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Scallop Production Area 3 and Scallop Fishing Area 29: Stock status and forecast

Zone de production du pétoncle 3 et Zone de pêche du pétoncle 29 : état du stock et prévisions

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Abstract

Landings in Scallop Production Area (SPA) 3 for 2001 were 163 t against a TAC of 200 t. The quota was not caught because the Full Bay fleet had redirected their effort to Scallop Fishing Area 29 where catch rates were higher. Commercial catch rates averaged 15 kg/h in 2001, compared to 13 kg/h in 2000. The 2001 research survey indicated an increase in the numbers of commercial-size scallops from 2000, although estimates from this survey are highly variable. A potentially above average year-class (1998) observed in the 2000 research survey did not appear in the 2001 survey as recruit size scallops in the numbers expected. A biomass dynamic model was fit to the landings and catch rate data for this stock. While the fit to the data was satisfactory, uncertainties about actual catches in the early 1990's will need to be resolved before the model can be used to give advice. The current TAC of 200 t should not be changed for 2002.

A fishery was conducted in the western portion of Scallop Fishing Area 29 in 2001. Scallop fishermen had consulted with lobster fishers in the area to deal with potential conflicts. The scallop fishery ran from June 11 to August 31, by which time, the 400 t TAC was caught. Commercial catch rates averaged 110 kg/h and meat weights averaged 24 g. A joint industry/DFO post-season survey found large concentrations of commercial size scallops, as well as localised distributions of recruits and pre-recruits. The catch that would be sustainable in this area cannot yet be determined.

Resumé

Les débarquements issus de la zone de production de pétoncles 3 en 2001 se chiffraient à 163 t d'un TAC de 200 t. Le quota n'a pas été récolté parce que la flottille de pêche ayant accès à l'ensemble de la baie a réorienté son effort vers la zone de pêche du pétoncle 29, où les taux de capture étaient meilleurs. Les taux de capture commerciale ont atteint en moyenne 15 kg/h en 2001, en comparaison de 13 kg/h en 2000. L'indice de navire de recherche pour 2001 indique une augmentation du nombre de pétoncles de taille commerciale par rapport à l'année précédente, bien que les estimations tirées de ce relevé sont très variables. Une classe d'âge potentiellement plus abondante que la moyenne (1998) observée dans le relevé de navire de recherche de 2000 ne s'est pas manifestée dans le relevé de 2001 sous la forme de recrues à la pêche en nombre prévu. On a ajusté un modèle de la dynamique de la biomasse en fonction des données sur les prises et les taux de capture pour ce stock. Bien que l'ajustement aux données était satisfaisant, les incertitudes entourant les prises réelles au début des années 1990 devront être éclaircies avant que le modèle puisse être utilisé pour formuler des avis. Le TAC actuel de 200 t devrait continuer à s'appliquer en 2002.

Une pêche a eu lieu dans le secteur ouest de la zone de pêche du pétoncle 29 en 2001. Les pêcheurs de pétoncle avaient auparavant consulté les pêcheurs de homard de la région afin de trouver des solutions aux conflits potentiels. La campagne de pêche s'est déroulée du 11 juin au 31 août et le quota de 400 t a été récolté. Les taux de capture commerciale se situaient en moyenne à 110 kg/h et le poids des chairs, à 24 g. Un relevé conjoint effectué par l'industrie et le MPO après la campagne de pêche a permis de trouver de grands bancs de pétoncles de taille commerciale et des bancs localisés de recrues et de prérecrues. Nous ne sommes pas encore en mesure de déterminer les prises qui pourraient être récoltées dans cette région sans nuire à la durabilité de la ressource.

Introduction

Scallop production area (SPA 3) encompasses the outer reaches and approaches to the Bay of Fundy and starting in 1999, St. Marys Bay (Fig. 1). This area has been under Total Allowable Catch (TAC) management since the introduction of the area-based management plan on 1 January 1997. In the 1950's and 1960's, this area was heavily exploited but after that period, there was negligible fishing until 1980 when both the inshore (LOA[1] under 19.8 m) and offshore (LOA over 19.8 m) fleets fished the area until 1986. In 1986 an agreement was reached between the two fleet sectors to separate fishing grounds as inshore grounds being north and offshore grounds being south of latitude 43°40′ N. After 1986, the inshore fleet did not fish the area now known as SPA 3 until 1991 probably due the record catches being made on the Digby beds in the late 1980's. Since 1991, landings from the area south of Brier Island have made up a significant proportion of the total landings of the inshore fleet.

The last full review of stock status for SPA 3 was reported in Smith et al. (1999). At that time doubts were expressed that all the landings reported as being from SPA 3 in 1999 actually came from this area. However there did not appear to be a problem of misreporting of landings in SPA 3 in 2000 (DFO 2000). In the reports cited above, the 1997 and 1998 year-classes were observed to be relatively abundant in the 1999 and 2000 research surveys, respectively, especially in the Lurcher Shoal area.

In this report, the stock status is reviewed using commercial catch rate indices and research survey abundance estimates. In previous reports, the landing series only included from 1991 onward while in this report we have extended the series back to 1980. The longer times series has allowed us to explore the use of biomass dynamic population models to reconstruct the past history of the stock dynamics and forecast future prospects. Uncertainties in the parameter estimates and stock dynamics have been incorporated in the forecasts using a Bayesian state-space model formulation. Advice on the impact of future catch levels are presented in terms of probabilities.

We also report on the 2001 fishery in Scallop Fishing Area (SFA) 29. This fishing area encompasses a very large inshore area, from the south of Yarmouth to Cape Breton. Scallop Fishing Area 29 scallop licenses usually refer to the inshore fishery east of Baccaro (East of longitude 65°30′ W) mainly made up of small inshore lobster vessels fishing near shore. In the context of this report, SFA 29 refers to the area south of latitude 43°40′ N continuing east from SPA 3 to longitude 65°30′ W (Fig. 1). The boundaries and seasons of any legal fishing in this area for the Full Bay fleet have not been consistent in the last 15 years. Fishing area boxes have been drawn and changed from year to year with specific catch limits. In recent years, fishing in the area had been allowed for the Full Bay fleet contingent on having observers onboard some of the vessels but there have been reports of and charges against vessels illegally fishing south and east of SFA 29, and no access was allowed by the department to SFA 29 in 1999 and 2000.

In 2000, all Full Bay scallop vessels were required to have electronic monitoring devices (black boxes) installed to monitor the vessels activity. An exploratory fishing season was initiated for the summer of 2001 with a post-season industry funded survey to follow. The results of this fishery and the subsequent survey are presented herein.

[1] Length Overall.

Fisheries data

Landings

The landings series presented in Table 1 were reconstructed from a number of data sources. For the period from 1976 to 1984, scallop landings were reported by NAFO unit areas and vessel size. Landings by vessels of $>$ 25.5 GT and $<$ 19.8 m LOA from NAFO unit areas 4XRS, 4XQ and 4Xu (4X, unknown unit area) were used to represent those of vessels now categorized as the Full Bay fleet. Landings in 4Xu were apportioned to 4XRS and 4XQ using the proportion of catches in these latter areas recorded in the fishing logs. Logged catches were used to apportion catches in 4XRS to the Bay of Fundy and the current Brier Island area of SPA 3 and St. Mary's Bay. Catches by the offshore scallop fleet from the current SPA 3 prior to 1987 were provided by G. Robert (pers. comm.).

Scallop landings were reported by licence type from 1985 to 1996 and landings of vessels by the Bay of Fundy fleet licence were assumed to be consistent with those by vessels now identified as Full Bay Fleet. Landings were not recorded by area in these records and include those from German, Browns and Georges Bank, as well as from the Bay of Fundy and approaches. Landings by vessel size and NAFO subarea were used to identify those from Georges and Brown's Bank. The proportion of catches reported, for what is now the Lurcher Shoal area of SPA 3 and German Bank, in the Full Bay log books were used to apportion total landings to these two areas. From 1997 to 2001, the landings data were reported by licence type and Scallop Production Area from the departmental quota reports.

During the RAP meeting fishing industry participants expressed doubt that landings in the the period 1991 to 1996 were as high as presented here (Fig. 3). At present we do not have any solid information to the contrary but the proportion of landings accounted for in the logbooks was quite low during this period (Table 2 and it is likely that we overestimated the landings that were assigned to SPA 3 compared to those in the Browns Bank/German Bank area

The lobster fishery in the area influences the scallop fishing seasons openings and closings in SPA 3. In 2001, the outside portion of SPA 3 opened on 19 March (Fig. 2) with all of SPA 3 including St. Marys Bay opening on 4 June. The St. Marys portion remained open for 45 days.

The TAC for the whole area was set to 200 t for 2001. Total landings for the year were less than the quota at 163 t (Table 2). These were the lowest landings for this area since 1991 (Fig. 3), but this does not necessarily reflect a decline in the stock. Instead, much of the fishing effort by the Full Bay fleet in the summer was directed toward the more lucrative beds in the SFA 29 area.

Catch rates continued to increase since the recent low of 1997 (Fig. 4). Fishing effort in 2001 was at the lowest level for this area since 1991. Catch rates by area exhibited similar trends in recent years (Fig. 5).

Scallop Fishing Area 29

The Full Bay fishing fleet requested access to SFA 29 in 2000 and volunteered 5 vessels to do exploratory fishing. This request was not approved by the department. However, the annual 2000 scallop research survey of Scallop Production Area 3 was completed before the allocated ship time for the J. L. Hart was used. The remaining ship time was used to collect some preliminary data in this area to confirm reports of high scallop densities. The survey was designed to be exploratory and not provide abundance estimates. The data from the survey were presented to the Inshore Scallop Advisory Committee in the spring of 2001. Survey catch rates were very high relative to adjacent areas and the commercial potential was judged to be significant. At the meeting the industry was given maps indicating the areas of high catch rates from the survey.

As this area is the most productive lobster area in the Maritimes Region there were significant concerns expressed about lobster bycatch. During the August 2000 research survey there was a significant bycatch of lobsters, however most were soft-shelled animals. From our 22 years experience conducting scallop research surveys it is apparent that when lobsters are moulting there is an increased incidence of bycatch due to the lobsters inability to escape the scallop gear. Given the results of the preliminary assessment of the area Resource Allocation recommended a limited fishery pending consultation with the lobster industry. The recommendation from Science was "…if scallop fishing in this area is approved it should be conducted as soon as possible i.e., June 1, 2001 and that industry be required to conduct a post-season scientific survey of this stock".

The lobster industry was consulted by the Full Bay Scallop Association to obtain their agreement for scallop fishing in this area. All parties agreed that there could be a 200 t scallop fishery with the condition that each vessel take an observer for one trip to monitor the lobster bycatch and record scallop shell height frequencies. The scallop industry targeted high catch rate areas from the 2000 survey maps and caught the 200 t TAC by late July at which time they requested additional TAC. The observer data showed that the bycatch of lobster was not significant and again the Full Bay Scallop Association approached the LFA 34 lobster Association to discuss additional scallop fishing in the area. Given the low lobster bycatch the lobster fishermen agreed and the scallop industry was allocated a further 200 t. The season ended Aug 31, 2001 with the quota being caught. The location of catches from the commercial logs is given in Fig. 6.

Meat weight sampling

The results of sampling the commercial catch for meat weight composition has been updated from Smith et al. (1999) to include the data for 2000 in Tables 3 and 4. Prior to 2000, samples were collected on a voluntary basis from fishermen and costs were covered by the department. Since 2000, samples have been collected through the dockside monitoring program. In 2001, meat counts remained well within the regulated level of 45/500 (or 55/500 at the beginning of the season) with the large meats generally coming from the Brier Island Area (Table 5).

New conditions of a minimum meat weight of 8 g and minimum shell height of 76 mm were introduced for the 2001/2002 season. The 8 g limit was monitored using meat weight samples of the catches with a tolerance of allowing for samples to have no more than 10 percent of the meats less than 8 g. The previous conditions of a meat count of 45 per 500 g and minimum shell height of 95 mm caused some confusion as one could have a meat sample that had a legal count but come from scallops with shell heights less than 95 mm. Although the regulation for meats to be greater than 8 g was not in place for the 2001 fishery, statistics on 8 g are included here for reference. Overall, there does not appear to be a problem with small meats in the catch.

