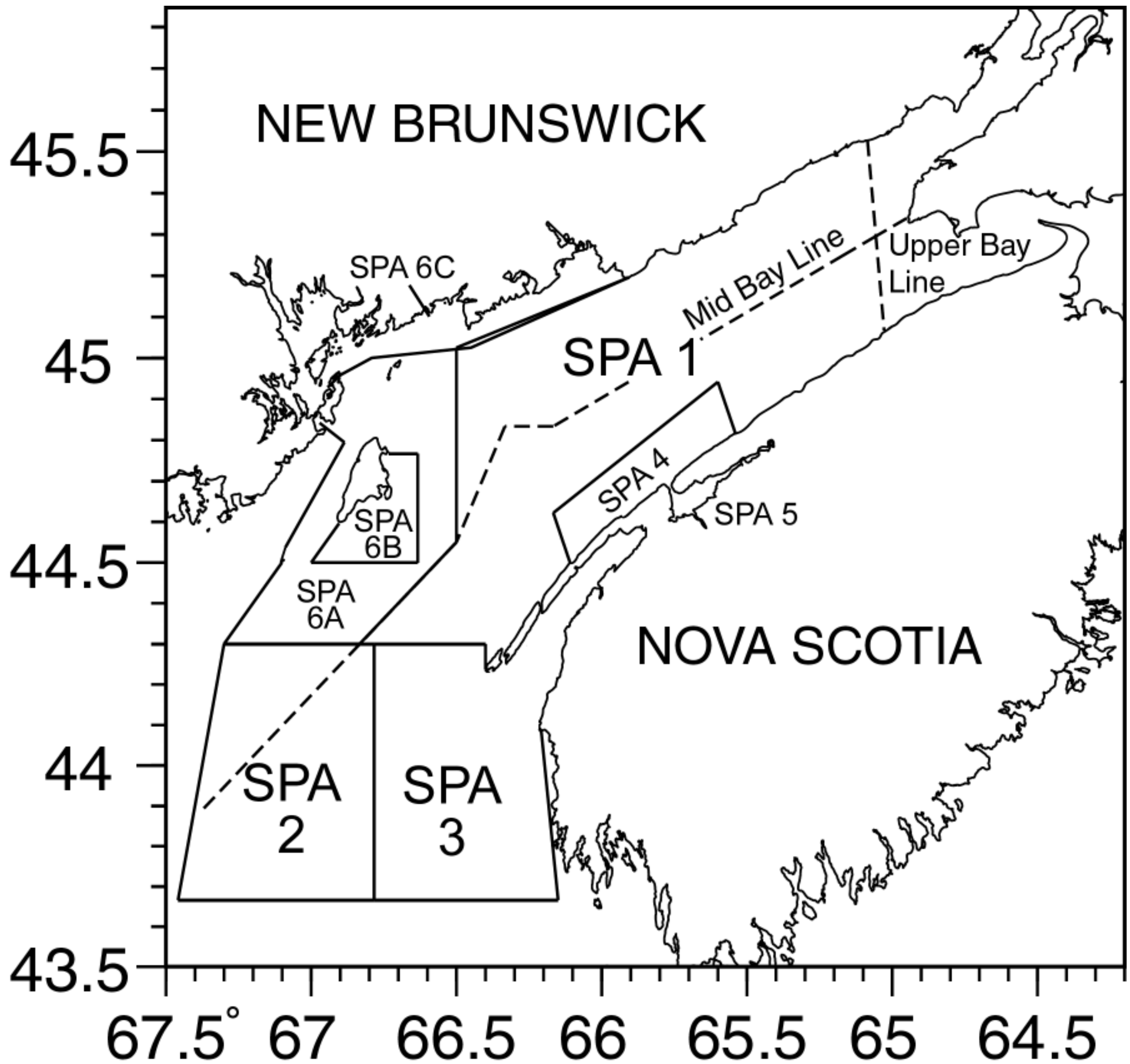

Fig. 1. Scallop Pproduction Areas (SPA) in the Bay of Fundy as established 1 January 1997. In 1999, the number of SPA's was reduced from 7 to 6.

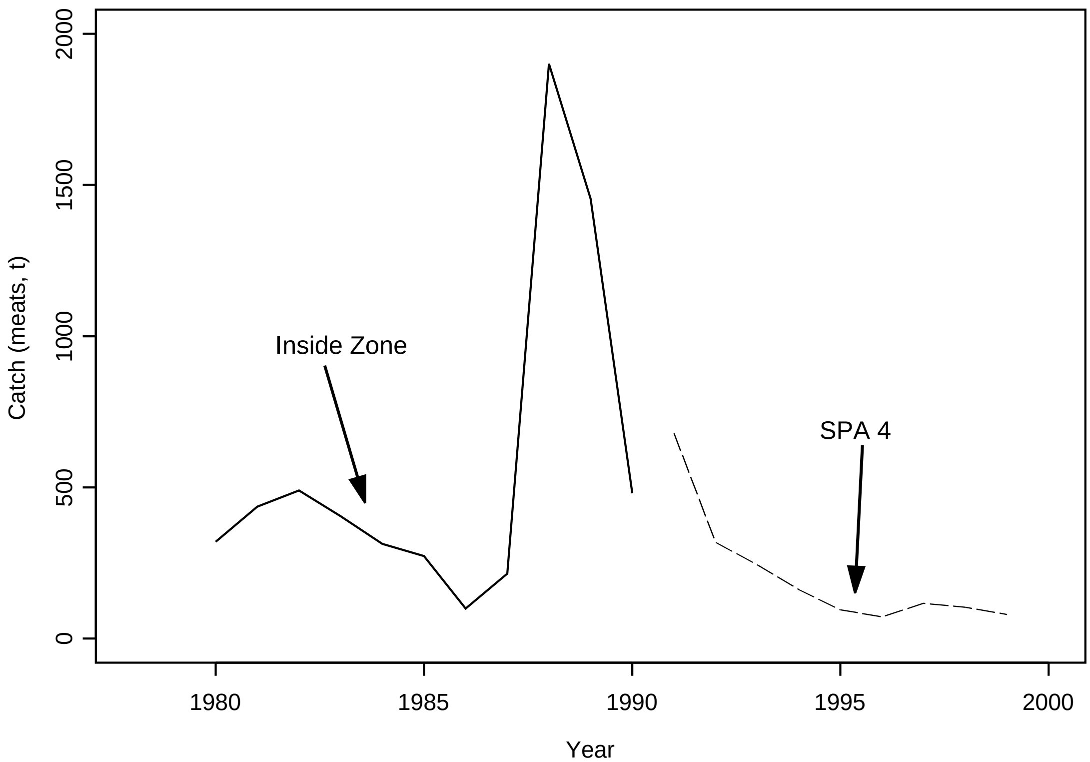

Fig. 2. Landings of scallop meats recorded for Scallop Production Area (SPA) 4. Prior to 1991, the landings can only be apportioned to the Inside Fishing Zone which extended 6 miles from the Nova Scotia and corresponds to 75 percent of the area of the current SPA.

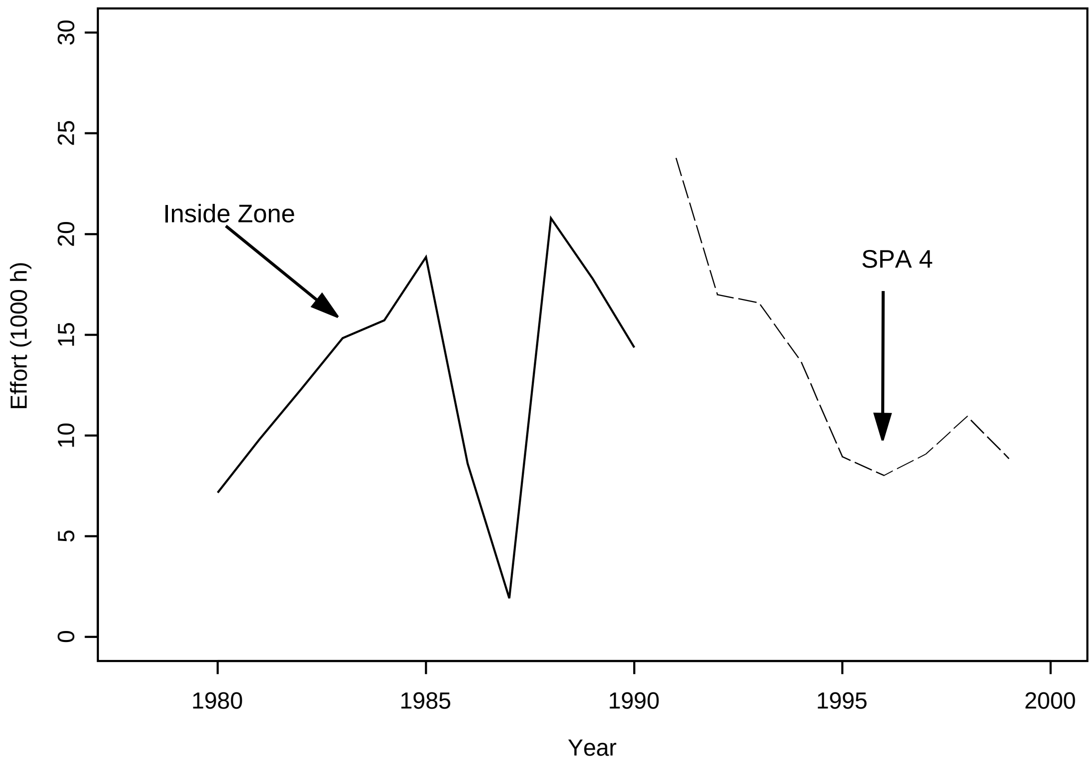

Fig. 3. Effort as measured by total hours that gear was towed over the bottom for scallops recorded for Scallop Production Area (SPA) 4. Prior to 1991, the landings can only be apportioned to the Inside Fishing Zone which extended 6 miles from the Nova Scotia and corresponds to 75 percent of the area of the current SPA.

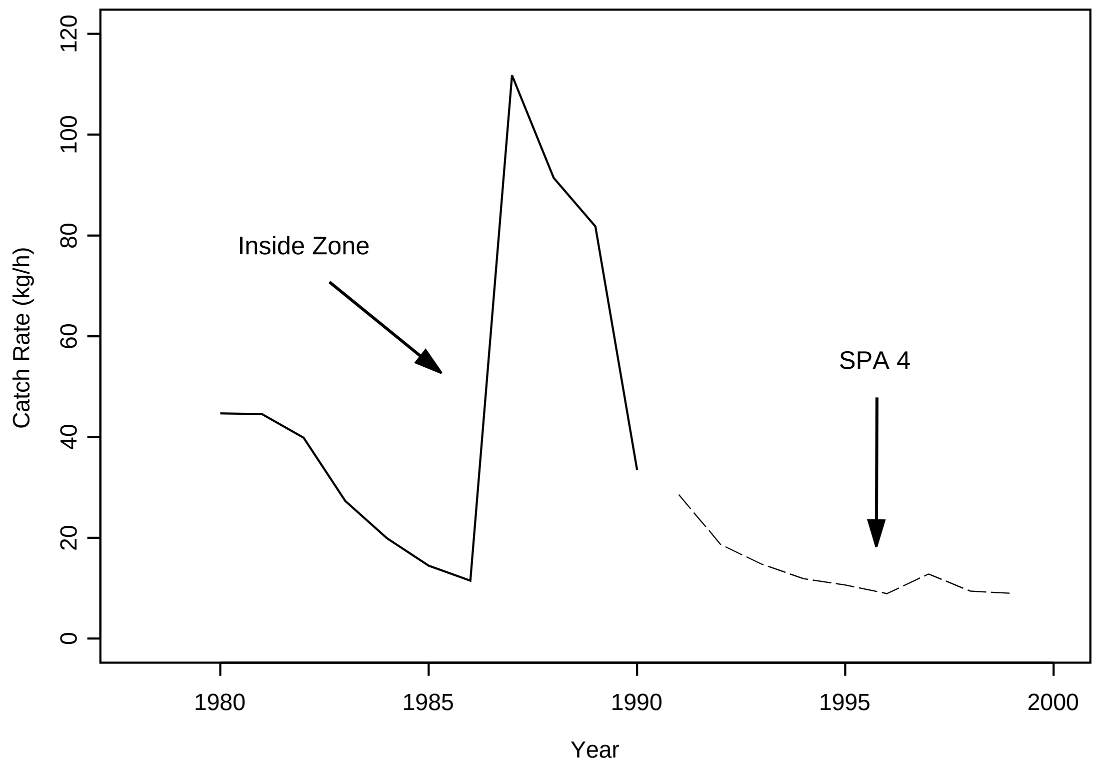

Fig. 4. The catch rates (kg of meats per hour) for Scallop Production Area (SPA) 4. Prior to 1991, the landings can only be apportioned to the Inside Fishing Zone which extended 6 miles from the Nova Scotia and corresponds to 75 percent of the area of the current SPA.

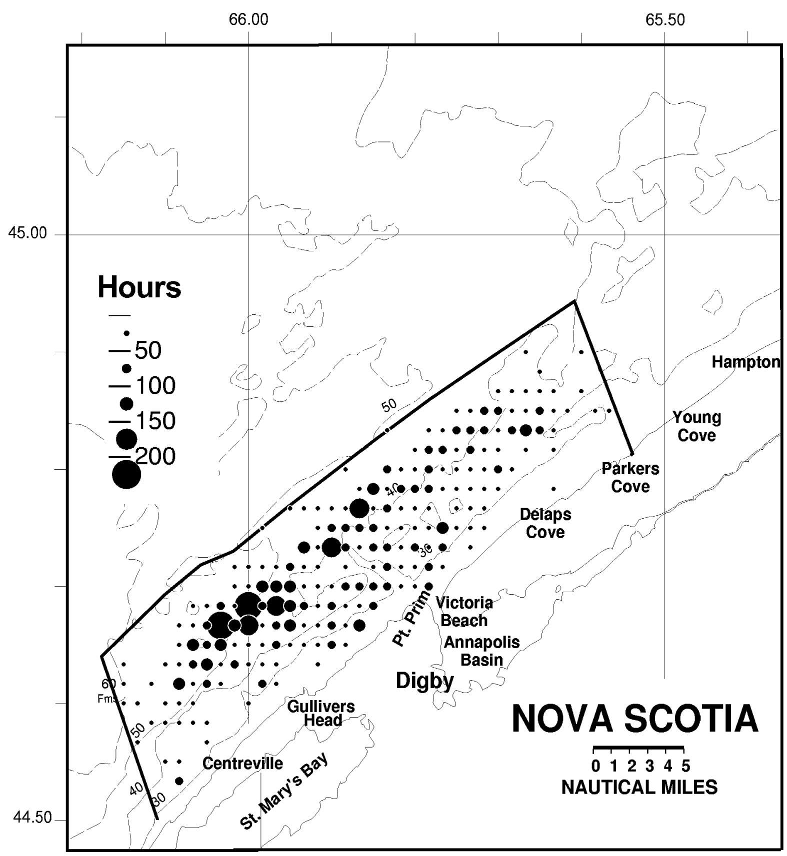

Fig. 5. Fishing locations from class 1 fishing logs in 1998 for Scallop Production Area 4. Fishing effort in hours. Depths are given in fathoms (1.83 m = 1 fm).