The results for SFA 29 are also included in Table 5 where the larger meats obtained from that area are evident.

Research Survey

SPA 3

Annual research surveys have been conducted every August since 1991 using the research vessel J.L. Hart. The four-gang dredge gear configuration has remained unchanged throughout the survey series (Kenchington et al. 1997). However, the survey design and the amount of area covered have both changed over time. The survey followed a grid pattern from 1991 to 1996 with area surveyed expanding each year until 1995 (Kenchington and Lundy 1998). The survey used random locations for stations in 1997 to 2001. The area covered by the surveys has been comparable since 1995. In 1999, surveys of the St. Marys Bay area were initiated as part of the August research survey series.

Two of the four survey 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 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. All catches were prorated to the expected catch of a seven-gang gear rig and numbers were standardized to a tow distance of 800 m.

The spatial distribution of the survey catches in the Brier Island and Lurcher shoal areas are presented in Figs 7 to 9 according to the size classes representing pre-recruits, recruits for 2002 and fully recruited scallops, respectively. These definitions are based upon analysis of the shell height/age data collected during the 1996 survey (Table 6). As in previous years, recruitment tends to be strongest in the western portion of Lurcher Shoal. In the 2000 research survey, the estimates of pre-recruits, identified as being from the 1998 year-class were the largest ever seen in this short survey series (Table 7). While the 2001 estimates for this year class (65–79 mm in Brier Island; 70-79 mm in Lurcher Shoal) are larger than for any previous year-classes at this same size in Brier and Lurcher, the 2001 estimates of this year-class abundance are much reduced from the previous year (Figs 10 and 11). The proportion of clappers in the research survey does not seem to indicate that the pre-recruits suffered higher than usual mortality (Table 7). However, there is evidence in the literature that the dissolution rate for small shells could be less than or equal to 50 days (Dickie 1955) and the clappers would not last until the research survey in the following year. On the other hand, the tendency for large estimates of year-classes at small shell sizes not carrying through to the recruit size class has been noted before for this survey (Smith et al. 1999). The sampling intensity is much lower than those of the long-term research surveys in SPA 1 and 4 where there appears to be much more coherence of year-class strength through time.

For both areas, the trends for fully-recruited scallops appears relatively flat over the seven years. The recruits in Lurcher Shoal have been steadily increasing since 1998.

The time series for the St. Marys Bay portion of the research survey is only three years long. In the 2001 survey pre-recruits and recruits have a very limited spatial distribution (Fig. 12) relative to previous years (Fig. 13 and Smith et al. 1999). The survey indices for these two size classes are at their lowest in the three year series (Fig. 14).

Smith et al. (1999) noted that scallops in the SPA 3 area, especially in the Lurcher Shoal area had larger meat weights at shell height compared to previous years. This difference with meat weights in previous years (1996-1998) appears to have continued in 2000 and 2001 with a slight dip in 2000 (Tables 8 and 9). Unfortunately, we do not have data prior to 1999 to make the same observation for St. Marys Bay (Table 10).

SFA 29

In September 2001, a research survey of SFA 29 was conducted aboard the commercial scallop dragger “Julie Ann Joan”, owned and operated by Captain Kevin Ross. A joint project agreement was set up prior to this work for industry to cover Science expenses and 2 t of catch was allocated to cover vessel expenses. The survey covered an approximate area of 600 sq. miles.

The vessel used nine miracle drags with 75–78 mm inside diameter rings knitted together with rubber washers. Drag # 1 was lined with 38 mm polypropylene mesh. The two end drags (# 1 and 9) were sampled at each tow. Sampling and measurements were conducted as per the standard scientific dredge research surveys described above.

A total of 125 random stations was assigned and successfully completed in the area. A DGPS receiver was used to identify tow positions and tow tracks. The tow track was recorded using the Nobeltec Navigation software on a laptop portable computer. Each tow was 8 minutes in duration.

The research survey of SFA 29 by the J. L. Hart in 2000 was limited with respect to covering the area. This survey detected limited numbers of pre-recruits (Fig. 15) and recruits (Fig. 16) relative to the large numbers of fully recruited scallops (Fig. 17). The coverage by the Julie Ann Joan survey was more extensive and detected sizable concentrations of pre-recruits (Fig. 18) and recruits (Fig. 19) in the southern area not covered by the J. L. Hart. Concentrations of fully recruited scallops were also extensive in the southern area as well as in the north where they were found in the previous year by the Hart survey (Fig. 20). The number-per-tow for fully-recruited scallops in 2001 are more than twice that recorded for the nearby Lurcher Shoal area (Table 7). The number-per-tow for the smaller sizes are well within the ranges of those observed in SPA 3. However, the spatial distribution for these size ranges are more restricted than that for the fully recruited scallops and densities are much higher in the southern area.

The shell height frequency for 2001 indicates that there may be a sizable year-class peaking at 32.5 mm which may recruit to the fishery in two to three years (Fig. 21). More work will need to be done on the growth rates in this area. In the meantime it looks like the fishery will be mainly cropping down the standing biomass of scallops with shell heights greater than 110 mm.

The meat weight-at-height of the scallops caught in the 2001 research survey are comparable to those of the Brier Island area (Table 8) and larger than those in nearby Lurcher Shoal (Table 9). Restricting the commercial catch to scallops with meat weights greater than 8 g will generally result in animals with shell heights greater than 90 mm in the catch.

A total of 185 lobsters were caught in the survey. However, lobsters only occurred in 50 of the 125 tows (Fig. 22). No lobsters were caught in the survey tows in the southern portion of the area east of Seal Island where the major part of the fishery occurred (see Fig. 6). The carapace condition of the lobsters was a mixture of hard and soft shell.

Gear Comparison Study

We conducted a comparative tow comparison between the J. L. Hart and the Lady J. L. N. during the SPA 3 research survey in August 2001 in preparation of having an industry funded survey of

SFA 29. However, the Lady J.L.N. was not able to conduct the survey and there was no opportunity in 2001 to conduct a comparable study between the Julie Ann Joan and the J. L. Hart.

Fortunately, we had conducted a comparative tow experiment between these two vessels in 1999 in the Digby area. At that time, the Coast Guard vessel J.L. Hart was due to be decommissioned in 2002 or soon after. During the time of the June 1999 SPA 4 research survey, the idea of using commercial scallop vessels to conduct the annual research survey was explored. The first step to evaluating the feasibility of this change was to conduct comparative tows between a commercial vessel and the J.L. Hart. Captain Kevin Ross volunteered his vessel and crew for one day to compare catch rates of the two vessels and gear types. This study should be considered as only a preliminary study of the comparative fishing power of the two vessels and their gear.

The types of gear used differed significantly between the two vessels. The research vessel J.L. Hart towed a 4 gang set of traditional Digby rubber gear (untoothed) with alternating lined and unlined drags (38 mm polypropylene stretch mesh). The drag opening is 0.77 m across. At each tow the combined catch of the 2 lined and 2 unlined drags were measured separately. The tow track was recorded by a MacIntosh PC connected to a DGPS receiver every 2 seconds. Data collection was typical of the regular research survey.

The commercial vessel towed a 9 gang set of Miracle rubber gear (toothed). The drag opening is 0.62 m across. At each tow the combined catch of two unlined drags (#4 and #9) and two lined drags (#1 and #5) were measured separately. It should be noted that all of the commercial gear (9 drags) were dumped at once using a dumping pole and it was often difficult to keep the catch of the individual drags totally separate. The determination of which scallops came from what drag was subjective. Tow track positions were recorded every 30 seconds.

Each vessel was to sample the same tow locations. Tow comparisons were completed at 4 general sites as follows (Fig. 23):

	Tow Numbers	
Location	J.L. Hart	Julie Ann Joan
Sites 1	1,2,3,4,5,6,8	1,2,3,4,5
Sites 2	9,10,11,12,13	6,7,8,9,10
Sites 3	14,15,16,17,18	11,12,13,14,15
Sites 4	19,20	16,17,18,19,20

The relative positions of individual tows are presented in Fig. 24 for the first two sites and in Fig. 25 for the later two sites. Each tow was approximately 800 m in length.

Preliminary analyses of these data indicate that the relative catch by the two vessels was quite variable with the Julie Ann Joan catching less than the J. L. Hart at the lower (Fig. 26) and upper end (Fig. 27) of the shell height frequency. As a result it appears unlikely that we will be able to use catchability coefficients from the biomass models in SPA 1 and 4, based on the results from the J. L. Hart research surveys, to convert survey estimates from the Julie Ann Joan to total biomass estimates. A separate modelling exercise will need to be undertaken once the time series in SFA 29 is long enough.

Population Models

Background

Biomass dynamic models for scallop population dynamics were introduced in Smith and Lundy (2002). The basic form for modelling changes in biomass over time t is given as,

$$(\text{Adult Biomass})_{t+1} = (\text{Surviving Adult Biomass})_t + (\text{Recruitment Biomass})_{t+1} \tag{1}$$

where,

$$\begin{aligned}(\text{Surviving Adult Biomass})_t \quad &= \quad (\text{Adult Biomass})_t + (\text{Biomass increase due to growth})_t \\ &\quad - (\text{Losses due to Natural Mortality})_t - \text{Catch}_t\end{aligned}$$

We can write the above in a more compact form,

$$B_{t+1} = B_t + G\,(B_t) - M\,(B_t) - C_t + R_{t+1} \tag{2}$$

The simplest form of this kind of model is the surplus production model in which growth, recruitment and mortality are all contained in one term.

$$B_{t+1} = B_t + g(B_t) - C_t \tag{3}$$

where B_t and C_t are the population biomass and the commercial catch in year t. The term $g(B_t)$ corresponds to the surplus production and as such represents increases due to growth and recruitment against losses due to natural mortality. The more common form for $g()$ is the following due to (Schaefer 1954).

$$g(B_t) = r\,B_t\left(1 - \frac{B_t}{K}\right) \tag{4}$$

In this equation r corresponds to the intrinsic growth rate. The carrying capacity or the level of stock biomass corresponding to equilibrium conditions, that is, growth balanced by mortality, is represented as K. For the equilibrium form of the model, K is assumed to be the stock biomass before fishing started on the stock.

Scallop populations in the Bay of Fundy and elsewhere characteristically exhibit episodic recruitment and mortality events (Dickie and Medcof 1963, Medcof and Bourne 1964, Kenchington et al. 1995). The surplus production model assumes that r is constant over time and therefore events such as large recruitment events would have to be balanced out by decreases in growth or increases in mortality or both. The basic data used to fit this kind of model are time series for catches and catch rates (or effort series) and these kind of data do not contain information on growth, recruitment or mortality.

A more realistic approach would be to model the terms in equation 2 individually.

Deriso (1980) developed such an approach by first defining the total stock biomass for recruited animals at the beginning of year t, B_t as,

$$B_t = \left[\sum_{a=k+1}^{\infty} N_{a,t} w_a \right] + w_k R_t, \tag{5}$$

where,

$N_{a,t}$	=	Population numbers of fully recruited scallops age a ($a = k+, k+1, \ldots$) in year t.
R_t	=	Population numbers of scallops that recruit in year t (at age $a = k$).
w_a	=	weight at age a.

Next, Deriso (1980) makes three assumptions about the growth, survival and harvesting for the population. With respect to growth, he assumed that the increase in mean body size with age can be modelled as,

$$w_a = \alpha + \rho w_{a-1}, \tag{6}$$

where w_a is as defined above and α and ρ are unknown parameters. Secondly, selection to the fishery is assumed to be "knife edge" for all ages k and older. Finally, the rate of natural mortality rate is the same for all animals recruited to the fishery.

Total survival rate is assumed to be the product of natural survival rate and survival through harvesting.

$$s_t = s_t^M s_t^F \tag{7}$$

Writing $N_{a,t} = s_{t-1} N_{a-1,t-1}$ and $w_a = \alpha + \rho w_{a-1}$ in equation 2 and factoring out the terms that do not depend on age (e.g., s_t, α) results in sums over ages k and older for year $t-1$ in terms of total biomass,

$$B_t = s_{t-1} \alpha N_t + s_{t-1} \rho B_{t-1} + w_k R_t \tag{8}$$

and total numbers

$$N_t = s_t N_{t-1} + R_t. \tag{9}$$

After more algebra and noting that $\alpha = w_k - \rho w_{k-1}$ these two equations can be combined to give the form of the delay-difference model suggested by Schnute (1985).

$$B_t = s_{t-1} B_{t-1} + (\rho s_{t-1} B_{t-1} - \rho s_{t-1} s_{t-2} B_{t-2} - s_{t-1} \rho w_{k-1} R_{t-1}) + w_k R_t. \tag{10}$$

The first and last terms in the model define biomass in the current year as being due to surviving biomass from last year and biomass of new recruits added to the stock this year, respectively. The middle term in brackets represents the growth of surviving individuals from last year.

Meyer and Millar (1999*a*) suggest scaling the state equations by a constant K to increase the convergence rate of the Gibbs algorithm.

$$P_t = \frac{B_t}{K} \tag{11}$$

and

$$E[B_1] = K$$

Therefore we will be estimating P_t, K and $r_t = R_t/K$ instead of B_t and R_t.

For SPA 4, 21 years of research survey information was available to provide information on population biomass, recruitment biomass, average annual meat weights and natural mortality through research survey estimates of clappers (Smith and Lundy 2002). Unfortunately, we have far less survey information for SPA 3 and will have to rely on a more complex formulation of the delay-difference model. That is,

$$\begin{aligned} P_t = (1+\rho)\exp(-M)\,(P_{t-1} - C_{t-1}/K) \\ - \rho\exp(-2M)\frac{(P_{t-1} - C_{t-1}/K)}{P_{t-1}}\,(P_{t-2} - C_{t-2}/K) \\ + r\left(1 - \rho\omega\exp(-M)\frac{(P_{t-1} - C_{t-1}/K)}{P_{t-1}}\right) \end{aligned} \quad (12)$$

where:

$\exp(-M)$	=	natural mortality assuming a constant value over time.
r	=	recruitment which is assumed to be a random variable with respect to time.
ω	=	w_{k-1}/w_k, as defined above.

The parameters ρ, w_{k-1} and w_k were estimated outside of the model from growth data. We used a Bayesian state-space formulation to estimate the remaining parameters in the model (For details see, Smith and Lundy 2002). The process error for equation 12 is denoted as μ_t.

We also assume that there is a proportional relationship between the commercial catch rate I_t and the population biomass.

$$I_t = q_I B_t \varepsilon_t \quad (13)$$

We assume that the error terms μ_t and ε_t are independent log normal random variates with unknown means and unknown variances σ^2 and σ_ε^2, respectively. The means will be derived from the expected values of equations 12 and 13.

The parameters to be estimated are the variance terms given above, the proportionality constant q_I as well as the state variables B_t and r, for all t in equation 12.

In the Bayesian approach, one proceeds by defining the probability distribution (or likelihood function) for the observations **y**, that is, the observations in equation 13. Here catches are assumed to be known constants, referred to as control variables in state-space models, although models with catch as a random variable can be constructed.

Prior distributions are assumed for variance terms, q_I and the state variables. The prior distribution reflects our view of the state of nature prior to collecting the data (Carlin and Louis 1996). Having collected these data, we update our view of the state of nature to create the *posterior* distribution.

In fact, we have little information on the terms in the model for scallops other than perhaps expected range. The general approach in this kind of situation is to assign "non-informative" priors and let the likelihood function for the observations dominate estimation of the posterior distribution (Carlin and Louis 1996). Intuitively, this would suggest using a uniform distribution as the form for the prior thus giving each possible value of any parameter an equal chance of being chosen.

Unfortunately, uniform distributions are not invariant under reparametrization and what might be non-informative on one scale may not be on another.

Alternatively, Box and Tiao (1973) suggest choosing a prior that is diffuse enough that the data will dominate whatever information there is in the prior. This is the approach that was followed here.

The proportionality constants and the variance terms were modelled using inverse gamma distributions — the recommended form of prior for scale variables (Carlin and Louis 1996, Meyer and Millar 1999*a*). In the context of the software used here (WinBugs) the priors for the proportionality constant was written as follows.

$iq_I \sim \text{dgamma}(0.0001, 0.0001)$
$q_I \leftarrow 1/iq_I$

This form of prior approximates Jeffrey's prior which is both noninformative and invariant to changes in scale (Congdon 2001).

The sample variances could be calculated for the catch rates in equation 13. However, for this study we set priors on the variance assuming an inverse gamma distribution with the mean and variance equal and set to correspond to a coefficient of variation for the lognormal variables (catch rate) equal to 0.5. The coefficient of variation for a lognormal random variate y is $(\exp(\upsilon^2)-1)^{0.5}$, where $\log(y)$ is a normal random variate with mean μ and variance υ^2. Therefore the coefficient of variation is independent of μ and the same expected value for υ^2 can be used for all of the variance terms in this model. A coefficient of variation of 0.5 corresponds to $\upsilon^2 = 0.22314$ which is the expected value of an inverse gamma with parameters (3,0.44629).

While the σ_ε^2 were initially generated from the inverse gamma version of the above, the effect of the low reporting rate for the commercial logs presented in Table 1 needs to be taken into account. For the current study this was naïvely done by dividing σ_ε^2 by the proportion of the total catch accounted for by the Class 1 catch each year, prop_t.

$$\sigma_{\varepsilon,t}^2 = \sigma_\varepsilon^2/\text{prop}_t$$

There were no vessels fishing (or log books) in SPA 3 in 1989 and 1990 and hence no catch rate data are available for these two years. Assuming that the catch rate would have linearly increased from 1988 to 1991, a stepwise increase of 10 kg/h and 15 kg/h was used for 1989 and 1990, respectively. However, the imputed values for prop_t for these two years was set as 0.0001 so that the model could sample a wide range of possible values for catch rate.

Given that K was set to be the population biomass in year 1, a lognormal distribution was used for the prior on this parameter. In this case, the prior was set to be semi-informative with the 0.025% and 97.5% quantiles, approximately equal to 130 and 3300, respectively. That is,

$K \sim \text{dlnorm}(6.15, 1/0.67)\text{I}(10, 30000)$

where where I(10, 30000) indicates that sampling was restricted between these lower and upper bounds.

Summaries of our updated knowledge about the elements of the parameter vector such as means, medians, etc., would be based on the posterior distribution. The integral in the denominator of posterior is far too complex to evaluate analytically for the delay difference model. Instead, a specific form of Monte Carlo Markov Chain (MCMC) integration, referred to as the Gibbs Sampler is used here (See Carlin et al. 1992, Carlin and Louis 1996, Meyer and Millar 1999*a*).

Bayesian modelling was carried out here using the windows version of the public domain package BUGS (WinBUGS) described in Speigelhalter et al. (1995).

Results

The only age information available for this stock at present is from the 1996 research survey. The relationship of weight at ages t and $t-1$ was calculated using data form both Brier Island and Lurcher. The relationship was quite linear and estimates of $\rho = 0.8951$ and $\omega = 0.598$ was used for the delay difference model (Fig. 28).

Details on monitoring the convergence of the Gibbs sampler are presented in Smith and Lundy (2002). The model for SPA 3 was run with a burn-in of 1000 samples, with thinning set to 15 and a total of 5000 samples kept for each of two chains. Application of the Raftery and Lewis method to these data indicated that essentially no additional thinning or burn-in was required and that 5000 iterations were more than adequate. In addition, all variables from these chains passed the Heidelberger and Welch test for stationarity and the halfwidth test for adequacy of the number of iterations (Heidelberger and Welch 1983).

Summaries of the posterior distributions for the main parameters are presented in Table 11 along with the projected biomass for the 2002 fishery. The posterior for K was more variable than assumed for the prior with a larger median (Fig. 29). The posteriors for the variance terms indicated that they were less variable than the priors and with resultant coefficients of variations being less than the assumed value of 0.5 (Fig. 30). The prior for the proportionality constant was flat and the resultant posterior indicates that the likelihood did have information on q_I Fig. 30.

The observed and predicted catch rates from the model are presented in Fig. 31. The catch rate for 1987 stands out as an outlier as does the observation for 1988. A plot of the residuals show these two points as being the most problematic for the time series. The catch rate for 1987 was based on a catch of 9 kg reported in one log from St. Marys Bay for a year in which the estimated landings were only 12 t. Landings in 1988 were less than 1 t and only one log, this one from the Brier Island area, was available. Neither catch rates were probably indicative of the stock dynamics in those years.

The residual plot for the process error does not indicate any serious problems with the model in equation 12 (Fig. 33).

The predicted biomass estimates from the model reflect the high variability associated with K in Table 11 (Fig. 34). A time trend of the landings and biomass estimates indicate that there have been a number of phases in the recent history of this fishery (Fig. 35). For the first six years of the series, catches declined as the biomass was fished down until the late 1980's when effort was redirected to the higher densities in SPA 1 and 4. Biomass began to slowly increase during this period of low or no catches until the fleet returned in 1991. Thereafter, increasing effort started the biomass to decline after 1993 and catches declined after 1994. Since 1997, the catch levels have not stopped the biomass from increasing to the level it was at in 1989/90. Time trends for fishing mortality estimates and fishing effort indicate that these are tightly linked (Fig. 36).

A useful diagnostic for population models regardless of the estimation method used is obtained from a technique known as retrospective analysis. This method evaluates the stability of the estimates of the parameters of a model as new data are added (NRC 1998). Published results from such analysis have shown that fisheries population models can consistently under or over-estimate quantities such as biomass (Sinclair et al. 1991). We conducted a retrospective analysis of the delay-difference model used here by fitting the model to the data time series for the periods 1980–1996, 1980–1997,..., 1980–2001 and monitoring the estimates of biomass, fishing and natural mortality. The estimates from each run of the model are compared against those from the full data set (1980–2001). The model would exhibit a retrospective effect, for example, if estimates of biomass, fishing mortality or natural mortality for 1996 in each of time series used, deviated systematically from that obtained from the full data set. The results for the SPA 3 scallop data indicate that the delay-difference model does not exhibit any serious retrospective effects for biomass, fishing mortality or natural mortality (Figs. 37 and 38). This stability is very encouraging as it indicates that the projections of future population biomass from past data should also be stable.

A number of assumptions were made to construct the delay difference model used here. A partial assessment of the impacts of these assumptions was made by fitting a surplus production model to these same data. The state-space Bayesian form of this model described by Meyer and Millar (1999*b*) was fit to the landings and catch rate data assuming the same prior structure for K, μ_t and q_I. However, all of the catch rate data including the imputed values for 1989 and 1990 were assumed to have equal precision. In addition the surplus production model assumes that the rate of increase in biomass is a balance between recruitment, natural mortality and growth affected only by the state of the population in relation to its carrying capacity (equation 4). The surplus production model predicts an overall higher biomass through time than the delay-difference model but the projected biomass for 2002 is only 294 t higher (Fig. 39). Note, that the surplus production model tries to fit the anomalous catch rate in 1987 and 1988 when all of the catch rates are assumed to have equal precision.

Finally, we present preliminary results from evaluating the impact of misreporting of landings in the 1991 to 1995 period. Industry participants at the RAP meeting suggested that a significant proportion of these landings actually came from German and Browns Banks. We fit the delay difference model the landing series for cases where the landings during this period were 0.75 or 0.50 of what we actually determined the landings to be in Table 2. Reducing the landings during the early 1990s did result in lower overall estimates of population biomass with biomass estimates for the 0.75 and 0.50 scenarios of 2038 and 1576, respectively (Fig. 40). Unfortunately, we do not know the actual extent of the misreporting.

Management Implications

SPA 3

The Bayesian structure of the state-space model used here allows us to incorporate the uncertainties identified in the model when evaluating its performance against some objective. No objectives for this fishery have been established yet nor are there reference points defined for this fishery. As a demonstration of the utility of the Bayesian approach we have evaluated various catch levels for 2002 against the criterion of minimizing growth overfishing. We have chosen $F_{0.1}$ which is estimated as 0.12 for this stock as a robust reference point for this criterion. That is fishing below this level should still allow the population biomass to grow.

The probability of F in 2002 for various catch levels exceeding 0.12 is presented in Table 12. While we would like this probability to be as small as possible, there are no hard and fast rules on how to choose a specific level. Assuming that a level of 0.10 (ten percent) is cautious enough, then these calculations suggest that a reasonable catch for 2002 would be around 175 t.