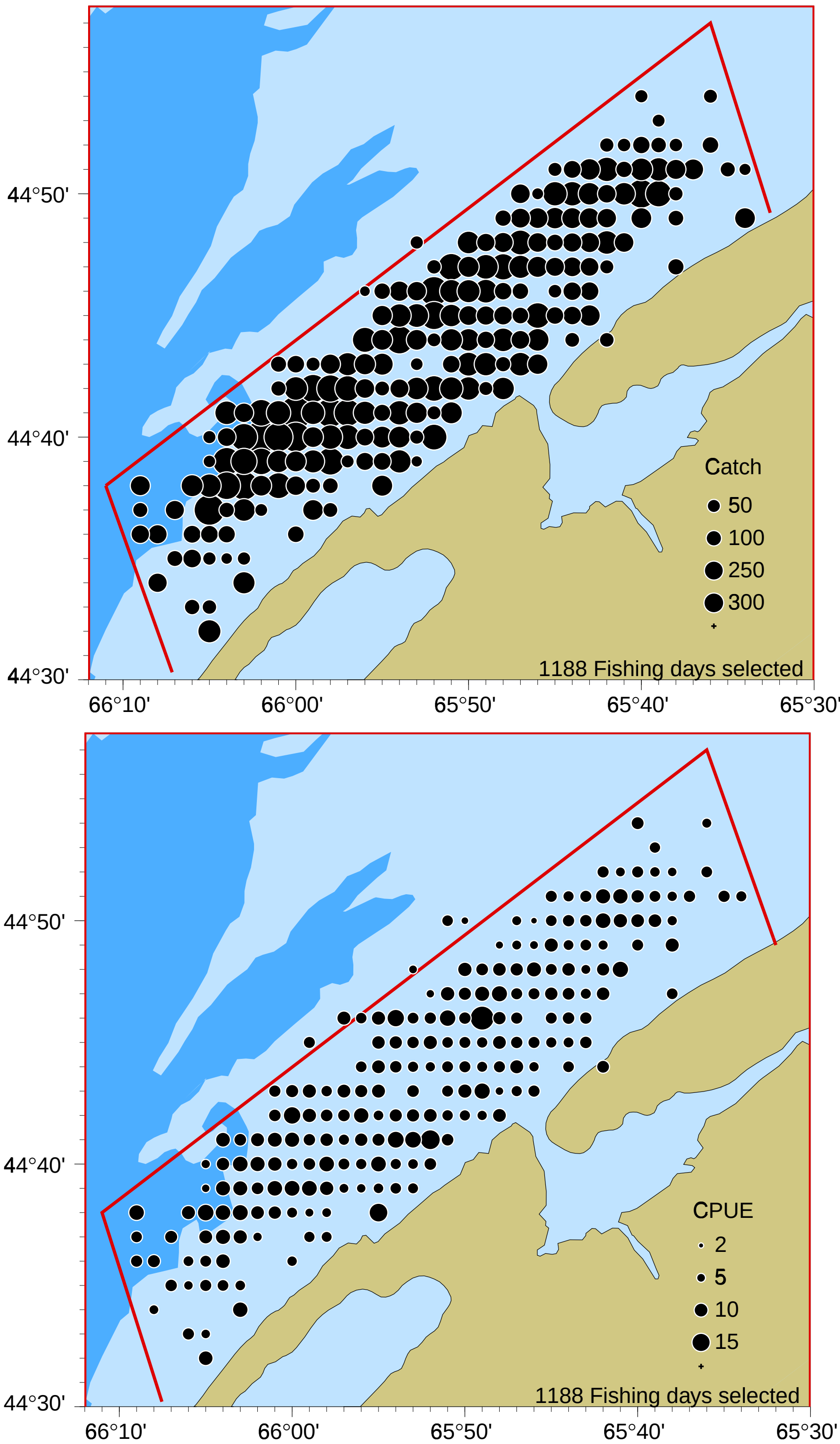

Fig. 6. Fishing locations from class 1 fishing logs in 1998 for scallops in Scallop Production Area 4. Upper panel: Catch (t). Lower panel: Catch-per-unit-effort (kg/h).

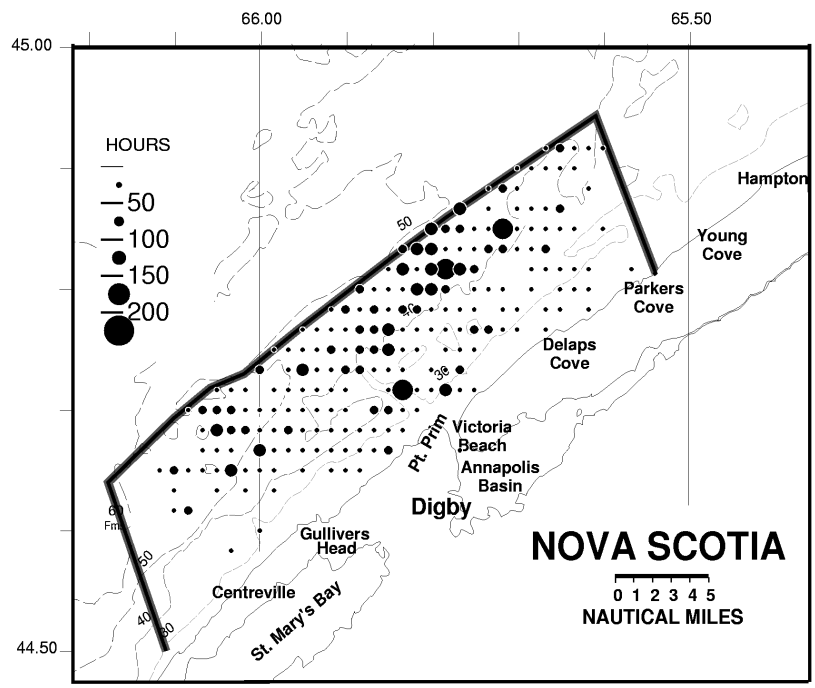

Fig. 7. Fishing locations from class 1 fishing logs in 1999 for scallops in Scallop Production Area 4. Fishing effort in hours. Depths are given in fathoms (1.83 m = 1 fm).

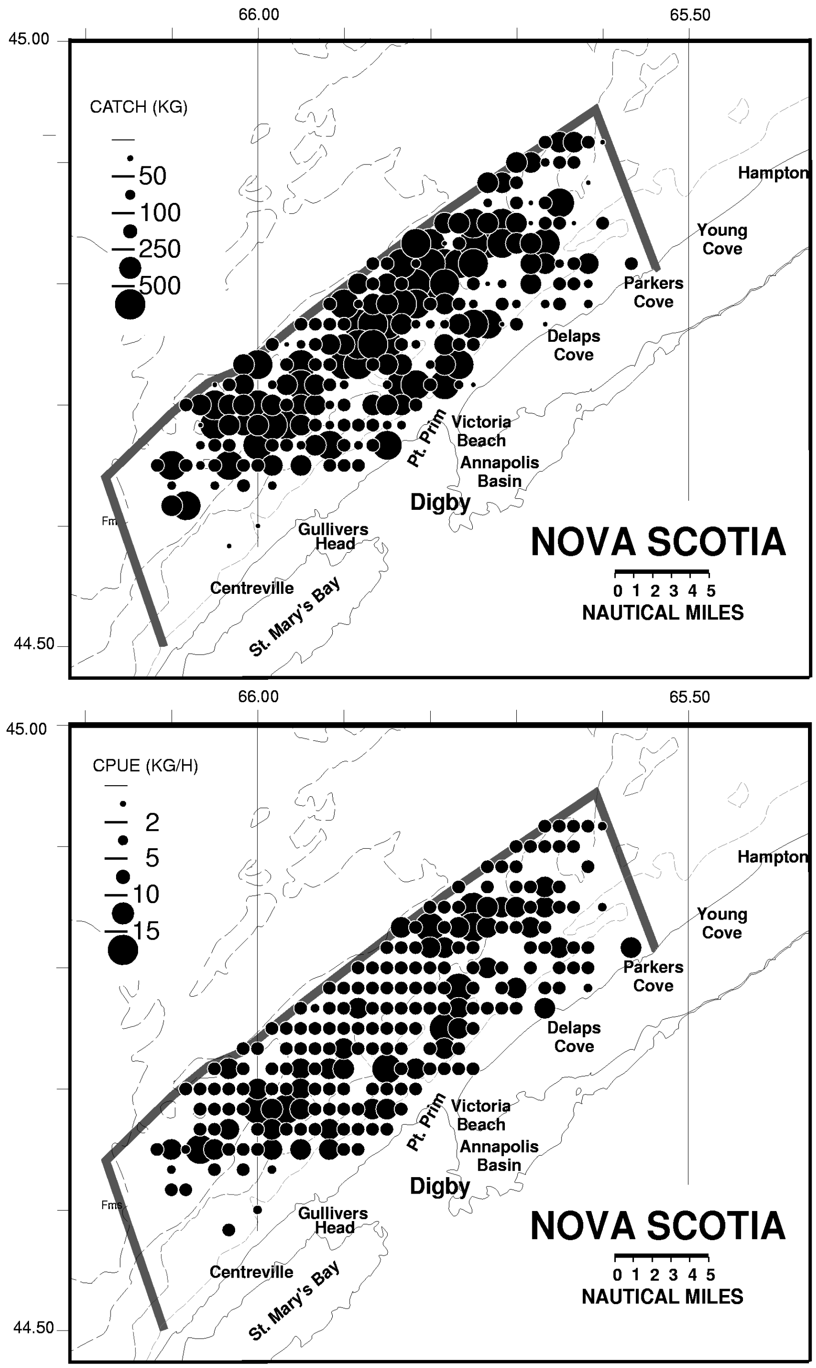

Fig. 8. Fishing locations from class 1 fishing logs in 1999 for scallops in Scallop Production Area 4. Upper panel: Catch (t). Lower panel: Catch-per-unit-effort (kg/h). Depths are given in fathoms (1.83 m = 1 fm).

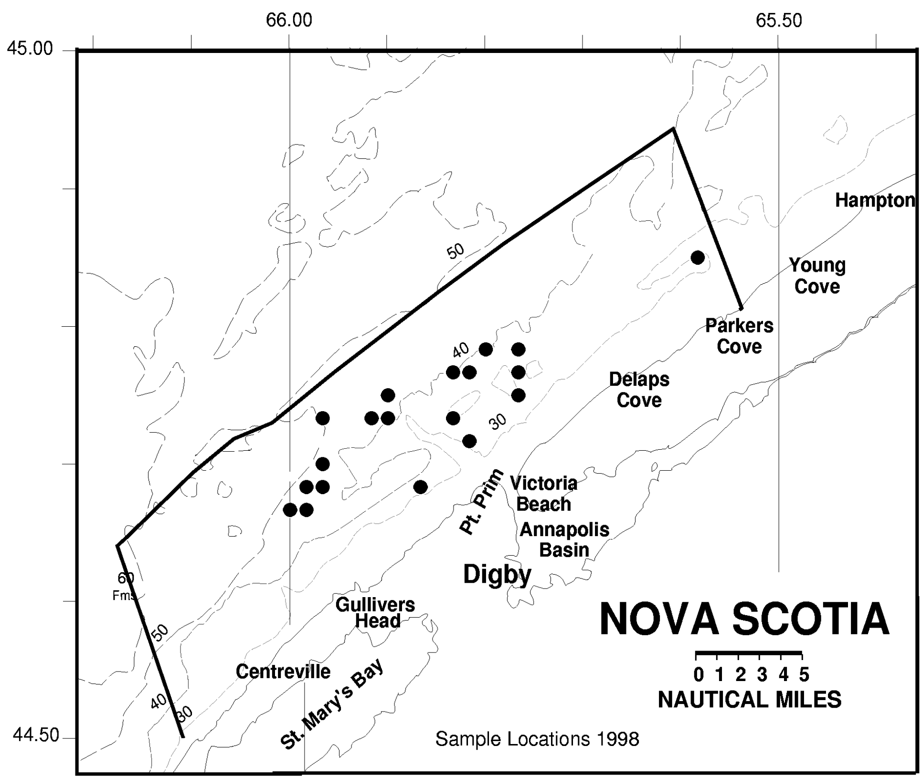

Fig. 9. Reported locations of catches sampled for meat weights in 1998 for scallops in Scallop Production Area 4. Depths are given in fathoms (1.83 m = 1 fm).

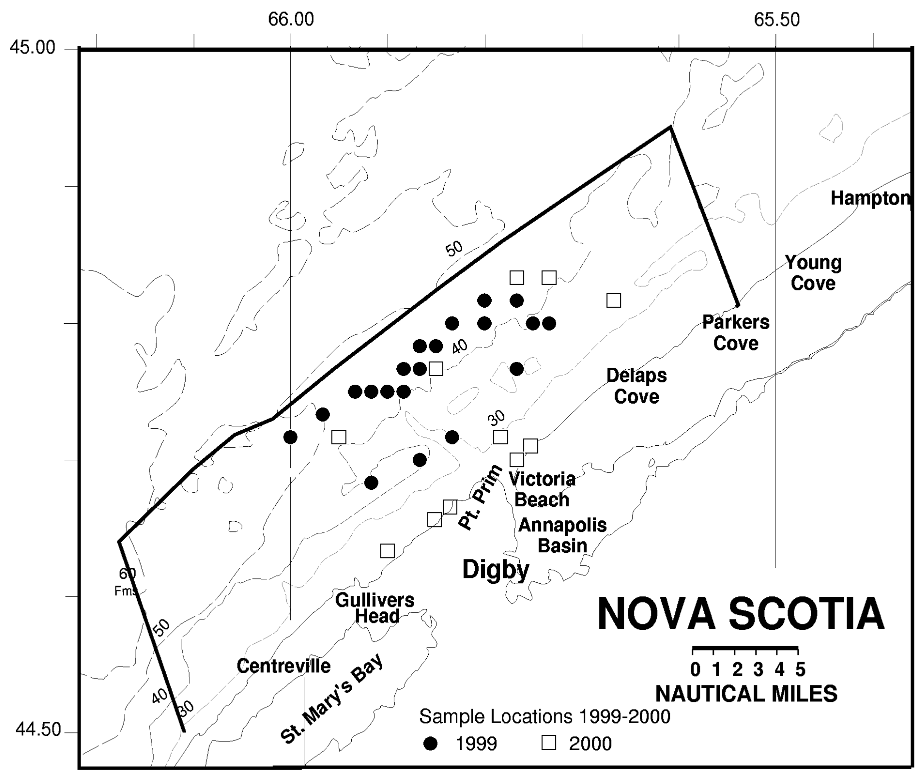

Fig. 10. Reported locations of catches sampled for meat weights in 1999 for scallops in Scallop Production Area 4. Depths are given in fathoms (1.83 m = 1 fm).

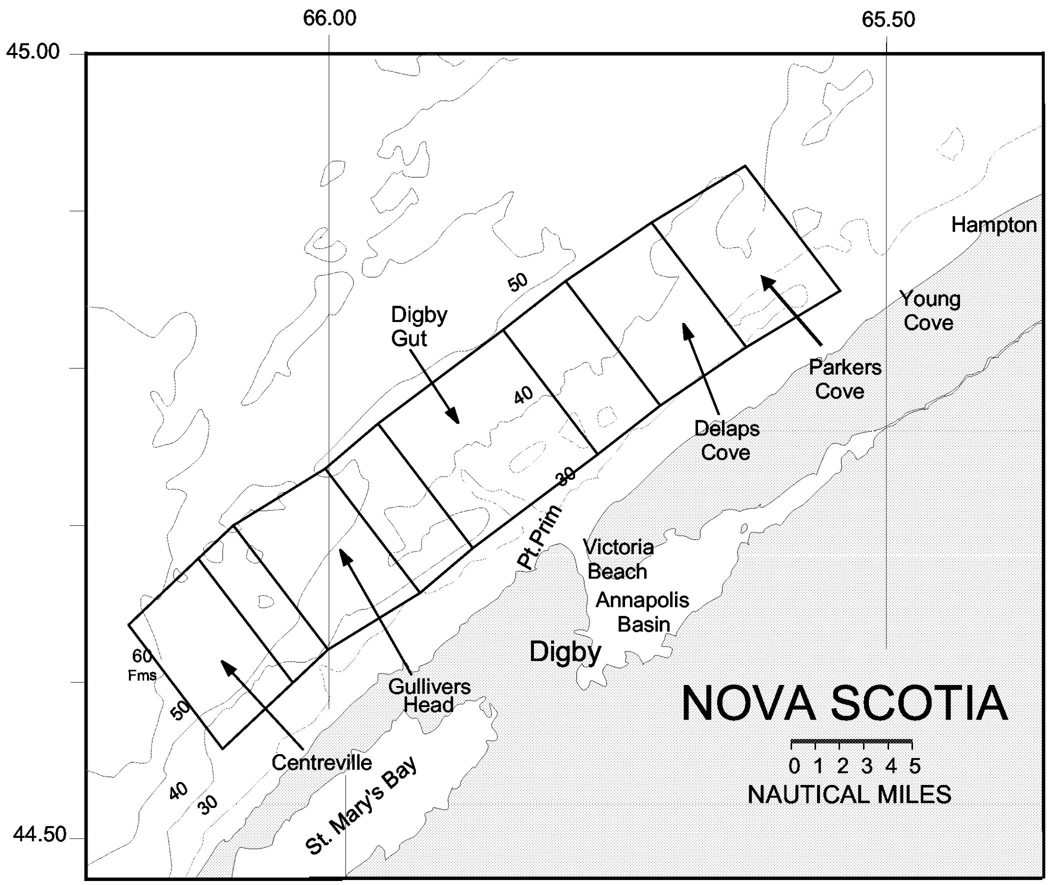

Fig. 11. Stratification scheme used in Scallop Production Area 4 in the Bay of Fundy.