We remarked earlier on concerns that the landings in 1999 may have been too high due to misreporting from other areas. The impact of using half of the reported catch in 1999 in the model on the advice for 2002 was assessed in Table 12. Using the same critical probability of 0.10, there would be no impact on our advice for 2002 — the recommended catch would still be around 175 t. Finally, we note that if the advice was based on the surplus production model, the recommended landings would be somewhere between 175 and 200 t.

The impact of misreporting scenarios considered above on the advice provided was also evaluated. The resultant lower population biomasses predicted from these scenarios suggest that lower TAC's would be more appropriate using the 0.10 rule for the probabilities (Table 13).

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It is difficult to estimate biomass with only one year's data and therefore catch levels are also difficult to recommend. However, the localized distributions of pre-recruits, recruits and fully-recruited scallops in this area may prove amenable to a rotational fishing plan. In this kind of plan, areas of high densities of recruits and pre-recruits would be off-limits to fishing until they had grown to commercial size. In the meantime the fishery could continue to be prosecuted in the areas where the fully-recruited scallops are dominant.

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Appendix 1: Script for WinBUGS version of Delay Difference Model

```
model; {

# Process equations
########################


 Pmed[1] <- 0

 Pmed[2] <-log(max(exp(-0.1)*(1+rho-rho*exp(-0.1))*(P[1]-Catch[1]/K)
    +rp*(1-rho*omega*exp(-0.1)*((P[1]-Catch[1]/K)/P[1])),0.001))

for (i in 3:NY) {
    Pmed[i] <-log(max((1+rho)*exp(-0.1)*(P[i-1]-Catch[i-1]/K) -
      rho*exp(-0.2)*(P[i-1]-Catch[i-1]/K)/P[i-1]*(P[i-2]-Catch[i-2]/K)
      + rp*(1-rho*omega*exp(-0.1)*((P[i-1]-Catch[i-1]/K)/P[i-1])),0.01))
    }


for (i in 1:NY) {
    P[i] ~ dlnorm(Pmed[i],isigma)I(0,5.0)
    }


        rp~dlnorm(0,1)I(0,3)


#Observation equations
#########################

#CPUE

for(i in 1:NY){
    Imed[i]<-log(qI*K*P[i])
     Iprmed[i]<-ivarepsilon*Iprec[i]
  }

for(i in 1:NY){
        I[i]~dlnorm(Imed[i],Iprmed[i])
}


#Distribution of K
###########################

K~dlnorm(6.5,1.5)I(10,30000)

#Distribution of q's
###########################

iqI~dgamma(0.0001,0.0001)
```

```
qI<-1/iqI


#Distribution of variance terms
############################

isigma~dgamma(3.,0.446) sigma<-1/isigma

ivarepsilon~dgamma(3.,0.446)

varepsilon<-1/ivarepsilon


# Output
#############################

for(t in 1:NY){ biomass[t]<-P[t]*K }

for(t in 1:NY){ Ipred[t]<-P[t]*K*qI }


Rec<-rp*K

#Diagnostics
###############################################


for(i in 1:NY){
    resid.p[i]<-log(P[i])-Pmed[i]
    sresid.p[i]<-resid.p[i]*sqrt(isigma)
    resid.I[i]<-log(I[i])-Imed[i]
    sresid.I[i]<-resid.I[i]*sqrt(Iprmed[i])
    }


for(i in 1:NY){
           I.rep[i]~dlnorm(Imed[i],Iprmed[i])
        p.I.smaller[i]<-step(I[i]-I.rep[i])
}

#Management quantities
####################################


for(i in 1:NY){
Fmort[i]<--log(max((biomass[i]-Catch[i])/biomass[i],0.001))
}

PrFmort<-step(Fmort[NY]-0.12)
```

```
P2002<-(1+rho)*exp(-0.1)*(P[NY]-Catch[NY]/K) -
      rho*exp(-0.2)*(P[NY]-Catch[NY]/K)/P[NY]*(P[NY-1]-Catch[NY-1]/K)
      + rp*(1-rho*omega*exp(-0.1)*((P[NY]-Catch[NY]/K)/P[NY]))

B2002<-P2002*K

Fmort2002a1<--log(max((B2002-125)/B2002,0.001))
Fmort2002a2<--log(max((B2002-150)/B2002,0.001))
Fmort2002a3<--log(max((B2002-175)/B2002,0.001))
Fmort2002a<--log(max((B2002-200)/B2002,0.001))
Fmort2002b<--log(max((B2002-250)/B2002,0.001))
Fmort2002c<--log(max((B2002-300)/B2002,0.001))
Fmort2002d<--log(max((B2002-350)/B2002,0.001))
Fmort2002e<--log(max((B2002-400)/B2002,0.001))
Fmort2002f<--log(max((B2002-450)/B2002,0.001))

PrFmort2002a1<-step(Fmort2002a1-0.12)
PrFmort2002a2<-step(Fmort2002a2-0.12)
PrFmort2002a3<-step(Fmort2002a3-0.12)
PrFmort2002a<-step(Fmort2002a-0.12)
PrFmort2002b<-step(Fmort2002b-0.12)
PrFmort2002c<-step(Fmort2002c-0.12)
PrFmort2002d<-step(Fmort2002d-0.12)
PrFmort2002e<-step(Fmort2002e-0.12)
PrFmort2002f<-step(Fmort2002f-0.12)

}
```

Table 1. Reconstructed landings for Scallop Production Area (SPA) 3 and 7 by Full Bay and Offshore scallop fleets. From 1999 to present SPA 7 has been considered part of SPA 3. Refer to text for methods used to produce these data.

	Full Bay		Offshore
Year	SPA 3	SPA 7	SPA 3+7
1976	0.00	0.00	0.00
1977	0.00	0.00	0.00
1978	0.00	0.28	5.41
1979	230.65	0.00	47.33
1980	260.95	0.00	579.29
1981	459.05	4.10	63.07
1982	346.60	3.53	298.36
1983	93.19	0.00	253.33
1984	56.29	1.11	117.43
1985	16.48	5.10	4.89
1986	0.81	10.21	
1987	0.00	12.10	
1988	0.17	0.00	
1989	0.00	0.00	
1990	0.00	0.00	
1991	385.99	45.56	
1992	726.87	82.26	
1993	1050.46	20.92	
1994	1347.42	92.13	
1995	764.65	156.41	
1996	286.25	66.75	
1997	190.04	35.67	
1998	162.09	57.89	
1999	222.05		
2000	248.84		
2001	162.87		

Table 2. Reconstruction of the history of scallop fishery within Scallop Production Area (SPA) 3 from 1980 to the present. Total effort and landings were calculated from the logbook data and total catch reported for this and adjacent areas (see text for details). Catch rate was calculated from Class 1 data from Full Bay scallop fleet logs only. Class 1 data refers to records from logbooks where catch, location and effort were all reported. The additional TACs of 15 and 50 t for 1999 and 2000, respectively, refer to limited re-openings of the area in the fall of each of those two years.

Year	CPUE (kg/h)	Total Effort ('000 h)	Propn. Catch (t)	Landings (meats, t)	TAC (meats, t)
1980	56.31	14.92	0.20	840.24	
1981	55.81	9.43	0.53	526.22	
1982	39.99	16.22	0.36	648.49	
1983	24.89	13.92	0.13	346.52	
1984	19.08	9.16	0.29	174.83	
1985	16.49	1.61	0.66	26.48	
1986	8.89	1.24	0.51	11.02	
1987	31.33	0.39	0.07	12.10	
1988	4.20	0.04	0.10	0.17	
1989		0.00	0.00	0.00	
1990		0.00	0.00	0.00	
1991	20.61	20.94	0.12	431.55	
1992	19.34	41.84	0.25	809.13	
1993	20.58	52.06	0.24	1071.38	
1994	16.94	84.98	0.38	1439.55	
1995	11.05	83.35	0.38	921.06	
1996	7.41	47.64	0.22	353.00	
1997	7.07	31.93	0.83	225.71	287
1998	9.40	23.40	0.97	219.98	200
1999	11.71	18.96	0.96	222.05	200(+15)
2000	13.31	18.70	0.97	248.84	200(+50)
2001	15.37	9.83	0.93	162.87	200
SFA 29					
2001	110.12	3.55	0.92	399.65	200 + 200

Table 3. Meat weight statistics for the Full Bay licence holders in SPA 3 (Brier Island/Lurcher Shoal) by month and year calculated from samples of the commercial catch.

		Meat weight (g)			Sample size	Meat count
Year	Month	Mean	Min.	Max.	(no. of meats)	per 500 g
Brier Island Fishing Grounds						
1983	May	10.62	3.7	18.0	85	47.1
	June	9.00	4.0	27.2	106	55.6
1991	May	13.55	6.5	38.8	74	36.9
	June	20.23	4.5	37.6	50	24.7
1992	June	12.91	5.6	26.2	77	38.7
	July	13.36	2.8	59.2	434	37.4
	Sept.	8.64	3.8	17.0	583	57.9
1993	April	12.50	3.3	25.6	318	40.0
	May	10.59	3.4	29.6	280	47.2
	June	9.98	3.9	26.7	200	50.1
	Sept.	11.31	3.6	42.9	379	44.2
	Nov.	14.00	7.3	23.7	71	35.7
1994	March	20.91	9.3	37.0	53	23.9
	April	19.00	4.9	42.0	419	26.3
	May	13.64	5.5	22.0	292	36.7
	June	16.18	4.6	51.5	1055	30.9
	July	22.00	11.0	37.5	111	22.7
1996	May	10.80	2.9	25.9	155	46.3
	July	19.80	15.8	23.9	35	25.3
	August	15.48	11.1	24.1	37	32.3
1997	May	13.46	6.3	24.4	120	37.1
	June	12.50	3.2	38.8	726	40.0
	July	15.05	5.1	41.7	1102	33.2
	August	13.61	4.4	45.1	341	36.7
	Sept.	13.91	5.3	49.0	358	35.9
	October	17.58	8.2	32.4	53	28.4
1998	June	16.97	5.0	28.7	744	29.5
	July	13.98	4.1	43.8	650	35.8
1999	June	20.45	13.1	37.7	552	24.4
	July	21.90	15.0	92.0	536	22.8
Re-Opening in Sept./Oct.						
1999	September	16.81	3.6	25.9	62	29.7
	October	17.92	5.7	34.2	281	27.9

Table 3. SPA 3 (Brier Island/Lurcher Shoal) Meat weight statistics, cont'd.

		Meat weight (g)			Sample size	Meat count
Year	Month	Mean	Min.	Max.	(no. of meats)	per 500 g
2000	June	19.98	6.0	50.7	267	26.3
	July	17.92	7.0	31.7	115	27.9
	November	20.97	10.9	34.1	49	23.8
Lurcher Shoal Fishing Grounds						
1991	June	6.67	2.2	27.6	1210	75.0
	July	9.17	3.1	33.7	437	54.5
	August	7.73	3.7	25.5	134	64.7
1992	June	9.84	3.3	29.0	312	50.8
	July	10.88	2.5	38.4	907	46.0
	August	15.20	9.4	27.0	66	32.9
	Sept.	9.17	4.6	15.7	446	54.5
1993	April	8.89	3.0	23.8	225	56.2
	May	7.00	3.0	25.3	711	71.4
	June	8.21	3.1	17.0	122	60.9
	Sept.	10.04	3.5	27.8	597	49.8
	Nov.	14.06	6.1	30.4	142	35.6
1994	April	15.72	5.6	43.5	380	31.8
	May	14.40	3.6	32.3	851	34.7
	July	12.31	4.8	34.3	971	40.6
1995	June	16.64	5.5	26.7	59	30.0
	July	14.33	5.7	29.3	344	34.9
	August	14.16	5.8	24.8	78	35.3
1996	June	11.83	4.3	29.2	350	42.3
	July	13.30	4.0	37.1	279	37.6
	August	17.58	10.4	25.3	75	28.4
	November	12.40	5.1	28.0	243	40.3
1997	May	10.87	3.2	33.7	951	46.0
	June	13.11	3.5	40.9	874	38.1
	July	12.96	3.7	38.4	1015	38.6
	August	11.72	4.0	38.4	574	42.7
	September	14.03	3.3	33.5	312	35.6
	October	14.79	5.1	32.4	125	33.8
1998	June	11.84	3.6	47.6	455	42.2
	July	12.21	4.3	55.1	601	41.0
	August	12.58	5.1	25.4	221	39.7
1999	May	19.42	15.4	23.5	69	25.7
Re-Opening in Sept./Oct.						
1999	October	13.33	6.3	27.3	302	37.5

Table 3. SPA 3 (Brier Island/Lurcher Shoal) Meat weight statistics, cont'd.

Year	Month	Meat weight (g) Mean	Min.	Max.	Sample size (no. of meats)	Meat count per 500 g
	November	13.04	6.7	22.5	77	38.3
2000	May	16.61	7.0	26.8	185	30.5
	June	19.25	7.3	31.5	264	26.0
	July	19.15	6.4	39.5	450	27.7
	November	19.33	10.0	34.7	68	25.9

Table 4. Meat weight statistics for the Full Bay licence holders in SPA 7 (St. Mary's Bay) by month and year calculated from samples of the commercial catch.

		Meat weight (g)			Sample size	Meat count
Year	Month	Mean	Min.	Max.	(no. of meats)	per 500 g
1996	June	23.65	7.3	46.3	23	21.1
1997	June	20.40	5.0	88.7	390	24.5
	July	17.24	6.5	44.3	158	29.0
	September	27.47	16.1	40.6	42	18.2
1998	June	30.05	9.7	64.2	139	16.0
1999	June	19.99	15.5	36.6	121	25.0
2000	June	28.24	9.1	56.1	154	18.7
	July	20.21	8.7	34.7	50	24.7

Table 5. Statistics from meat weight samples of Full Bay fleet scallop vessels in Scallop Production Area 3 for the 2001 fishing season. All samples collected by industry supported dockside monitoring program. Statistics on the percentage by number of meats in the sample that were less than 8 g are also given.

		Meat Weight (g)			Count	Number of	Percent $<$ 8 g		
Month	N	Mean	Min.	Max.	per 500 g.	Samples	Mean	Min.	Max.
St. Marys Bay									
June	154	19.6	6.4	49.5	25.6	3	0.6	0.0	1.8
Brier Island									
June	199	21.0	7.2	43.6	24.5	4	0.9	0.0	1.9
July	746	20.3	9.2	51.3	24.9	15	0.0	0.0	0.0
August	339	19.2	4.8	41.7	26.2	7	2.0	0.0	7.8
September	282	21.1	7.5	47.7	23.8	6	0.6	0.0	3.6
Lurcher Shoal									
March	273	14.9	5.2	29.4	33.8	4	3.3	0.0	7.7
April	76	13.4	5.4	29.1	37.4	1	19.7	19.7	19.7
May	744	13.5	4.4	30.8	37.1	10	6.6	0.0	18.2
July	281	18.7	7.7	43.8	27.9	5	0.3	0.0	1.5
August	180	18.3	6.9	36.2	30.1	3	2.6	0.0	5.7
September	185	18.3	8.3	44.9	28.8	4	0.0	0.0	0.0
SFA 29									
June	1846	22.0	7.6	44.7	22.9	36	0.5	0.0	1.8
July	513	23.8	11.1	64.9	21.2	11	0.0	0.0	0.0
August	1536	24.7	5.0	46.0	20.9	37	0.6	0.0	2.4
September	28	32.9	23.7	45.4	15.2	1	0.0	0.0	0.0

Table 6. Average shell height (mm) and meat weight (g) at age for scallops from the 1996 annual dredge research surveys of Scallop Production Area (SPA) 3.

	St. Marys Bay		Brier Island		Lurcher Shoal	
Age	Height	Weight	Height	Weight	Height	Weight
1			25.7	0.2	25.2	0.2
2	52.4	2.1	39.8	0.8	48.8	1.0
3	65.3	3.5	64.8	3.2	70.2	2.9
4	88.0	8.1	84.6	6.2	83.2	4.9
5	99.7	11.5	97.3	9.2	93.8	7.1
6	109.5	12.8	105.0	11.8	101.7	9.2
7	113.0	16.4	109.7	12.8	107.4	10.6
8	119.0	18.8	113.9	13.6	110.2	10.8
9	136.0	28.4	117.9	14.3	112.5	10.8
10			119.5	13.8	114.2	10.9
11			122.5	14.7	116.0	10.5
12			124.9	14.9	121.8	12.9
13			126.3	14.9	123.9	13.3
14			130.7	14.8	127.6	13.4
15			137.4	17.2	134.1	17.1
16			141.6	20.2	138.5	19.4

Table 7. Mean numbers per tow for the 1995–2001 scallop research surveys in scallop production area 3. The percentages of clappers are shown in brackets.

		Shell Height (mm)			
Subarea	Year	< 65	65–80	≥ 80	No. of tows
St. Mary's	1999	38.49 (2.6)	9.99 (1.8)	43.57 (1.5)	38
	2000	18.90 (1.2)	5.57 (1.9)	21.02 (3.4)	40
	2001	3.63 (0.0)	1.68 (0.0)	36.77 (0.7)	31
Brier Island	1995	14.22 (2.0)	3.52 (7.1)	64.59 (9.1)	43
	1996	12.46 (2.7)	3.69 (0.0)	56.73 (8.8)	43
	1997	57.92 (1.7)	4.12 (9.5)	70.48 (7.7)	47
	1998	38.32 (1.0)	1.19 (8.2)	76.25 (8.5)	31
	1999	14.64 (2.0)	4.63 (4.7)	63.30 (7.9)	52
	2000	430.43 (0.1)	2.17 (0.0)	51.95 (3.2)	48
	2001	30.50 (0.0)	16.75 (1.1)	78.28 (2.8)	41
Subarea	Year	< 70	70–80	≥ 80	No. of tows
Lurcher	1995	29.99 (7.8)	21.23 (22.2)	151.90 (16.5)	65
	1996	9.44 (12.3)	36.34 (4.1)	112.70 (13.1)	62
	1997	43.66 (1.1)	10.00 (6.4)	133.40 (6.0)	84
	1998	32.05 (2.0)	0.60 (8.6)	110.10 (4.2)	69
	1999	130.17 (0.6)	19.60 (0.3)	111.60 (2.4)	62
	2000	539.10 (0.5)	45.03 (0.0)	110.70 (0.8)	75
	2001	81.02 (2.8)	92.45 (0.5)	127.80 (2.3)	76
SFA 29	2001	40.08 (1.7)	10.54 (1.3)	252.59 (10.7)	125

Table 8. Average meat weight (g) at shell height for scallops from annual dredge research surveys of Scallop Production Area (SPA) 3, Brier Island area from 1996 to the present. Data for Scallop Fishing Area (SFA) 29 from the 2001 Julie Ann Joan Survey included for comparison.

Shell	Meat weight (g)						SFA 29
Height (mm)	1996	1997	1998	1999	2000	2001	2001
40	0.7	0.8	0.6	0.7	0.8	0.9	0.8
45	1.0	1.0	0.9	1.2	1.1	1.0	1.0
50	1.6	1.5	1.2	1.6	1.5	1.5	1.7
55	1.9	1.9	1.8	2.2	1.8	2.2	2.0
60	2.8	2.7	2.2	3.0	2.6	2.7	2.6
65	3.1	2.9	2.8	3.4	3.3	3.6	3.6
70	4.0	3.6	3.1	4.4	4.0	4.6	4.6
75	4.4	4.0	5.0	5.4	4.9	5.3	5.7
80	5.4	4.5	5.0	6.4	5.8	6.5	6.0
85	6.3	5.1	7.0	8.2	6.2	8.1	7.1
90	7.0	6.0	7.2	9.1	8.2	10.2	8.6
95	8.2	7.0	8.8	10.9	9.2	9.5	10.0
100	9.7	8.6	9.7	11.7	9.8	11.8	11.7
105	11.1	10.2	10.6	13.3	11.0	13.4	13.5
110	11.8	11.7	11.3	15.5	14.0	14.3	16.0
115	13.3	11.8	13.3	16.7	15.0	16.7	18.3
120	14.7	13.4	14.2	18.0	17.7	20.1	20.8
125	16.7	14.6	15.8	19.7	20.0	20.8	24.5
130	19.3	16.3	15.9	23.4	22.1	23.1	26.2
135	20.5	19.5	17.5	24.6	24.1	27.1	29.1
140	21.3	22.5	21.5	27.6	24.0	27.8	30.9
145	23.2	21.4	19.7	26.0	21.9	29.4	35.3
150	23.6	24.3	24.2	25.1	30.1	24.9	37.2
155	22.2	28.1	21.8	25.2	28.1	18.0	
160		21.3	26.4	34.2			37.0

Table 9. Average meat weight (g) at shell height for scallops from annual dredge research surveys of Scallop Production Area (SPA) 3, Lurcher Shoal area from 1996 to the present.

Shell	Meat weight (g)					
Height (mm)	1996	1997	1998	1999	2000	2001
40	0.4	0.7	0.5	0.6	0.8	0.6
45	0.9	0.8	0.8	0.9	1.1	0.7
50	1.0	1.0	1.2	1.4	1.5	1.3
55	1.4	1.2	1.7	1.8	1.8	1.8
60	1.7	1.4	2.1	2.4	2.4	2.5
65	2.3	2.1	2.2	3.2	3.0	3.1
70	2.8	2.6	3.4	3.8	3.9	3.6
75	3.6	3.2	4.3	5.1	4.8	4.3
80	4.4	3.8	4.8	6.4	5.7	5.6
85	5.1	4.6	5.5	7.5	6.7	6.5
90	6.1	5.6	6.2	8.5	7.6	7.7
95	7.3	6.7	7.3	9.6	8.6	8.7
100	8.1	7.6	9.0	11.4	10.2	10.5
105	9.2	8.4	10.1	12.8	11.8	11.5
110	10.6	9.7	11.2	14.4	13.6	13.4
115	11.6	10.4	12.5	16.5	16.0	16.1
120	13.7	12.6	14.3	18.4	17.5	18.3
125	15.3	16.4	16.2	20.7	20.3	20.6
130	18.3	19.8	19.2	22.5	21.3	22.4
135	20.2	22.5	21.5	26.6	23.9	25.6
140	23.2	24.8	25.0	31.0	26.0	27.5
145	21.7	28.7	22.7	31.1	25.8	30.9
150	32.8	20.4	25.0	33.6	26.9	37.5
155	15.4	28.5	35.1	28.8	18.1	29.0
160	34.6	0.0	0.0	0.0	22.8	20.2

Table 10. Average meat weight (g) at shell height for scallops from annual dredge research surveys of Scallop Production Area (SPA) 3, St. Marys Bay area from 1999 to the present.

Shell	Meat weight (g)		
Height (mm)	1999	2000	2001
40	1.0	1.0	1.2
45	1.4	1.5	1.3
50	1.7	1.7	1.6
55	2.5	2.5	2.2
60	3.3	3.6	3.1
65	4.0	4.5	3.6
70	5.1	5.6	4.0
75	6.2	6.3	5.2
80	7.5	7.6	6.3
85	9.0	9.5	8.0
90	11.3	11.2	9.7
95	13.2	12.7	12.2
100	15.6	15.3	13.5
105	18.1	17.8	17.6
110	20.2	19.4	19.9
115	24.9	21.4	21.1
120	26.8	25.0	24.6
125	28.5	28.9	29.2
130	33.0	30.9	30.7
135	33.3	35.3	33.9
140	38.1	38.0	36.4
145	42.9	45.4	40.6
150	42.0	36.4	
155	56.4	31.0	45.0
160			

Table 11. Summary of posterior distributions for model parameters. The column labelled SD corresponds to a naïve estimator of the standard deviation — assumes no autocorrelation. The columns labelled 0.025 and 0.975 refer the quantiles for these quantities and also provide the lower and upper limits for credible regions for the posterior distribution of the parameter.