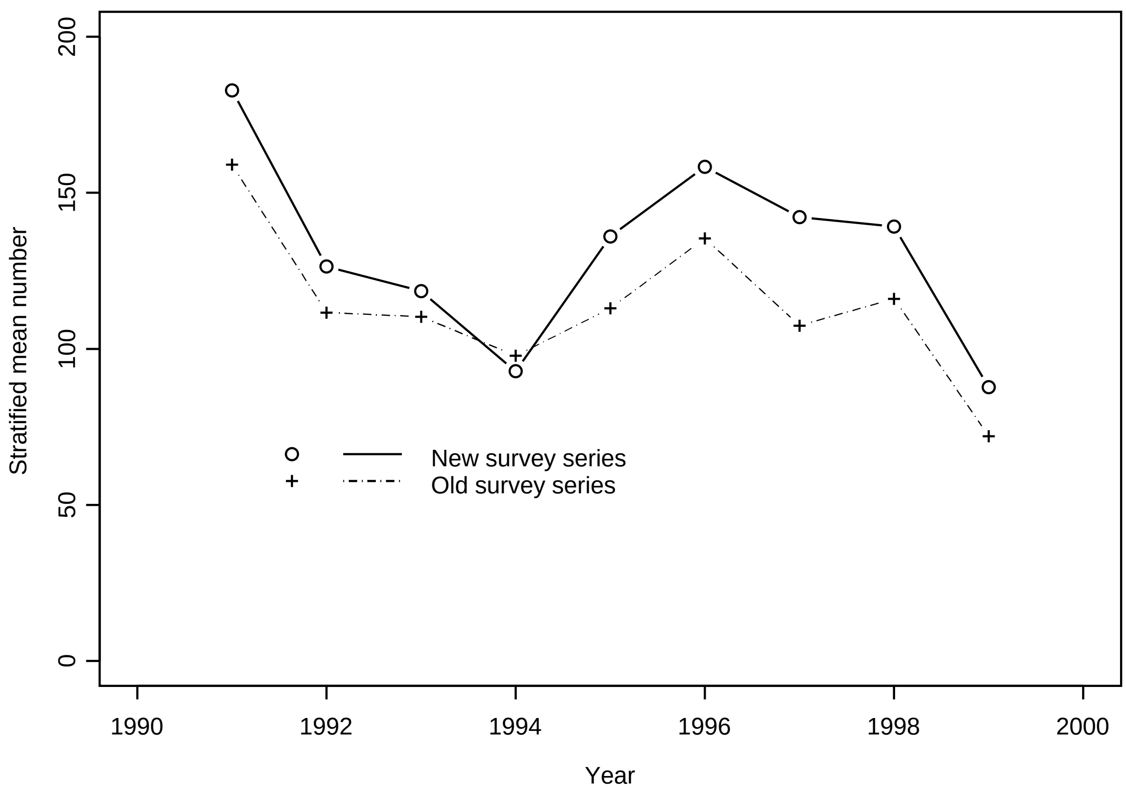

Fig. 12. Comparison between new and old survey series of stratified mean number per tow for all sizes of scallops combined. June survey of Scallop Production Area 4.

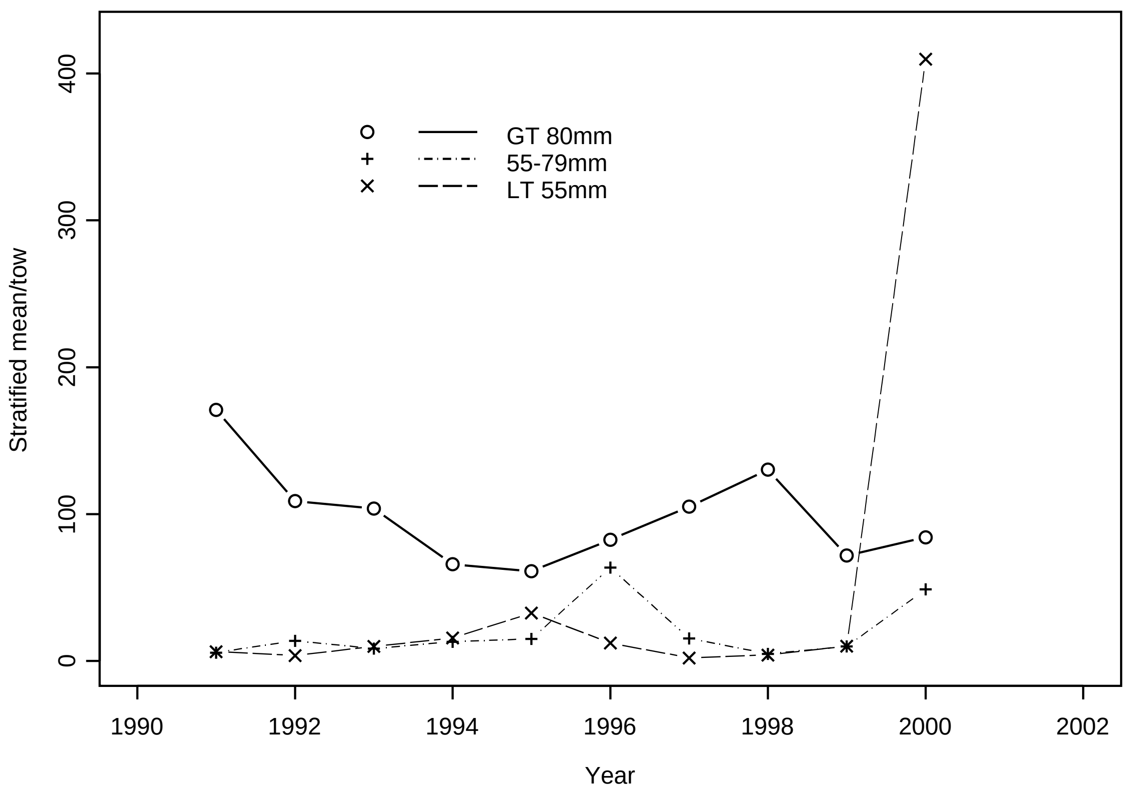

Fig. 13. Stratified mean number per tow from new survey series for specific shell height groups from June survey of Scallop Production Area 4.

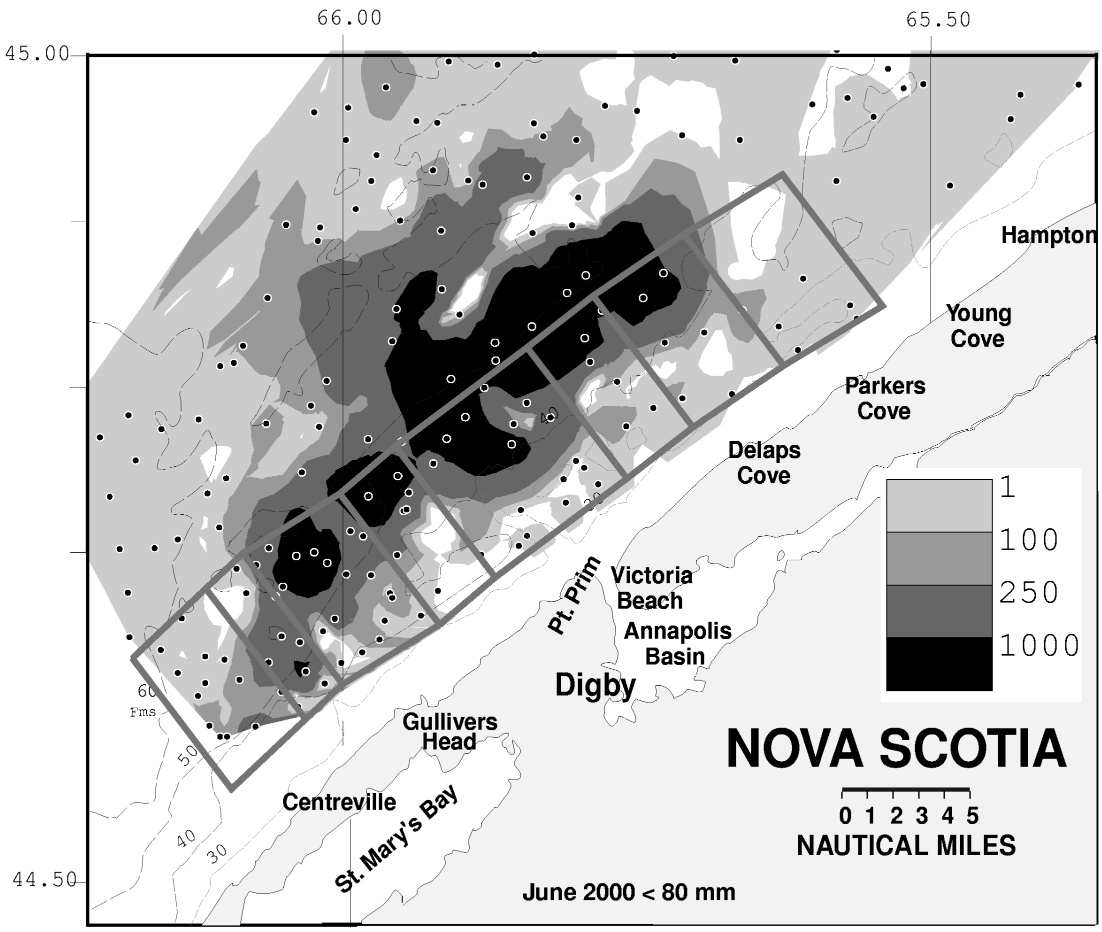

Fig. 14. Spatial distribution of scallop catches from the June 2000 survey of Scallop Production Area 4 for scallops with shell heights less than 80 mm. Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm).

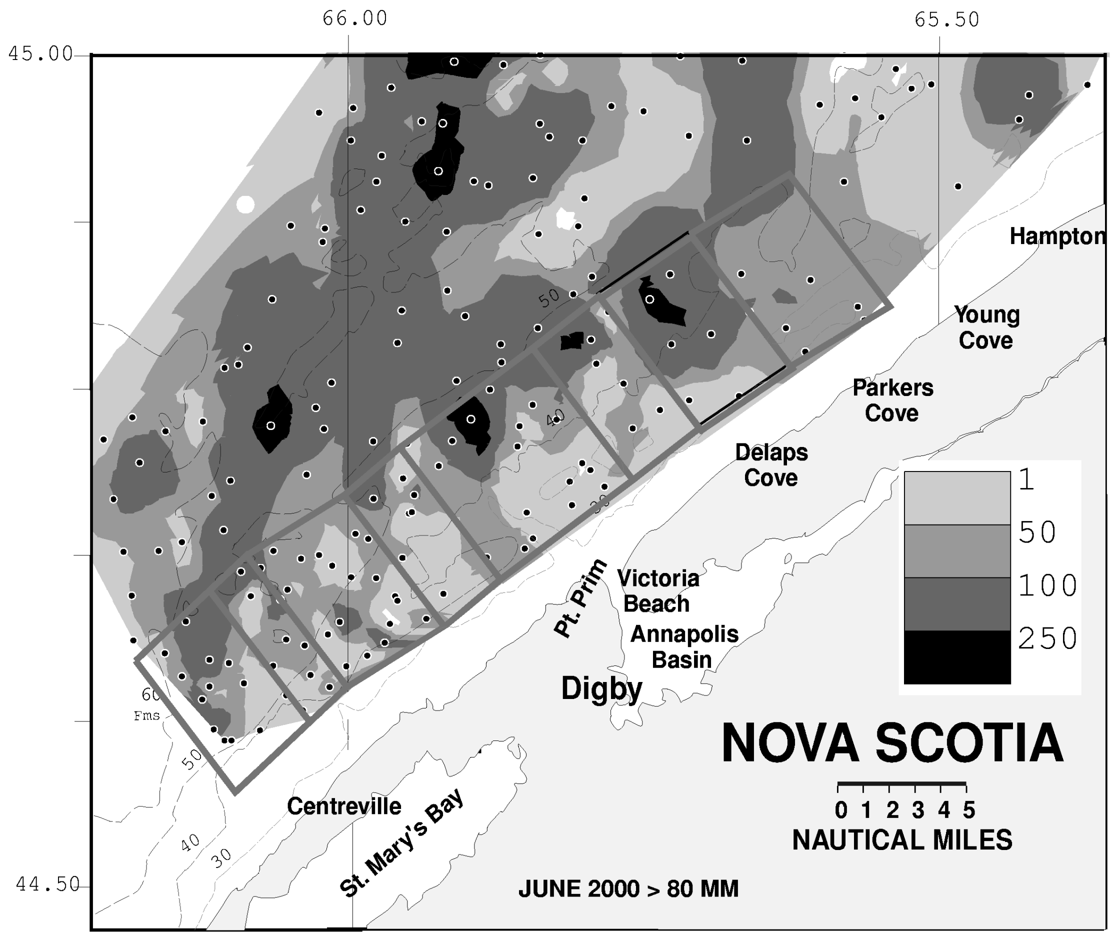

Fig. 15. Spatial distribution of scallop catches from the June survey of Scallop Production Area 4 for scallops with shell heights greater than or equal to 80 mm. Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm).

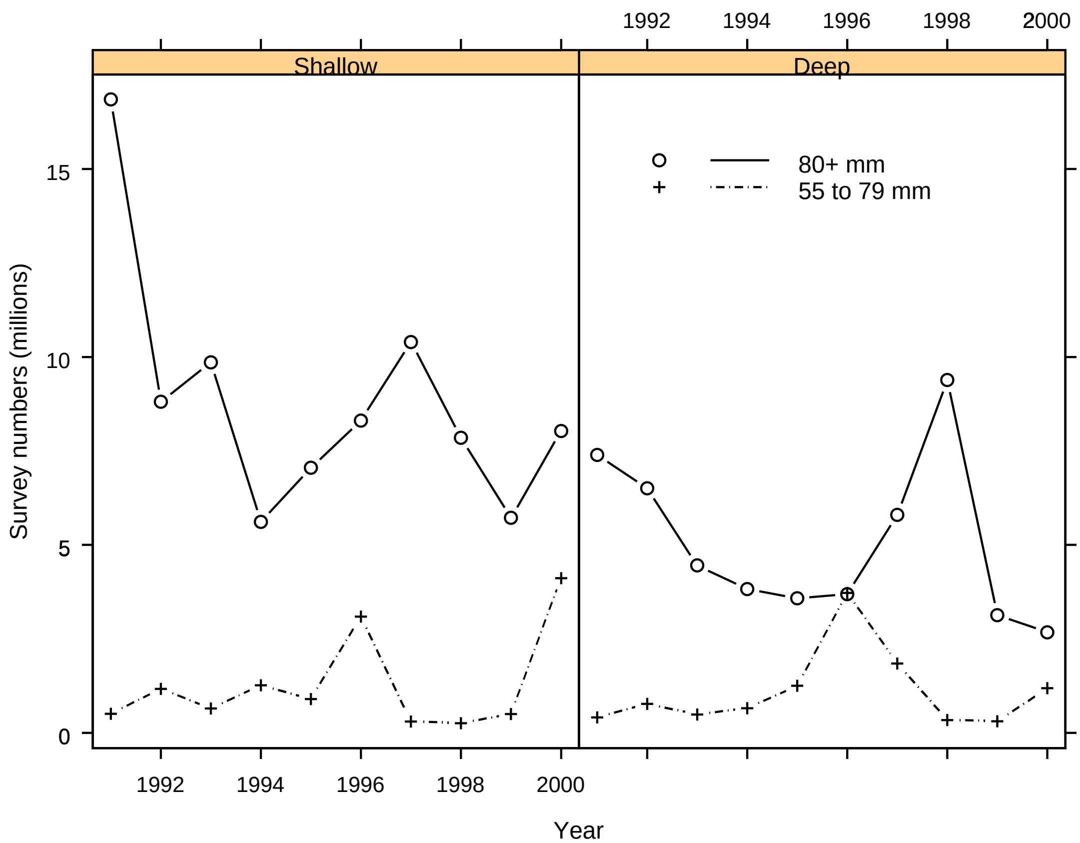

Fig. 16. Estimates of stratified total numbers of scallops by size range and depth range from June surveys of Scallop Production Area 4. The panel labelled Shallow corresponds to trends for depths less than or equal to 90 m while the Deep panel is for depths greater than 90 m. Research survey series corrected for editing changes and recalculated tow distances.

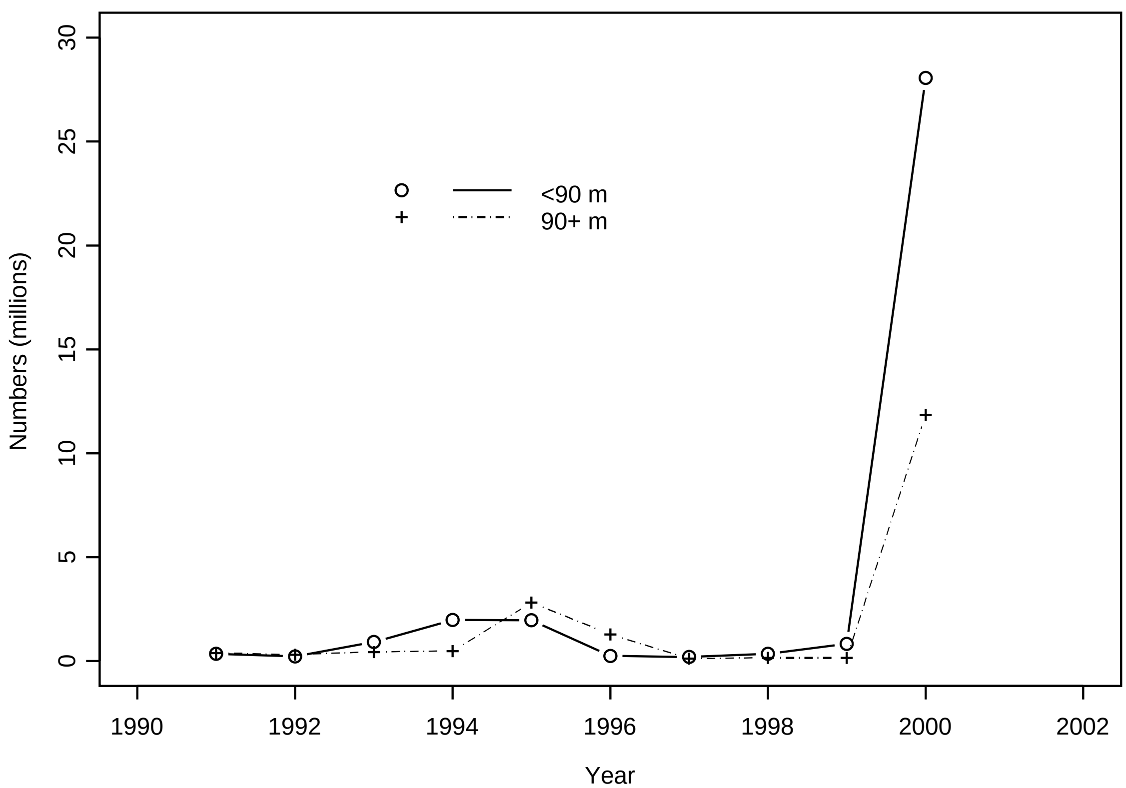

Fig. 17. Estimates of stratified total numbers of scallops with shell height less less than 55 mm and by depth range from June surveys of Scallop Production Area 4. Research survey series corrected for editing changes and recalculated tow distances.

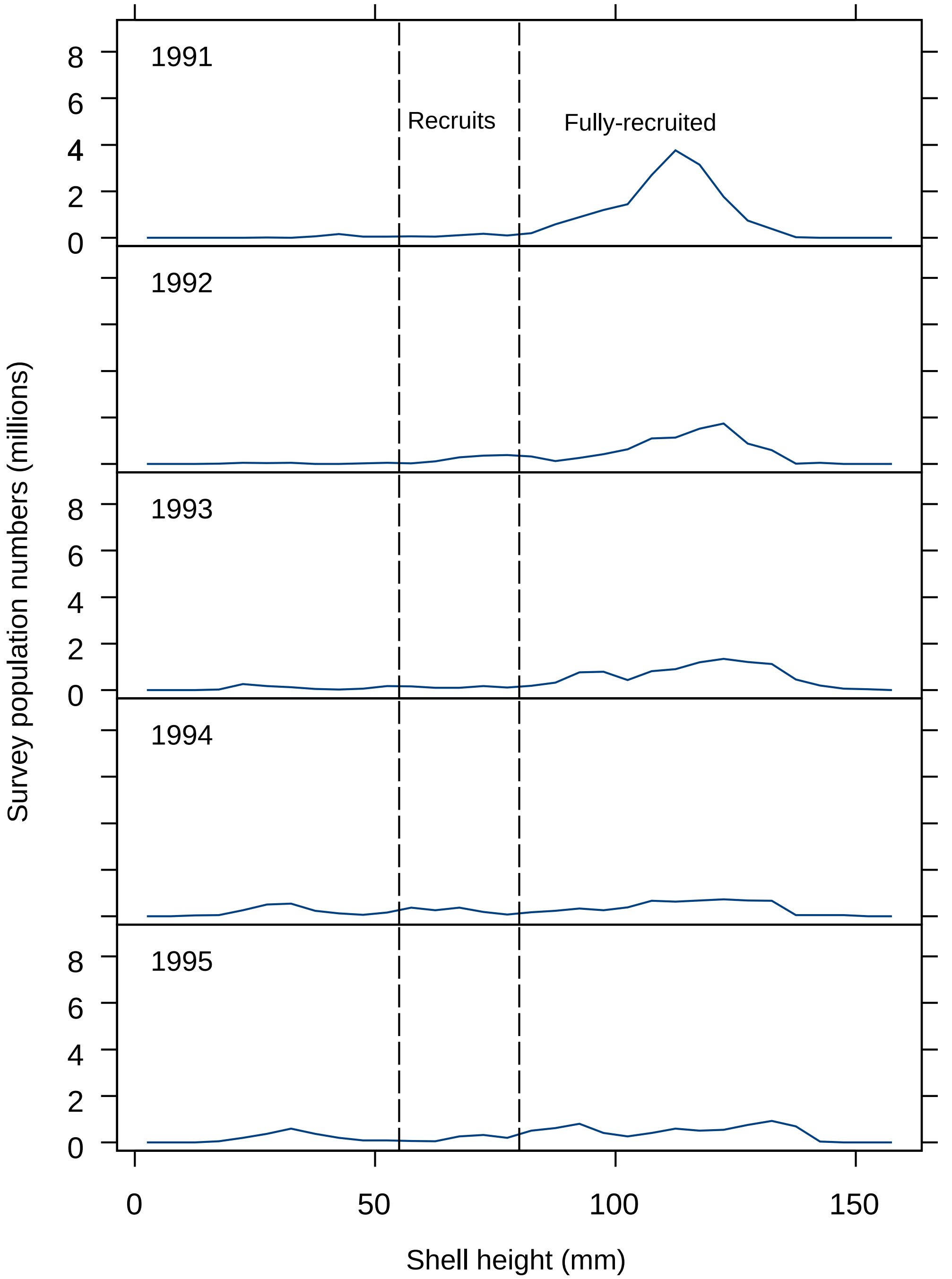

Fig. 18. Shell height frequencies (stratified total number) from the June 1991 to 1995 survey of Scallop Production Area 4 for areas with depth less than or equal to 90 m.

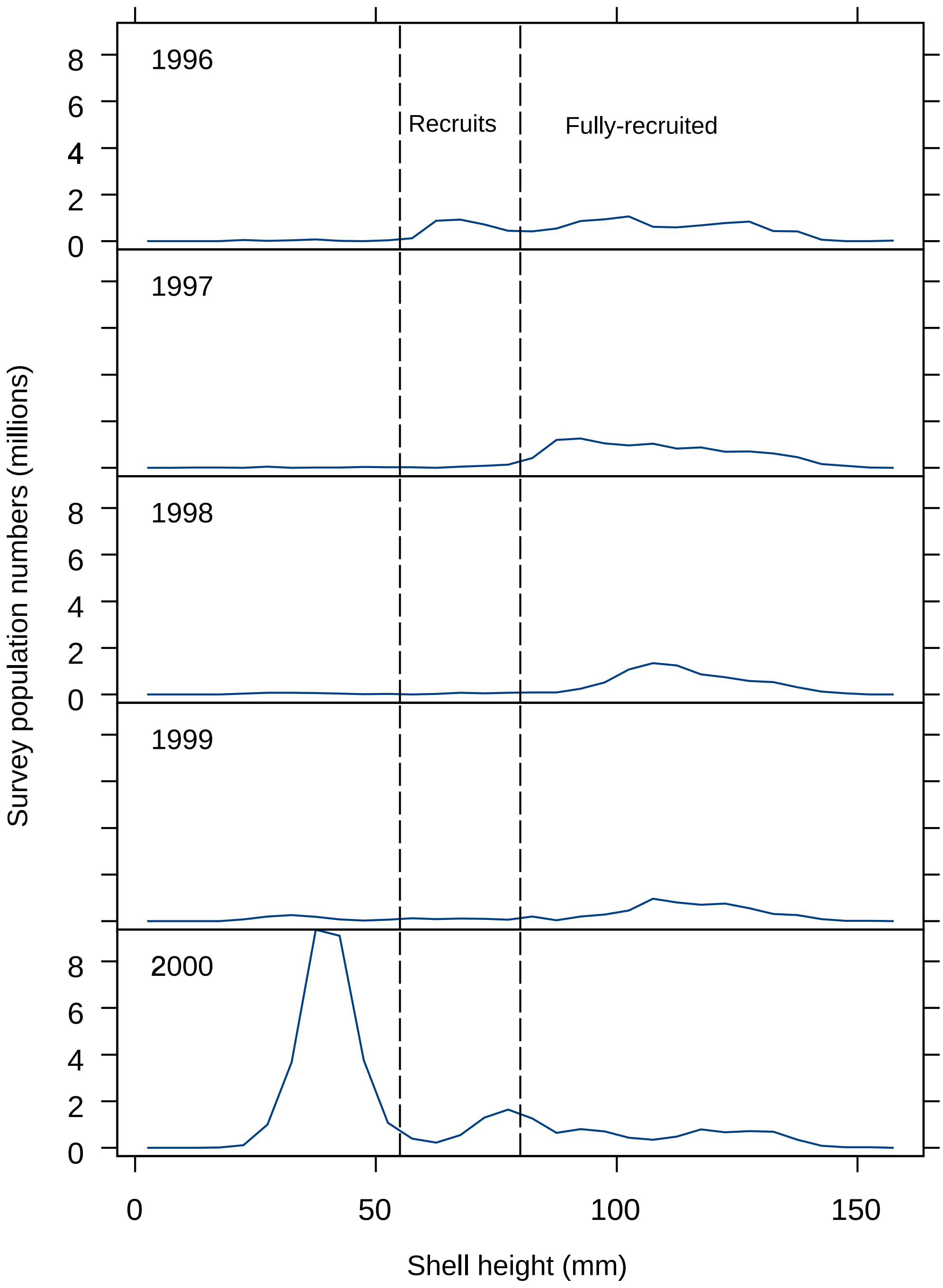

Fig. 19. Shell height frequencies (stratified total number) from the June 1996 to 2000 survey of Scallop Production Area 4 for areas with depth less than or equal to 90 m.

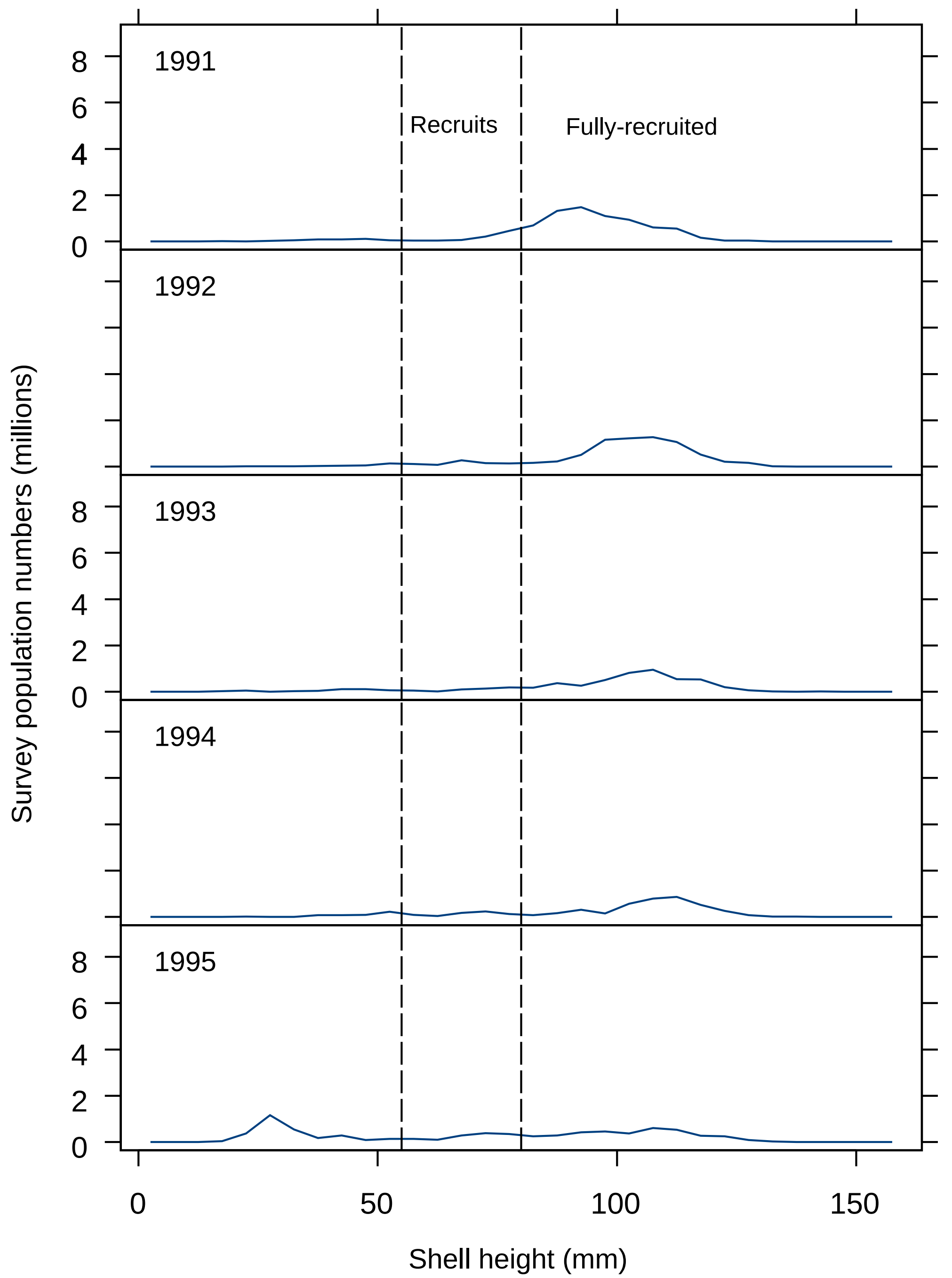

Fig. 20. Shell height frequencies (stratified total number) from the June 1991 to 1995 survey of Scallop Production Area 4 for areas with depths greater than 90 m.

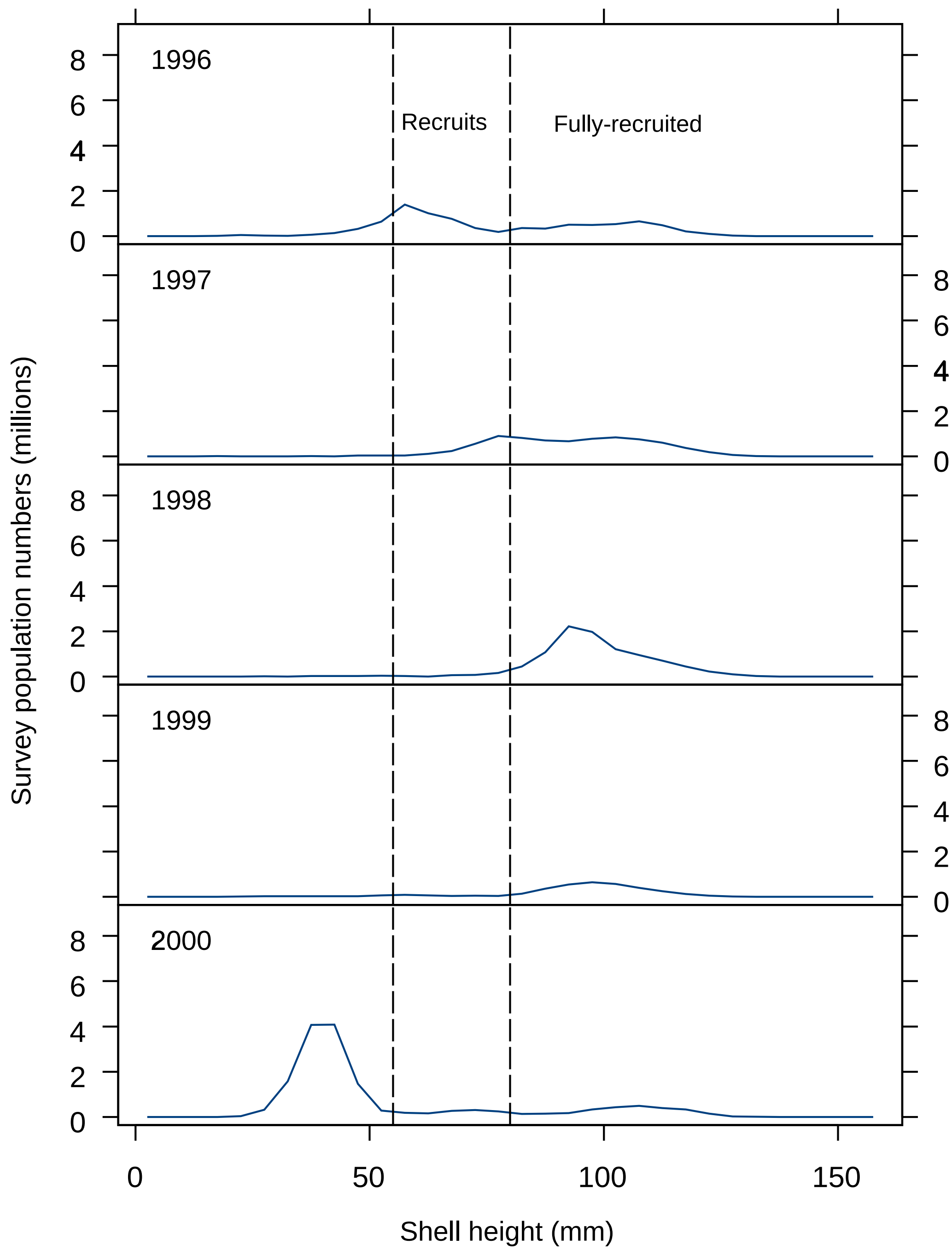

Fig. 21. Shell height frequencies (stratified total number) from the June 1996 to 2000 survey of Scallop Production Area 4 for areas with depths greater than 90 m.