Node	Mean	SD	0.025	Median	0.975
K	2216	1099	891.6	1972	5055
σ^2	0.1026	0.0459	0.0458	0.0924	0.2208
σ_ε^2	0.0642	0.0220	0.0336	0.0604	0.1191
q_I	0.0079	0.0029	0.0028	0.0077	0.0141
Recruit Biomass	663.7	347.9	271.3	589.2	1522
Biomass in 2002	3041.0	1833.0	1168.0	2564.0	7809.0

Table 12. Various catch levels (TAC) for 2002 with Posterior median fishing mortalities. The results for the delay difference model are for using all of the catch data as reported and assuming that the 1999 landings were actually half as much as reported. The surplus production model is discussed in the text. Posterior probabilities are for exceeding $F_{0.1} = 0.12$.

	Delay Difference Model					
TAC	All reported catches		$\text{Catch}_{1999}/2$		Surplus Production Model	
(meats, t)	Fishing Mortality	Prob($F > F_{0.1}$)	Fishing Mortality	Prob($F > F_{0.1}$)	Fishing Mortality	Prob($F > F_{0.1}$)
125	0.05	0.02	0.05	0.02	0.05	0.01
150	0.07	0.05	0.07	0.05	0.06	0.03
175	0.08	0.11	0.08	0.11	0.07	0.07
200	0.09	0.18	0.09	0.19	0.08	0.12
250	0.10	0.37	0.11	0.37	0.10	0.27
300	0.12	0.53	0.14	0.52	0.12	0.42
350	0.15	0.65	0.16	0.66	0.14	0.56
400	0.17	0.74	0.18	0.75	0.17	0.67
450	0.19	0.81	0.21	0.81	0.19	0.76

Table 13. Evaluation of scenarios for potential misreporting of landings during the 1991 to 1995 period. Results are for catch levels (TAC) in 2002 with Posterior median fishing mortalities and probabilities from delay difference model. Posterior probabilities are for exceeding $F_{0.1} = 0.12$. The columns labelled $\text{Catch}_{1999}/2$ are for all landings as reported except for 1999 where the 1999 landings were assumed to be half as much as reported. The columns labelled $0.75\times$(1991–1995) and $0.50\times$(1991–1995) use this same series except that the landings for 1991–1995 have been reduced by 0.75 and 0.50, respectively.

TAC	$\text{Catch}_{1999}/2$		$0.75\times$(1991–1995)		$0.50\times$(1991–1995)	
(meats, t)	Fishing Mortality	Prob($F > F_{0.1}$)	Fishing Mortality	Prob($F > F_{0.1}$)	Fishing Mortality	Prob($F > F_{0.1}$)
125	0.05	0.02	0.06	0.08	0.09	0.25
150	0.07	0.05	0.08	0.16	0.10	0.39
175	0.08	0.11	0.09	0.27	0.12	0.52
200	0.09	0.19	0.10	0.37	0.15	0.62
250	0.11	0.37	0.13	0.57	0.18	0.76
300	0.14	0.52	0.16	0.71	0.22	0.84
350	0.16	0.66	0.19	0.79	0.26	0.89
400	0.18	0.75	0.22	0.85	0.31	0.92
450	0.21	0.81	0.25	0.89	0.35	0.94

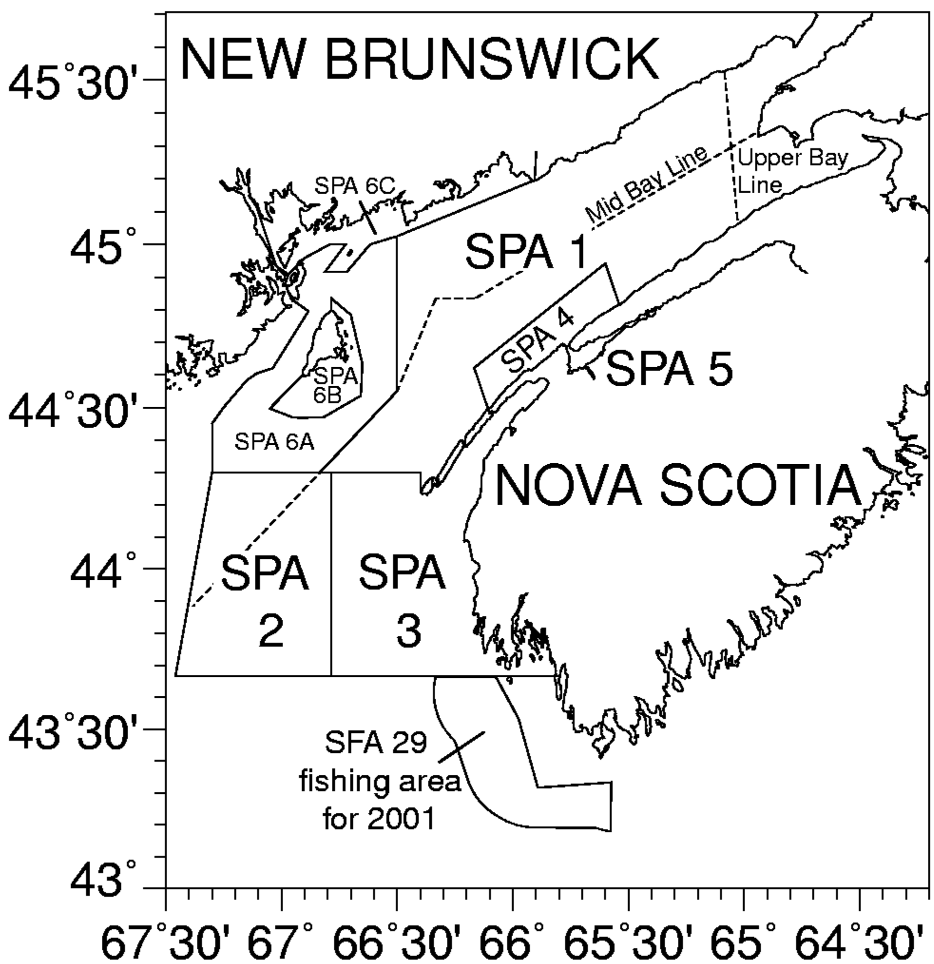


Fig. 1. Scallop Production Areas (SPA) in the Bay of Fundy. The boundaries of the SPA's were established 1 January 1997. In 1999, the number of SPA's was reduced from 7 to 6 (St. Mary's Bay (SPA 7) was combined with Brier Island/Lurcher Shoal (SPA 3)). The area labelled SFA 29 fishing area was that portion of the larger scallop fishing area that was open to fishing by the Full Bay scallop fleet.

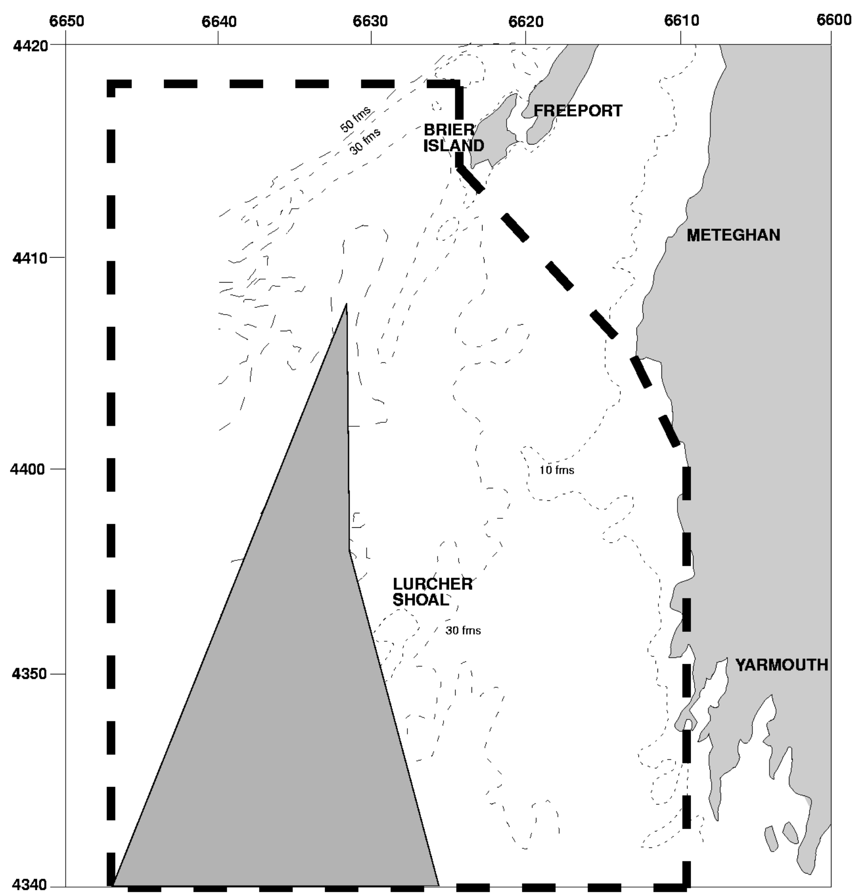


Fig. 2. Scallop production area 3. Shaded area was open from 19 March 2001 to 4 June 2001 and the dashed area was open from 1 June 2001 to 22 July 2001.

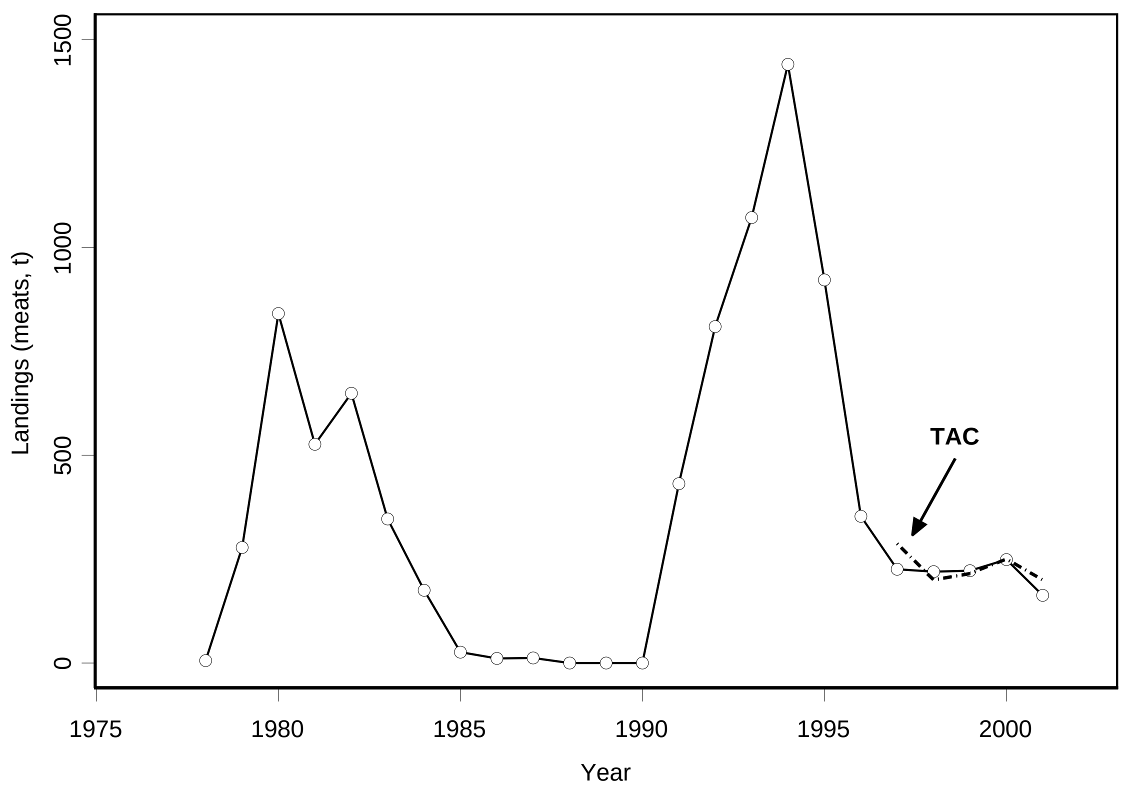


Fig. 3. Scallop landings (meats, t) in Scallop Production Area 3. Total allowable catch (TAC) levels were introduced in 1997.