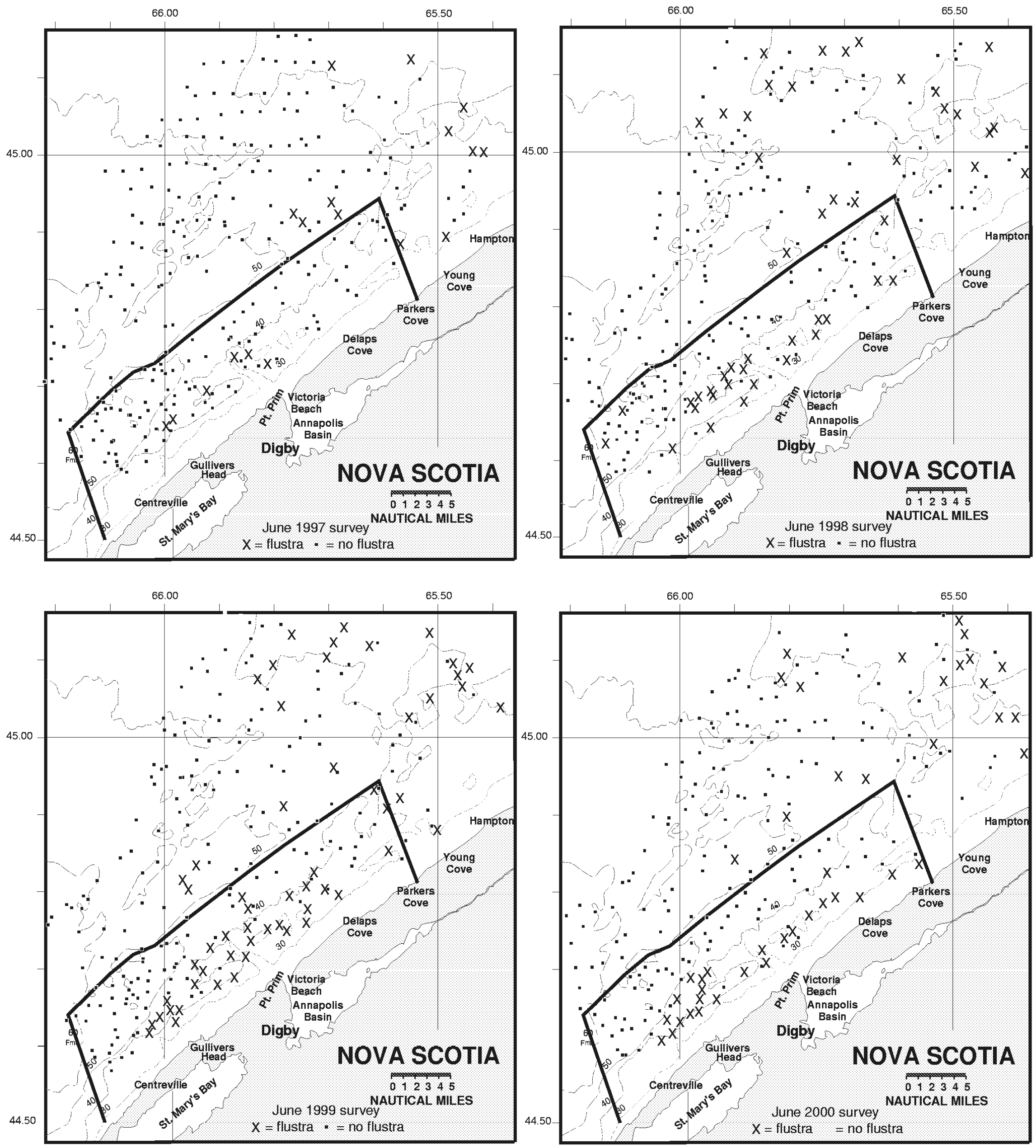

Fig. 22. Positions of tows made during the June survey of Bay of Fundy from 1997 to 2000 inclusive. Tows with lemonweed (*Flustra foliacea*) in the dredge indicated by an X and tows with no lemonweed indicated as (.). Depths are given in fathoms (1.83 m = 1 fm).

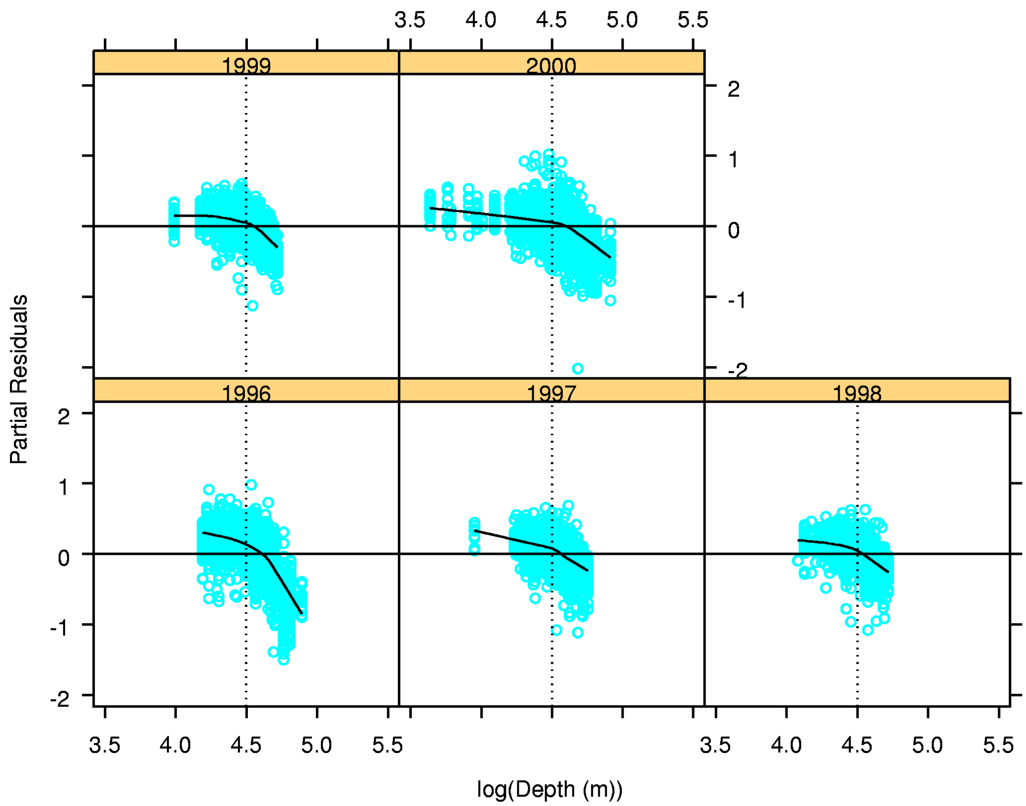

Fig. 23. Partial residual plots for model log(weight)=log(height)+log(depth) for each year for scallops in Scallop Production Area 4. Dotted vertical line indicates position of log(depth=90 m). Trend line fitted using a loess curve.

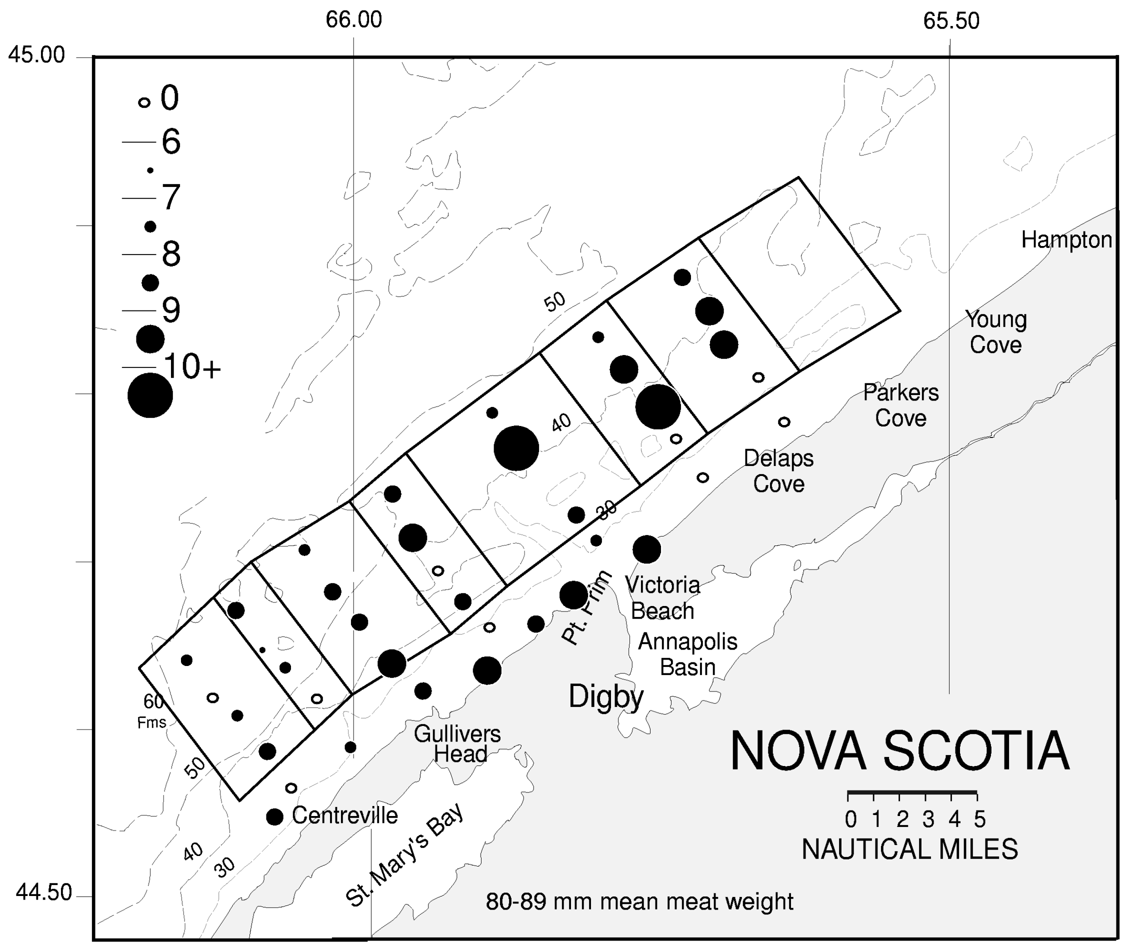

Fig. 24. Average meat weight for scallops with shell heights of 80 to 89 mm from February 2000 survey of Scallop Production Area 4. Depths are given in fathoms (1.83 m = 1 fm).

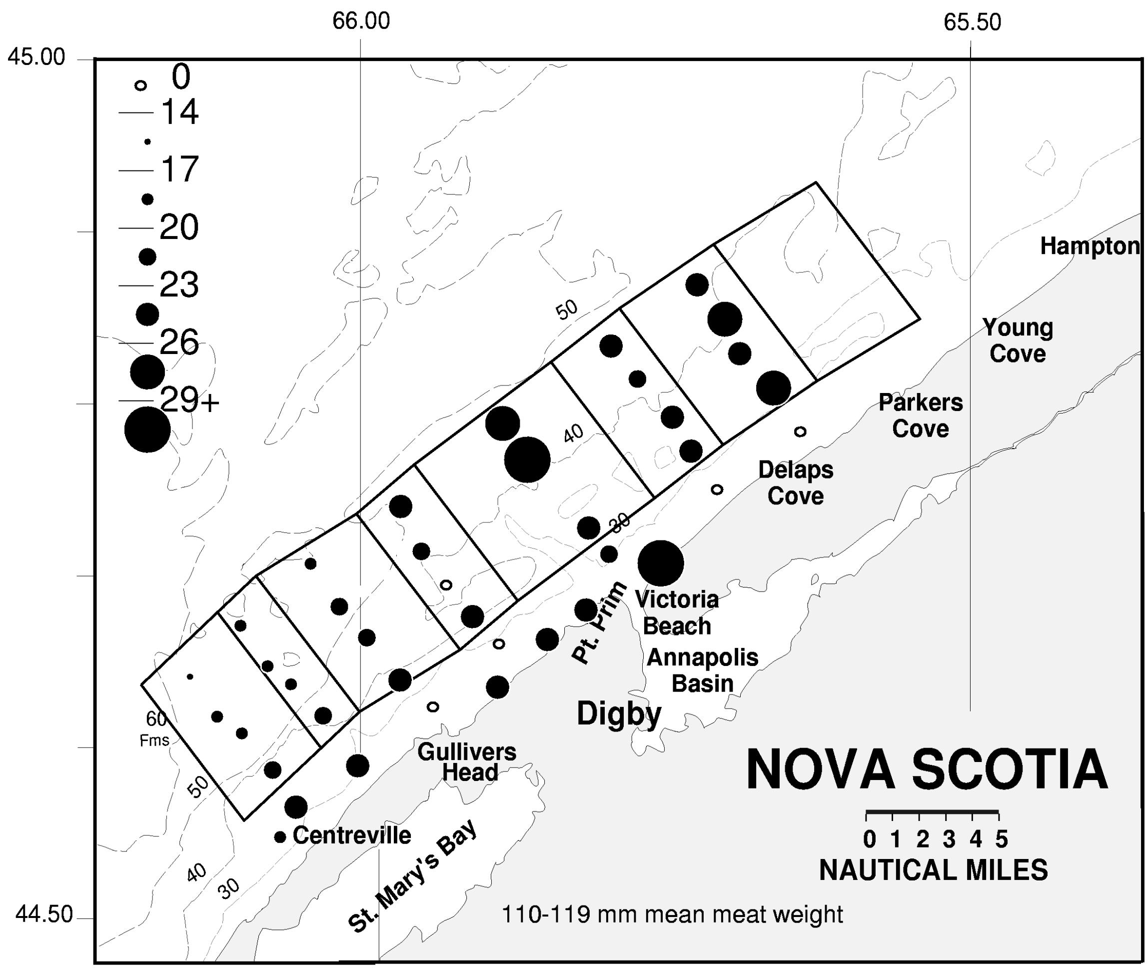

Fig. 25. Average meat weight for scallops with shell heights of 110 to 119 mm from February 2000 survey of Scallop Production Area 4. Depths are given in fathoms (1.83 m = 1 fm).

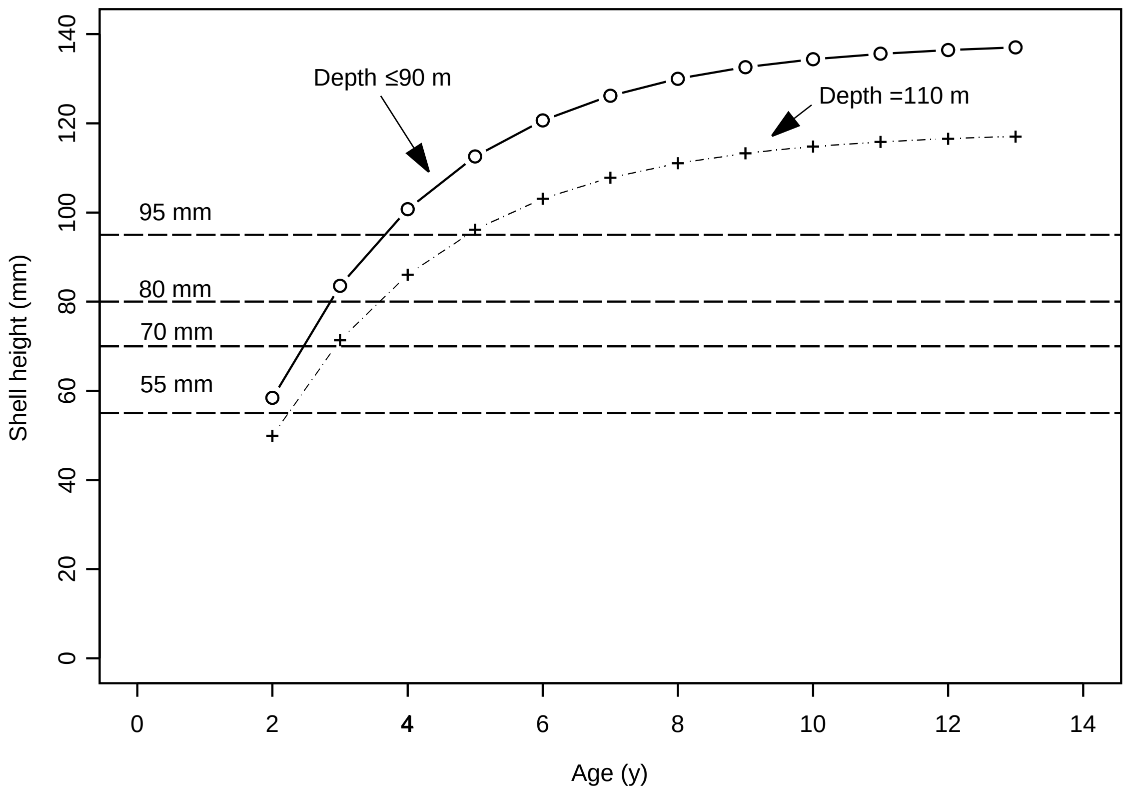

Fig. 26. Estimates of shell height-at-age for scallops in Scallop Production Area 4 based on the growth models developed in Smith et al. (in press). Specific shell heights used in paper to define recruits and fully-recruited are indicated. Only two growth curves are shown here for illustration purposes.