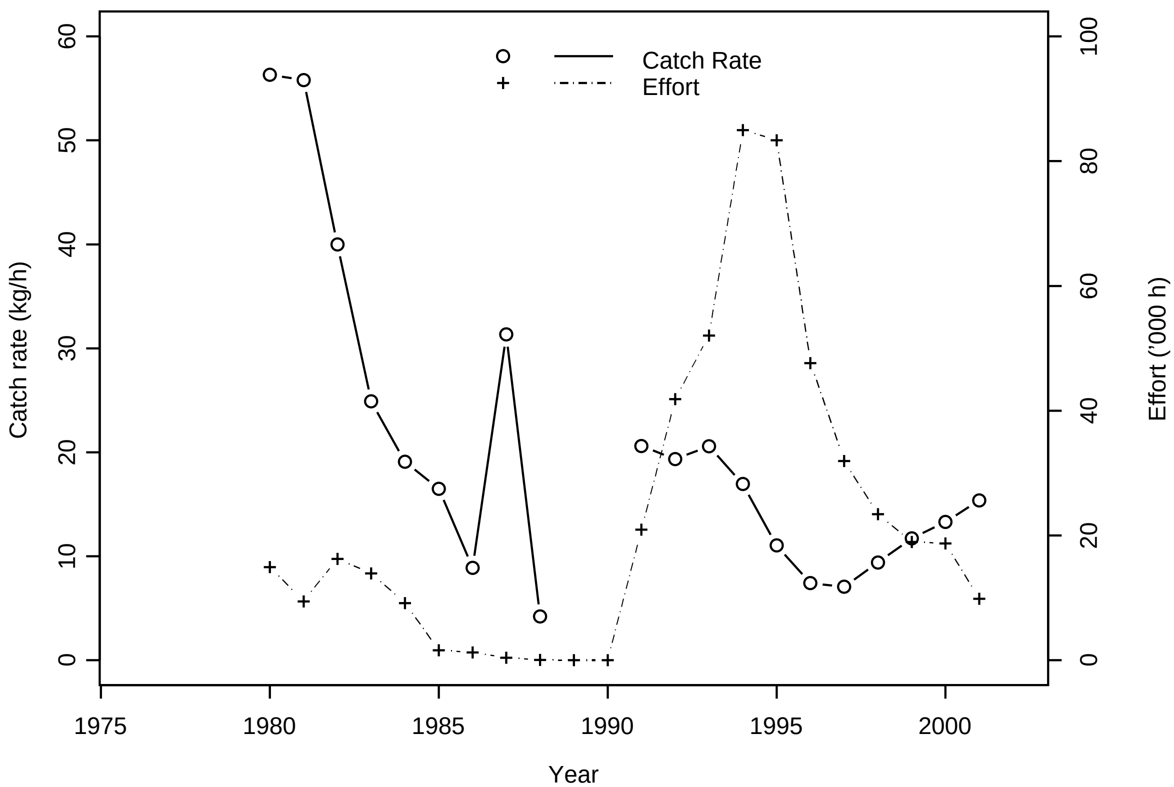


Fig. 4. Commercial catch rate (kg/h) for Full Bay fleet in Scallop Production Area 3. Commercial effort measured in thousands of hours fishing.

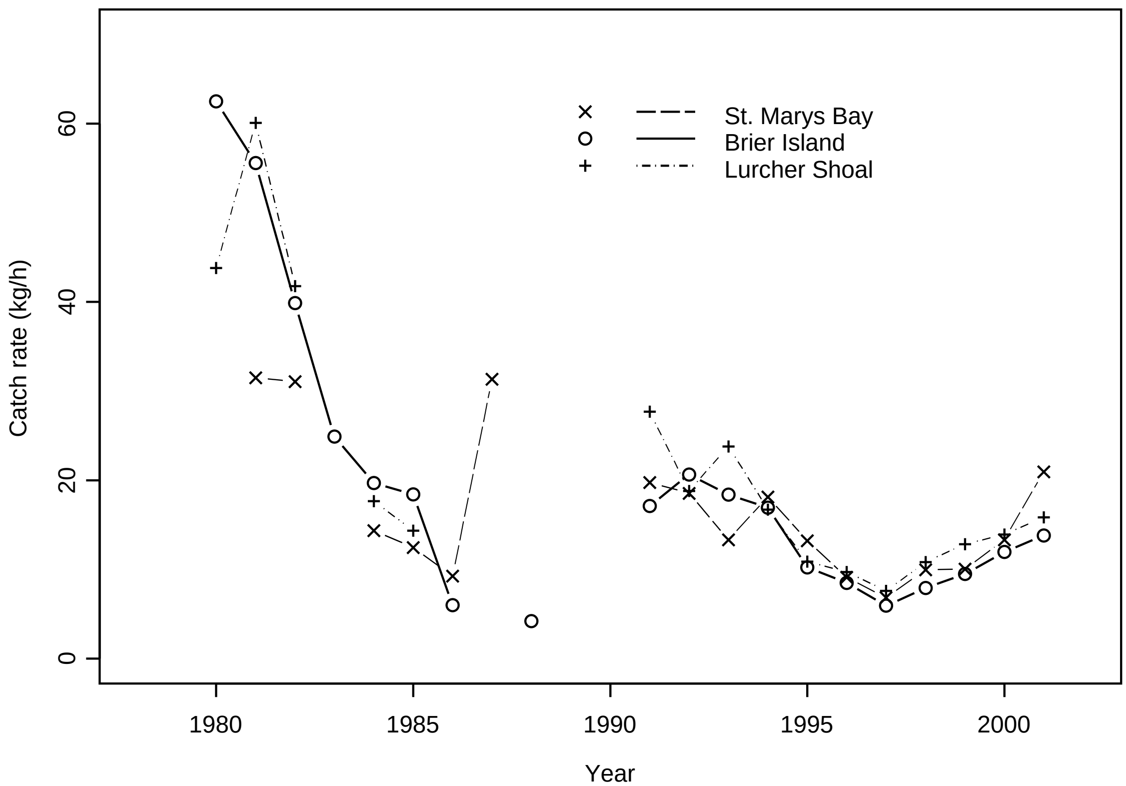


Fig. 5. Commercial catch rate (kg/h) for Full Bay fleet in Scallop Production Area 3 for each of the major subareas.

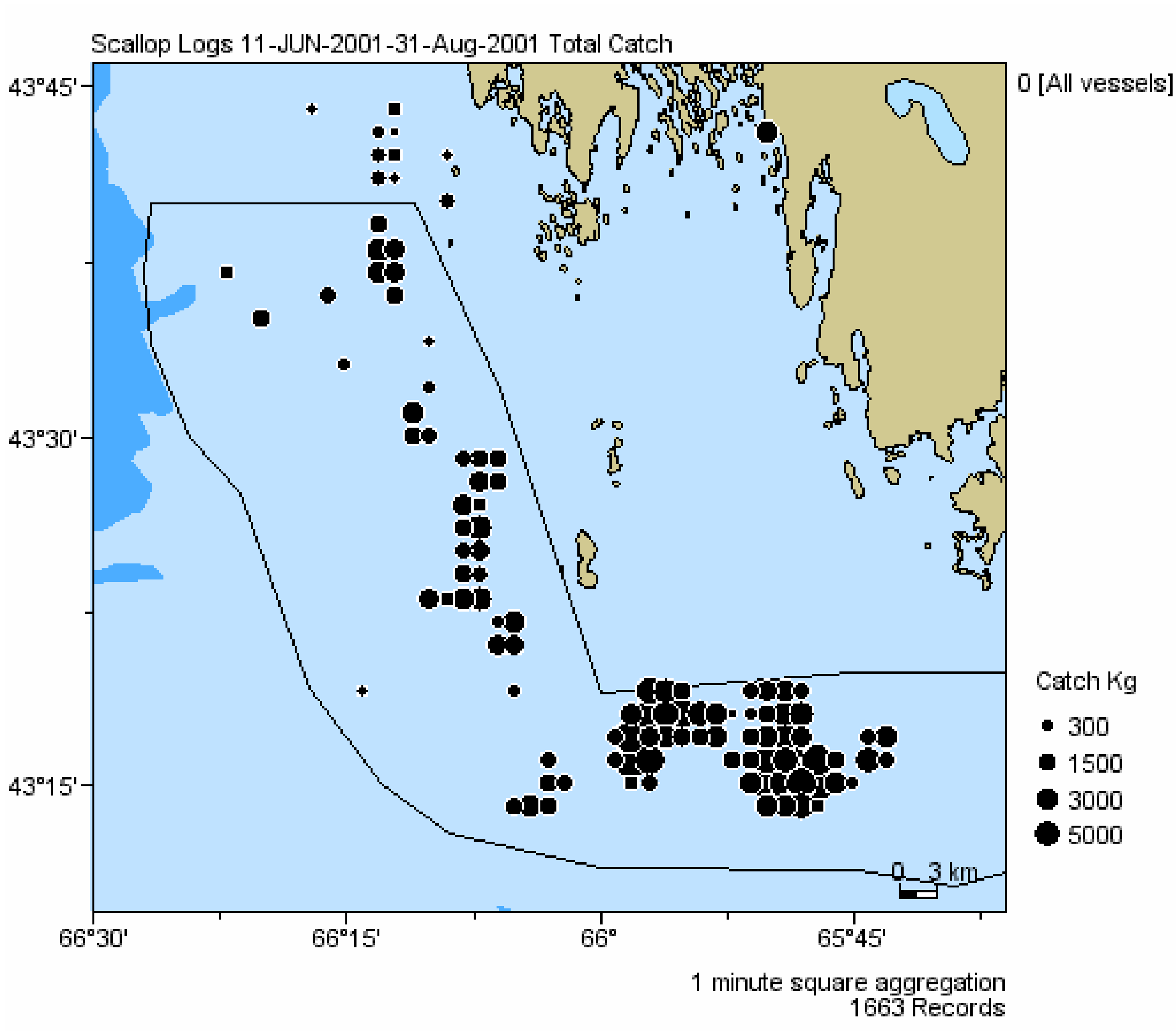


Fig. 6. Location of catches in Scallop Fishing Area 29 from Full Bay fleet commercial fishing logs in 2001.

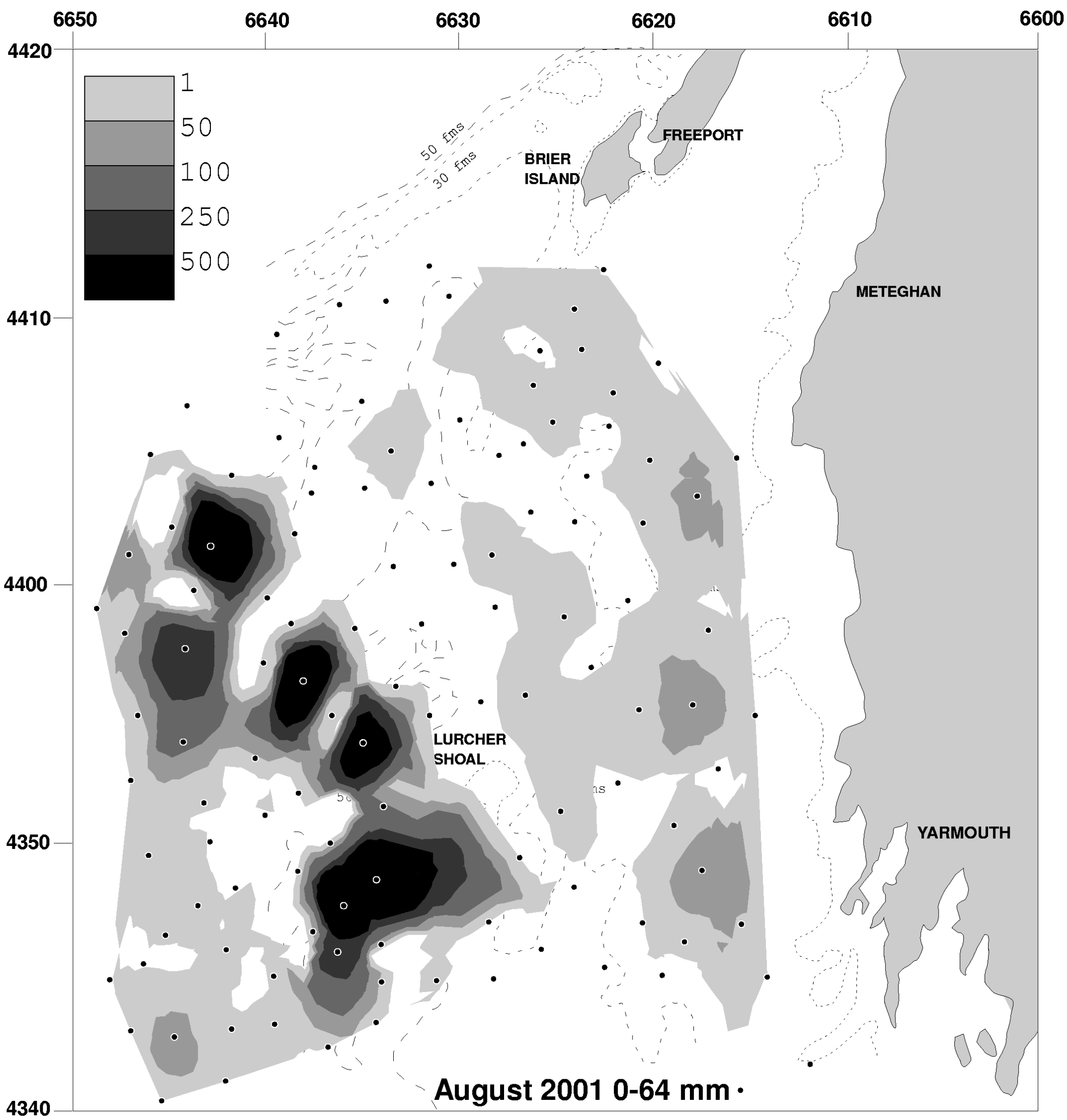


Fig. 7. Spatial distribution of scallops with shell height less than 65 mm caught during the 2001 research survey in SPA 3. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