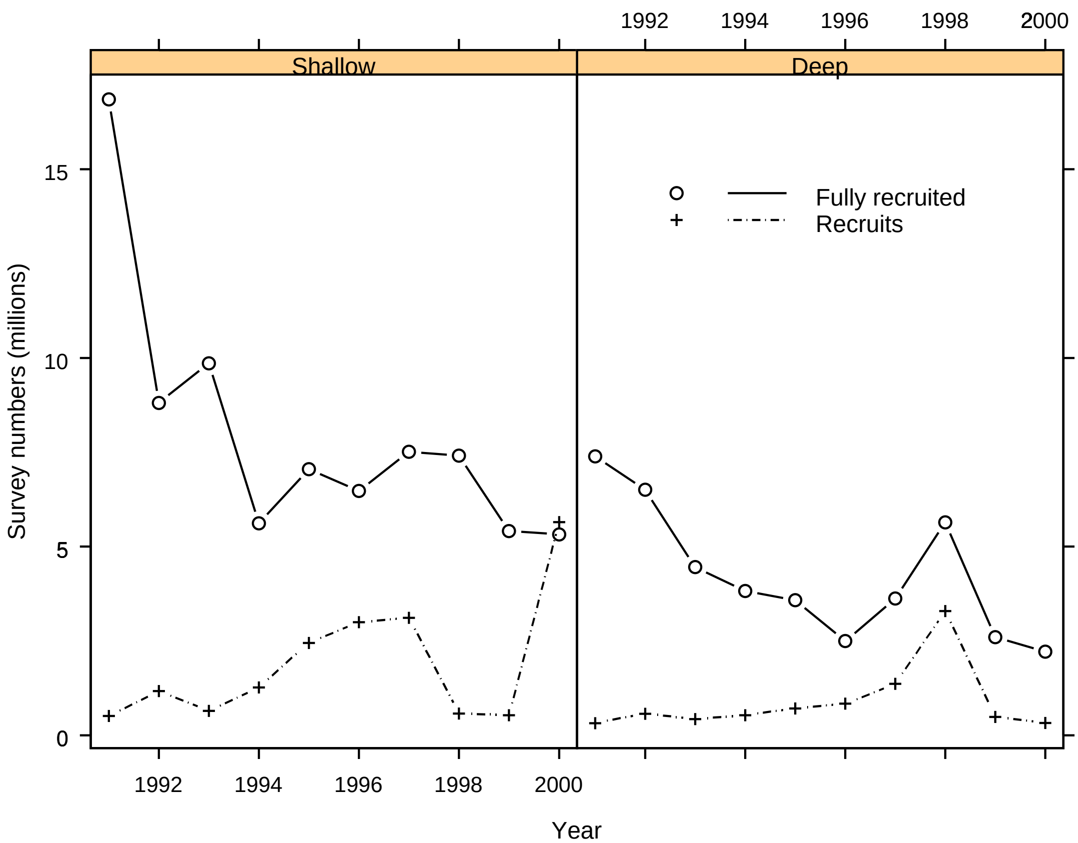

Fig. 27. Estimates of stratified total numbers of scallops by size class and depth range from June surveys of Scallop Production Area 4 used for updated modified DeLury model. The panel labelled Shallow corresponds to trends for depths less than or equal to 90 m while the Deep panel is for depths greater than 90 m.

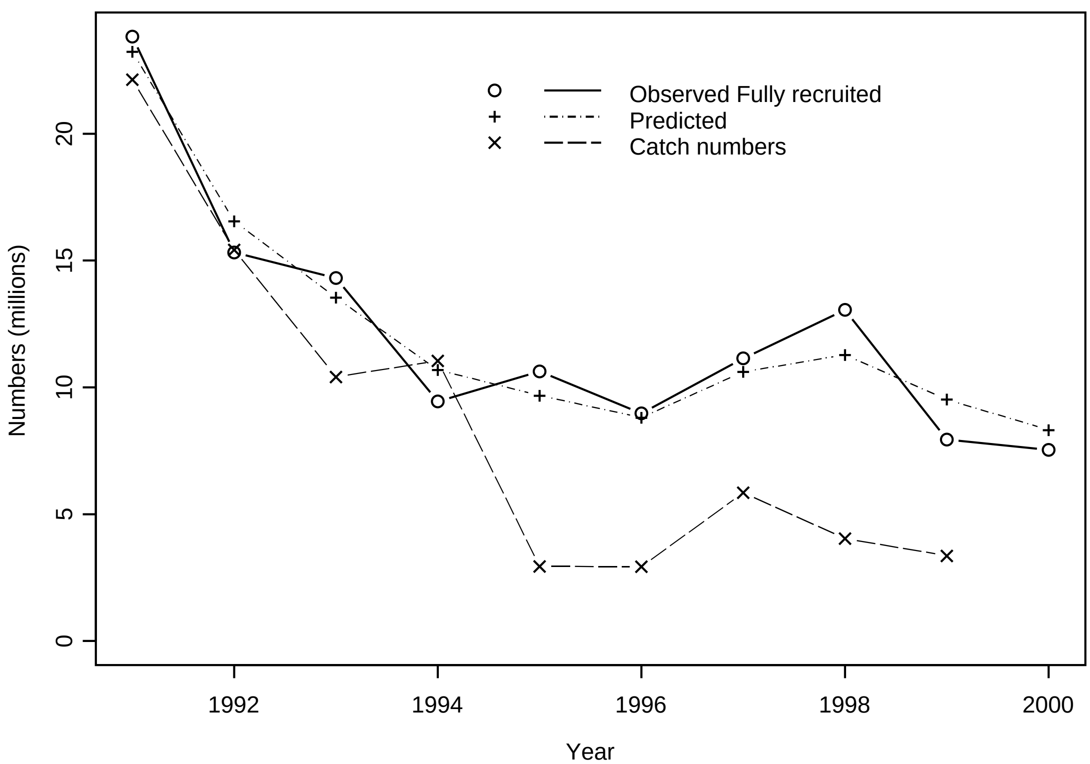

Fig. 28. Observed and predicted survey indices for fully-recruited scallops in Scallop Production Area 4 from the modified DeLury model 1 — all weights equal in objective function. Commercial catch shown for reference.

Fig. 29. Population estimates of numbers of fully-recruited and recruits for Scallop Production Area 4 from the modified DeLury model 1 — all weights equal in objective function. Estimated fishing mortality included as well. Note $\hat{q}_n = \hat{q}_r = 0.26$.

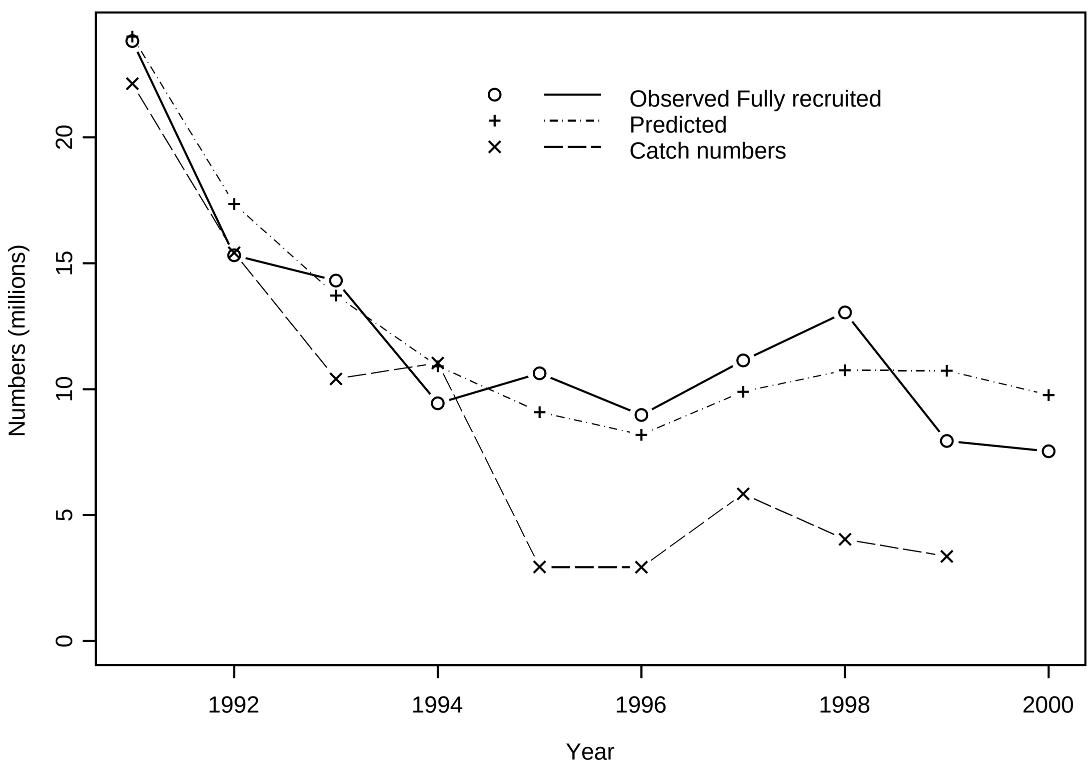

Fig. 30. Observed and predicted survey indices for fully-recruited scallops in Scallop Production Area 4 from the modified DeLury model 2 — minimize process error. Commercial catch shown for reference.

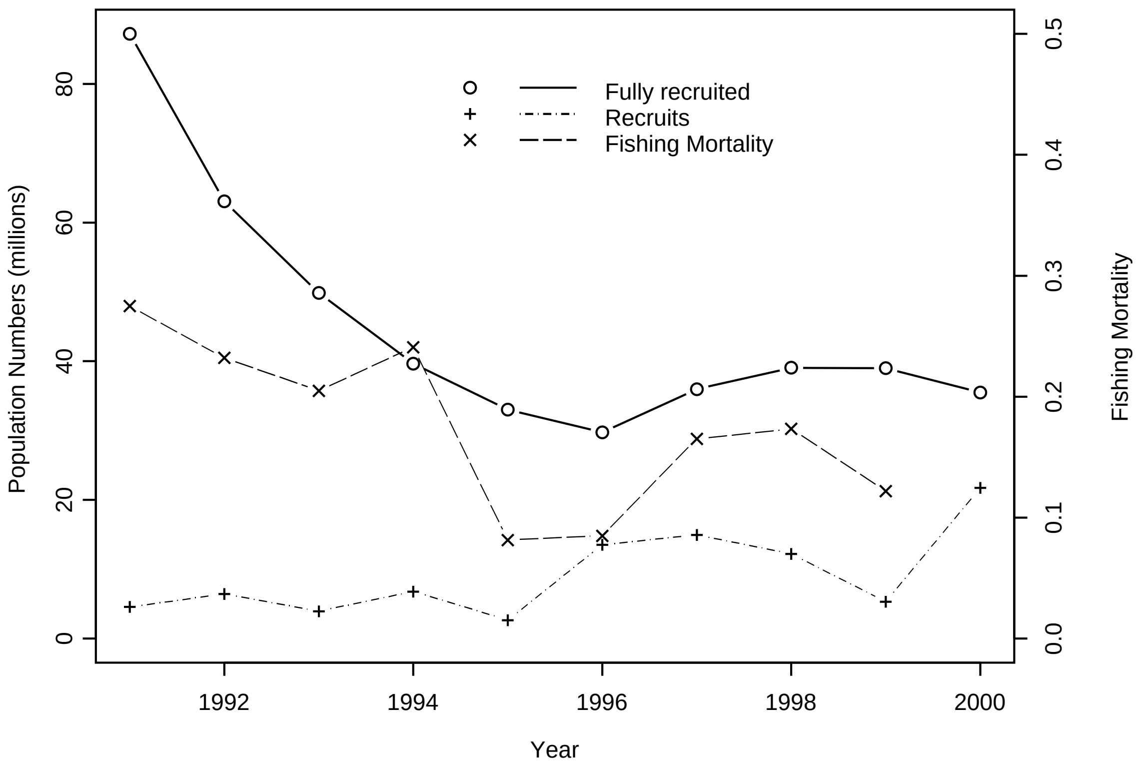

Fig. 31. Population estimates of numbers of fully-recruited and recruits for Scallop Production Area 4 from the modified DeLury model 2 — minimize process error. Estimated fishing mortality included as well. Note $\hat{q}_n = \hat{q}_r = 0.28$.

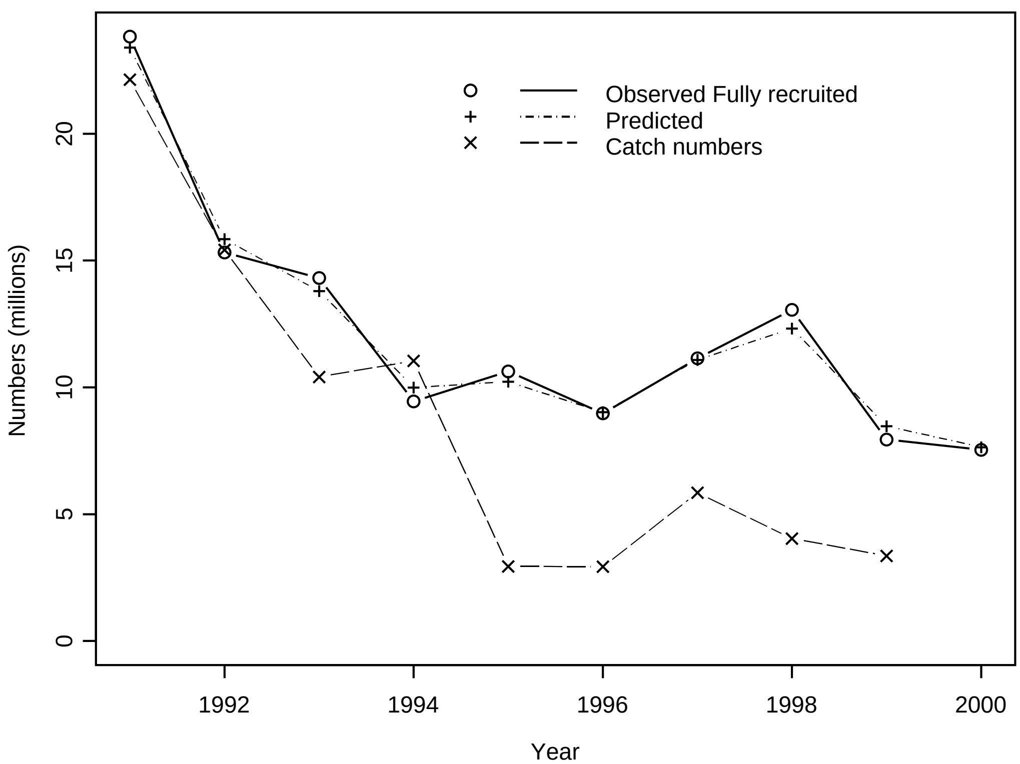

Fig. 32. Observed and predicted survey indices for fully-recruited scallops in Scallop Production Area 4 from the modified DeLury model 3 — minimize measurement error. Commercial catch shown for reference.

Fig. 33. Population estimates of numbers of fully-recruited and recruits for Scallop Production Area 4 from the modified DeLury model 3 — minimize measurement error. Estimated fishing mortality included as well. Note $\hat{q}_n = \hat{q}_r = 0.24$.

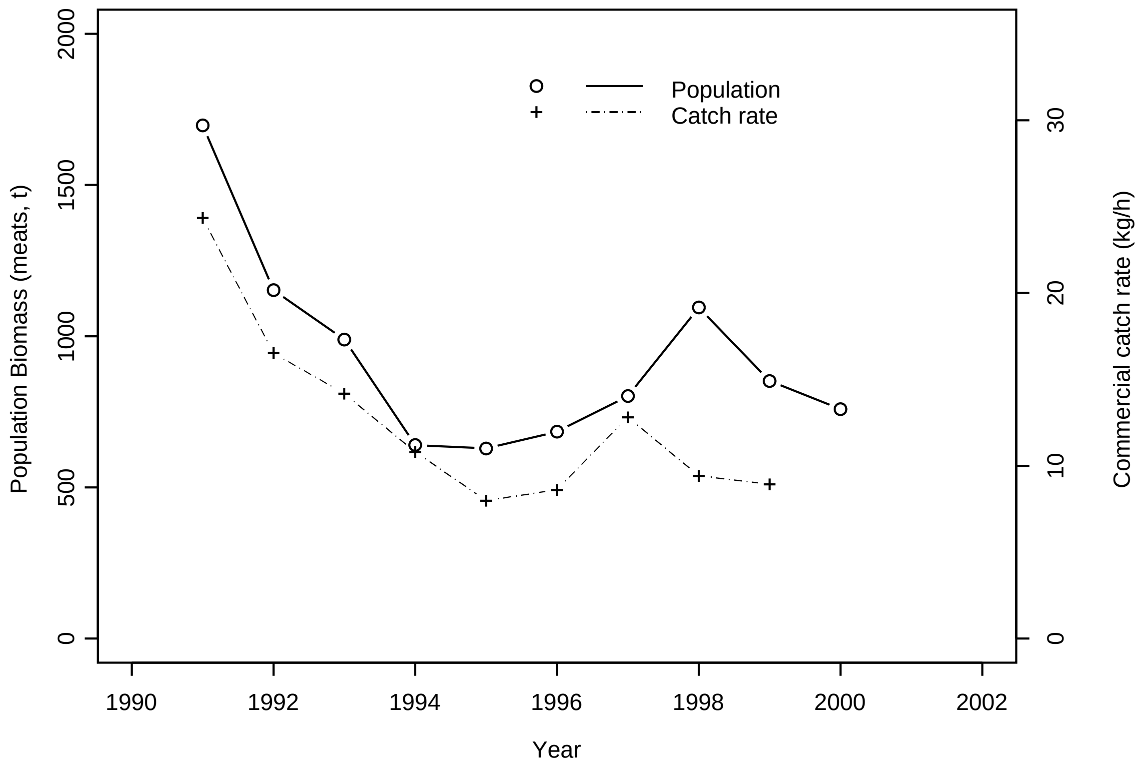

Fig. 34. Predicted population biomass of fully recruited scallops in Scallop Production Area 4 from the re-formulated modified DeLury model. Commercial catch-per-unit effort also presented for comparison.

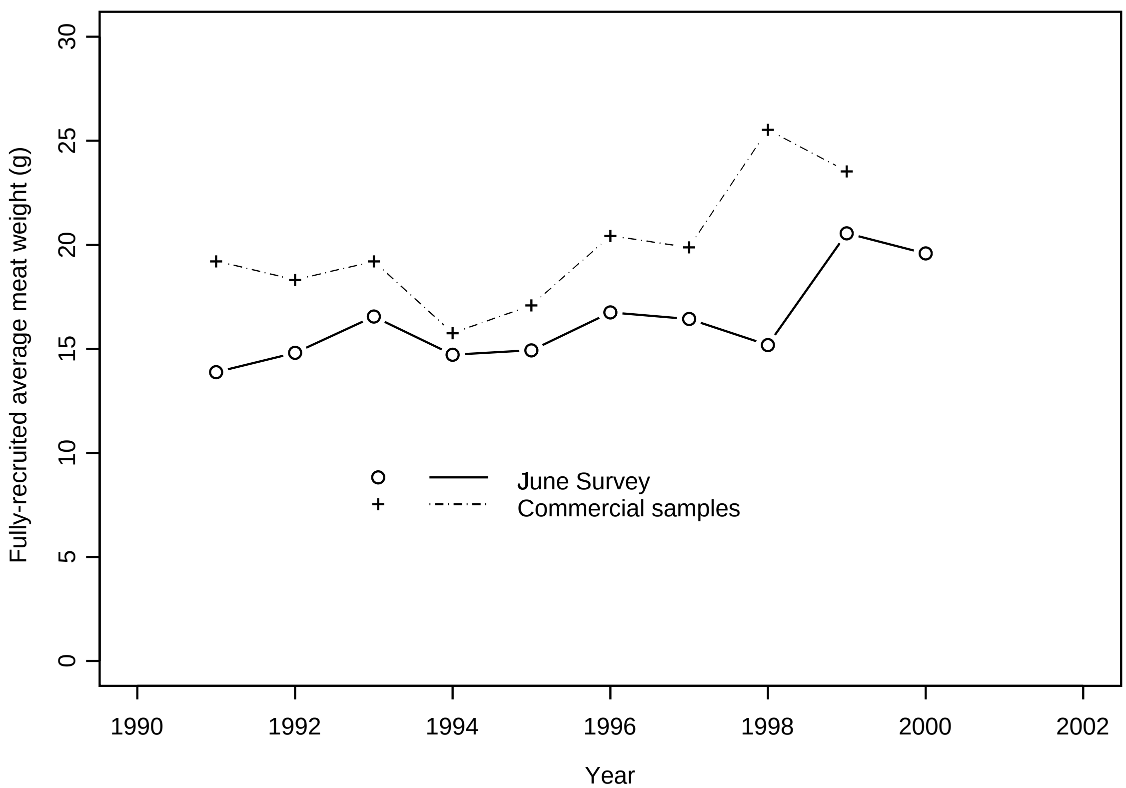

Fig. 35. A comparison of average meat weights from fully recruited scallops from June survey with those from commercial samples for Scallop Production Area 4.

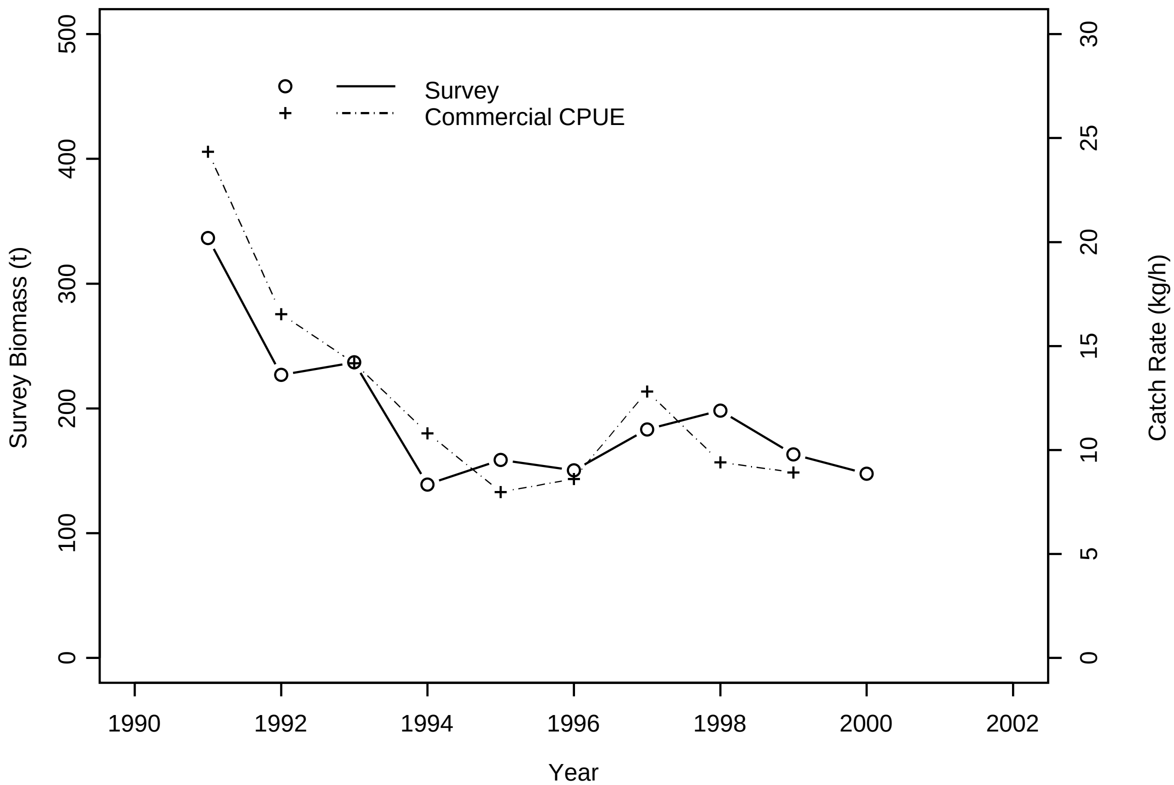

Fig. 36. Comparison of total biomass of scallops meats estimated from the research survey with the commercial catch per unit effort based on survey year for Scallop Production Area 4. Note biomass for surveys in 1991 to 1995 were estimated using the shell height/meat weight relationship from the 1996 survey.

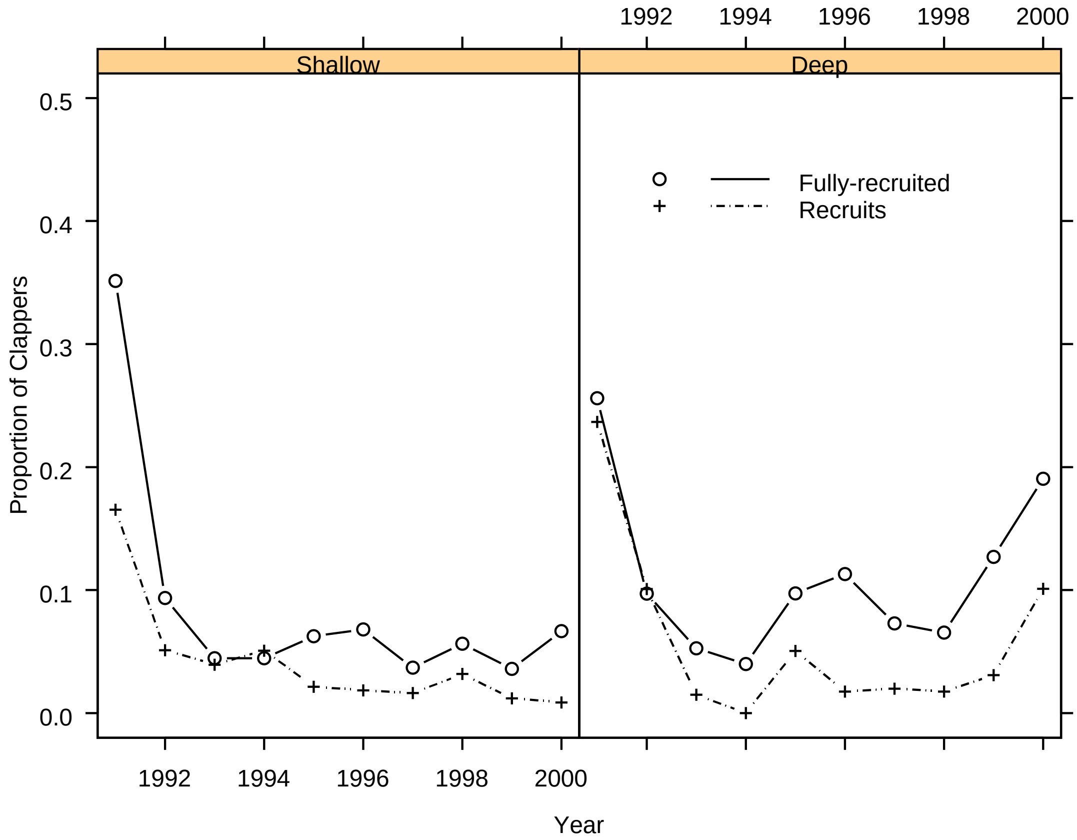

Fig. 37. Estimated proportion of clappers (dead paired shells) from survey for depths less than or equal to 90 m (Shallow) and greater than 90 m (Deep) in Scallop Production Area 4. Fully recruited and recruits are as defined for modified DeLury model.

Fig. 38. Estimated mortality rate from clappers (dead paired shells) caught in survey in Scallop Production Area 4. Fully-recruited and recruits scallops are as defined for modified DeLury model. Note that the average expected length of time that the shells remain attached at the hinge was assumed to be one year for these calculations. See text for more details.

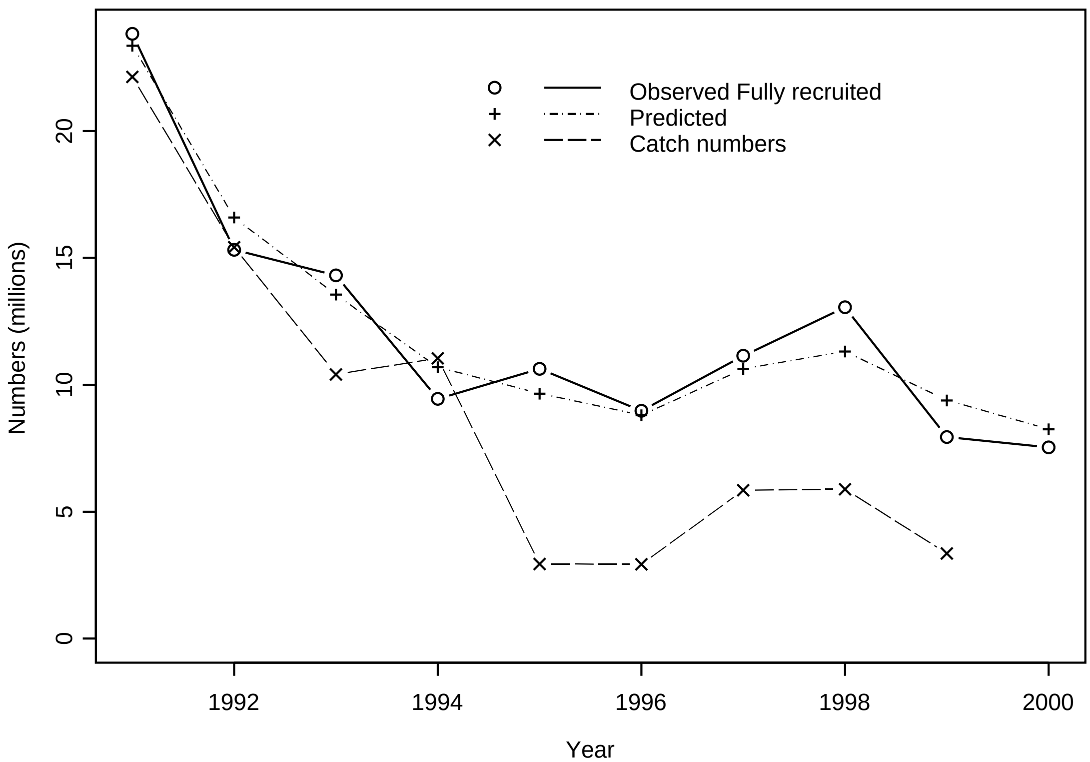

Fig. 39. Observed and predicted survey indices fully-recruited scallops in Scallop Production Area 4 from the modified DeLury model 1 — all weights equal in objective function. Commercial catch shown for reference. Average meat weight for 1998 set to 17.5 g.

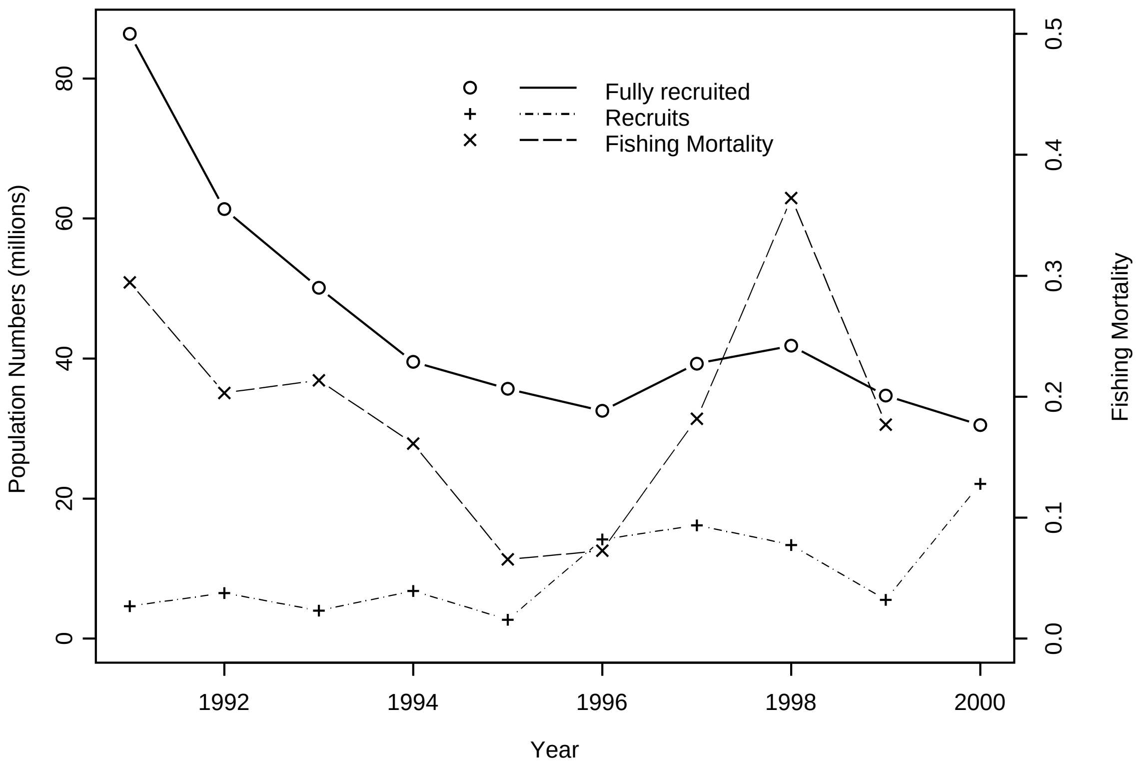

Fig. 40. Population estimates of numbers of fully-recruited and recruits for Scallop Production Area 4 from the modified DeLury model 1 — all weights equal in objective function. Average meat weight for 1998 set to 17.5 g. Estimated fishing mortality included as well. Note $\hat{q}_n = \hat{q}_r = 0.26$.