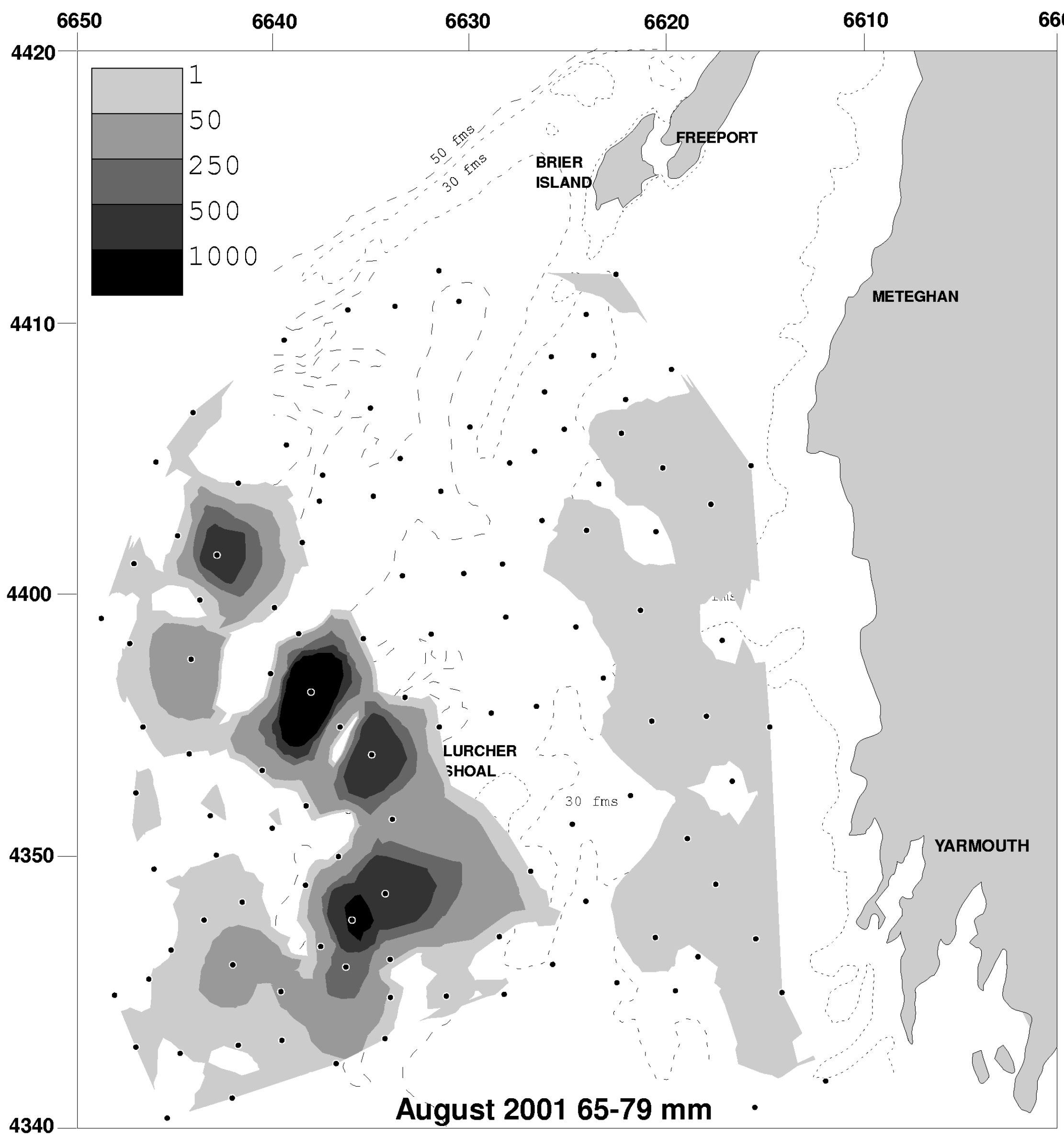


Fig. 8. Spatial distribution of scallops with shell height greater than 65 and less than 80 mm shell height caught during the 2001 research survey in SPA 3. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

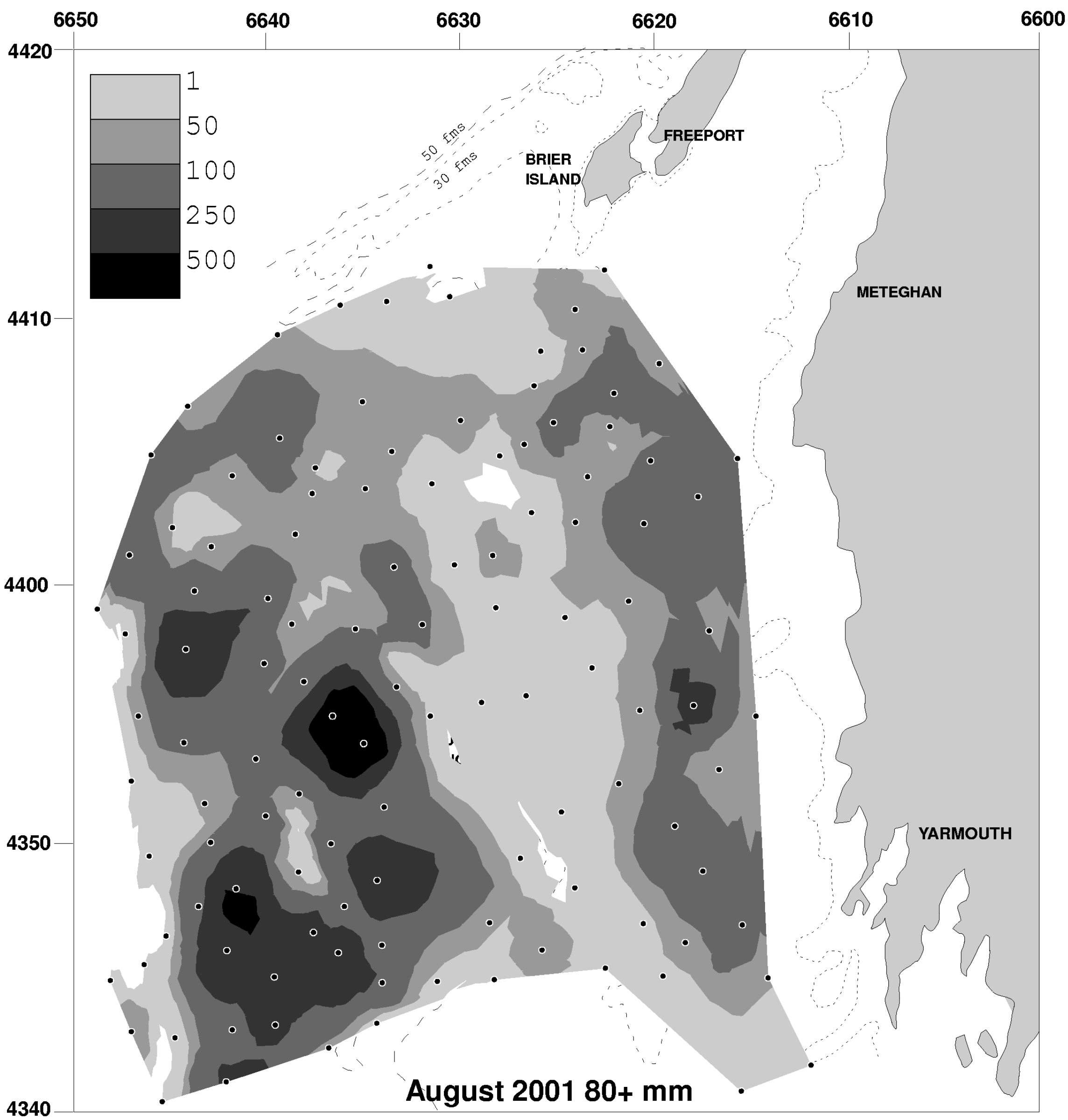


Fig. 9. Spatial distribution of scallops greater than 80 mm shell height caught during the 2001 research survey in SPA 3. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

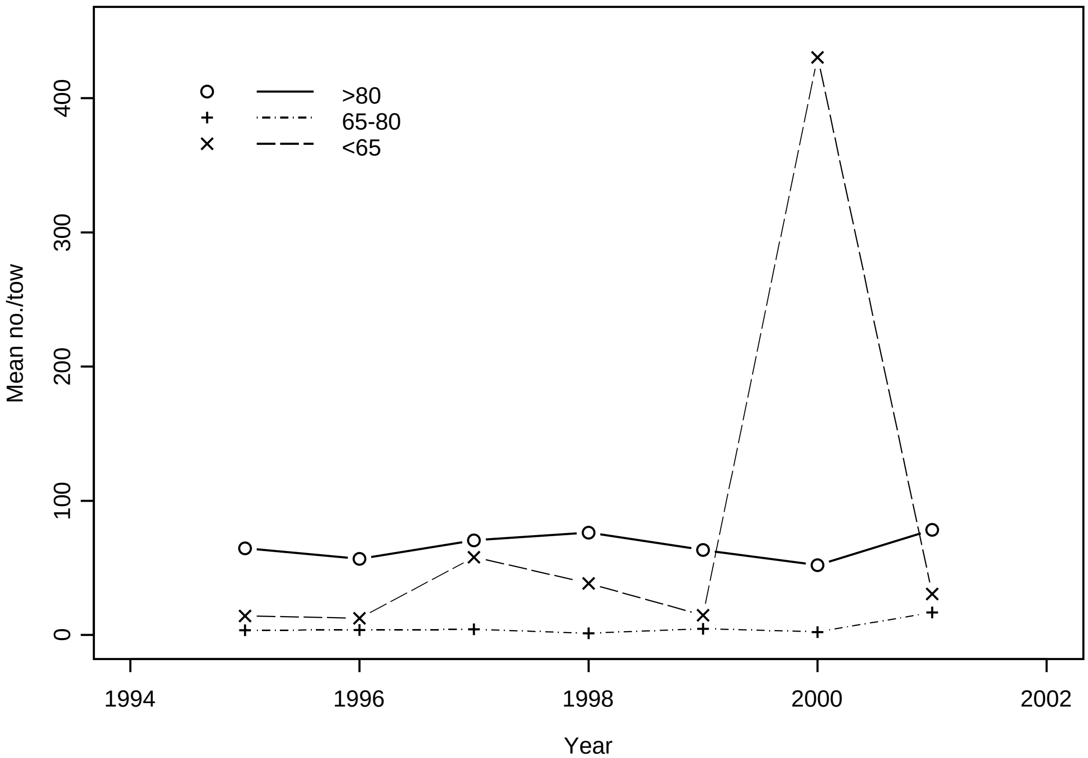


Fig. 10. Estimates of mean number of scallops per tow by size range for the Brier Island Area from August annual research surveys.