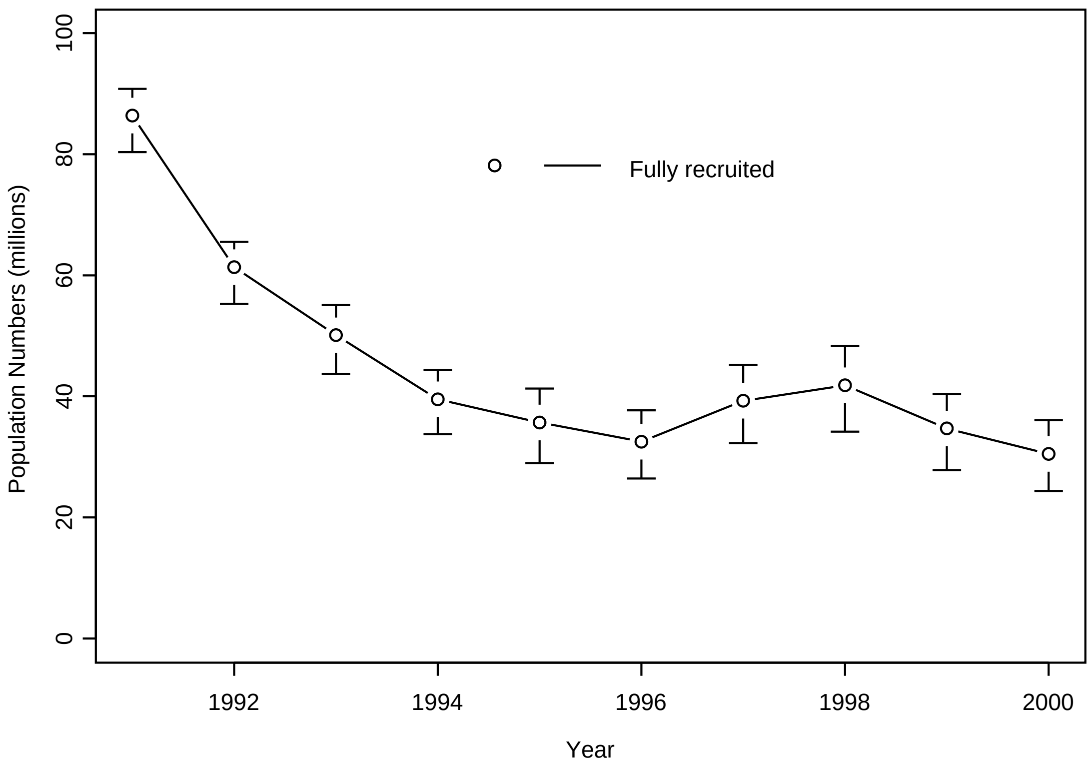

Fig. 41. Bootstrap confidence limits (1000 replicates) for estimated population numbers in Scallop production area 4 from the modified DeLury model 1 — all weights equal in objective function. Average meat weight for 1998 set to 17.5 g.

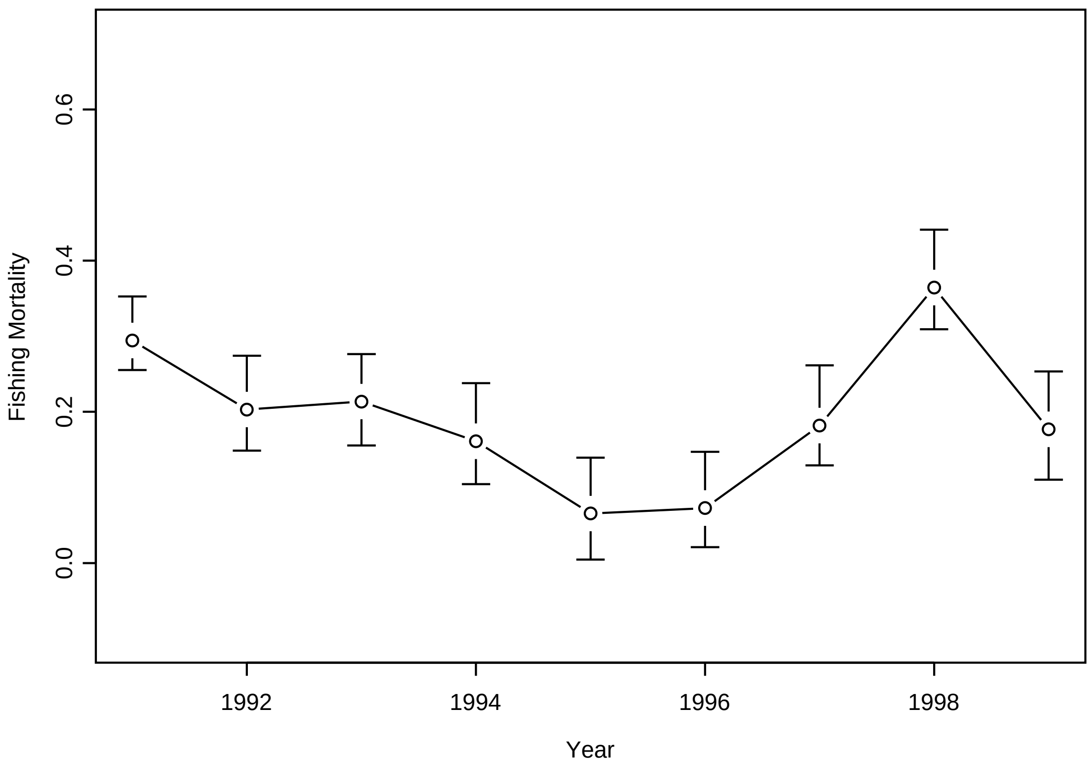

Fig. 42. Bootstrap confidence limits (1000 replicates) for estimated fishing mortality in Scallop production area 4 from the modified DeLury model 1 — all weights equal in objective function. Average meat weight for 1998 set to 17.5 g. Scallop production area 4.

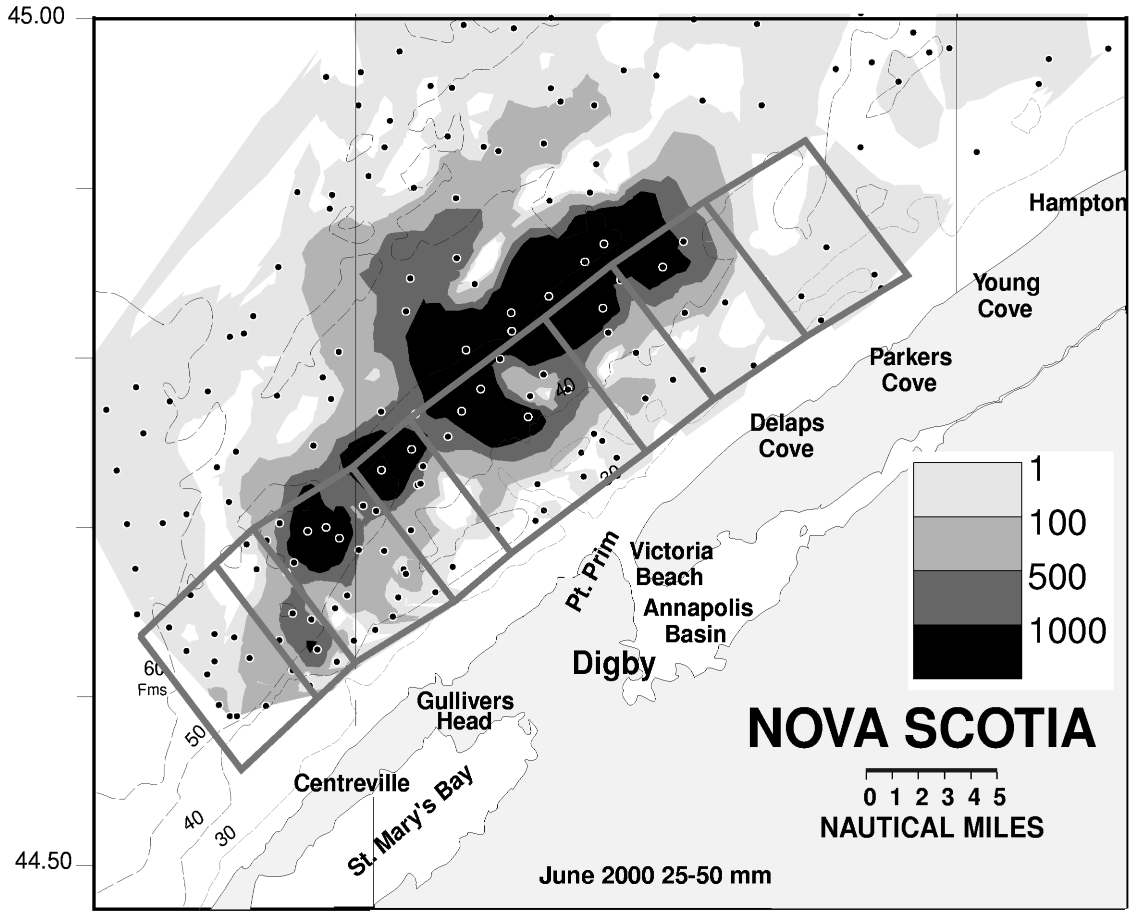

Fig. 43. Spatial distribution of scallop catches from the June survey of Scallop Production Area 4 for scallops with shell heights between 25 and 50 mm (1998 year-class). Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm).

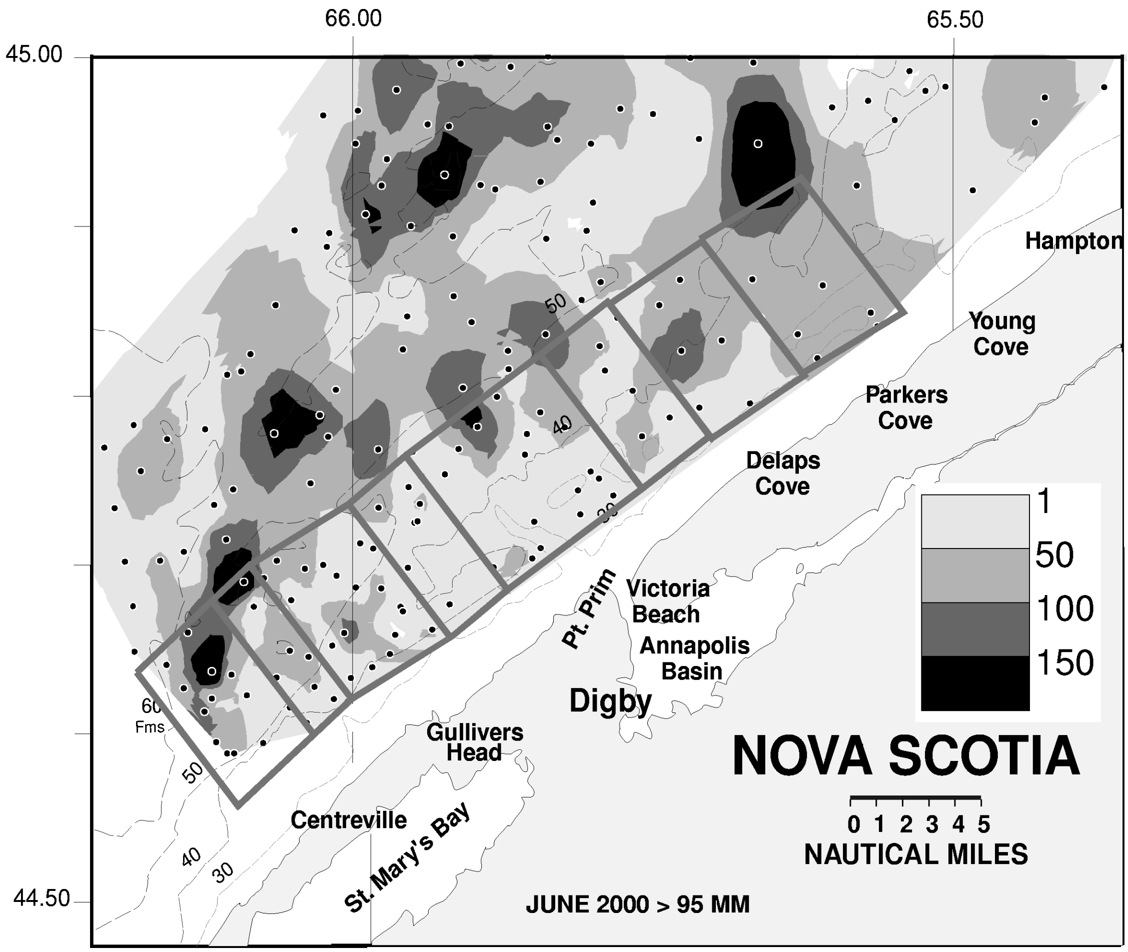

Fig. 44. Spatial distribution of scallop catches from the June survey of Scallop Production Area 4 for scallops with shell heights greater than or equal to 95 mm (1998 year-class). Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm).

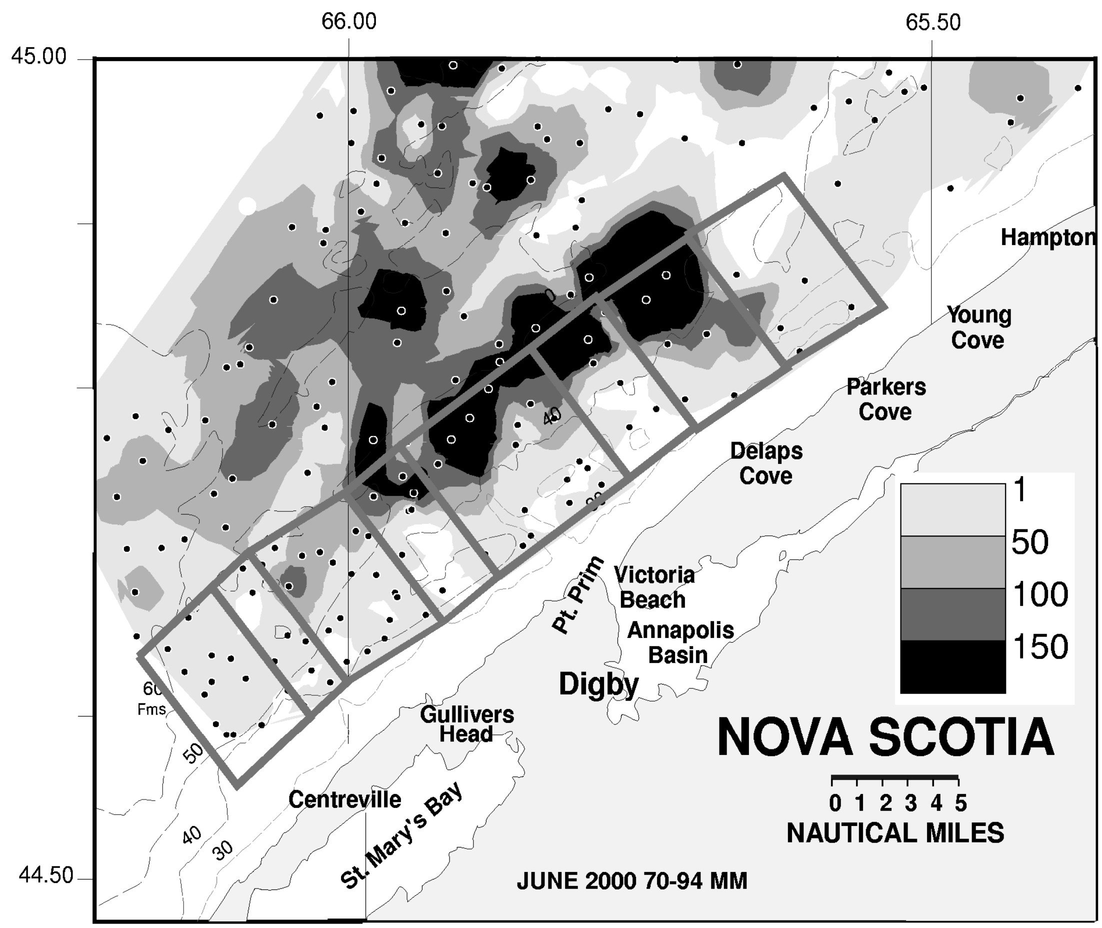

Fig. 45. Spatial distribution of scallop catches from the June survey of Scallop Production Area 4 for scallops with shell heights between 70 and 94 mm (1998 year-class). Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm).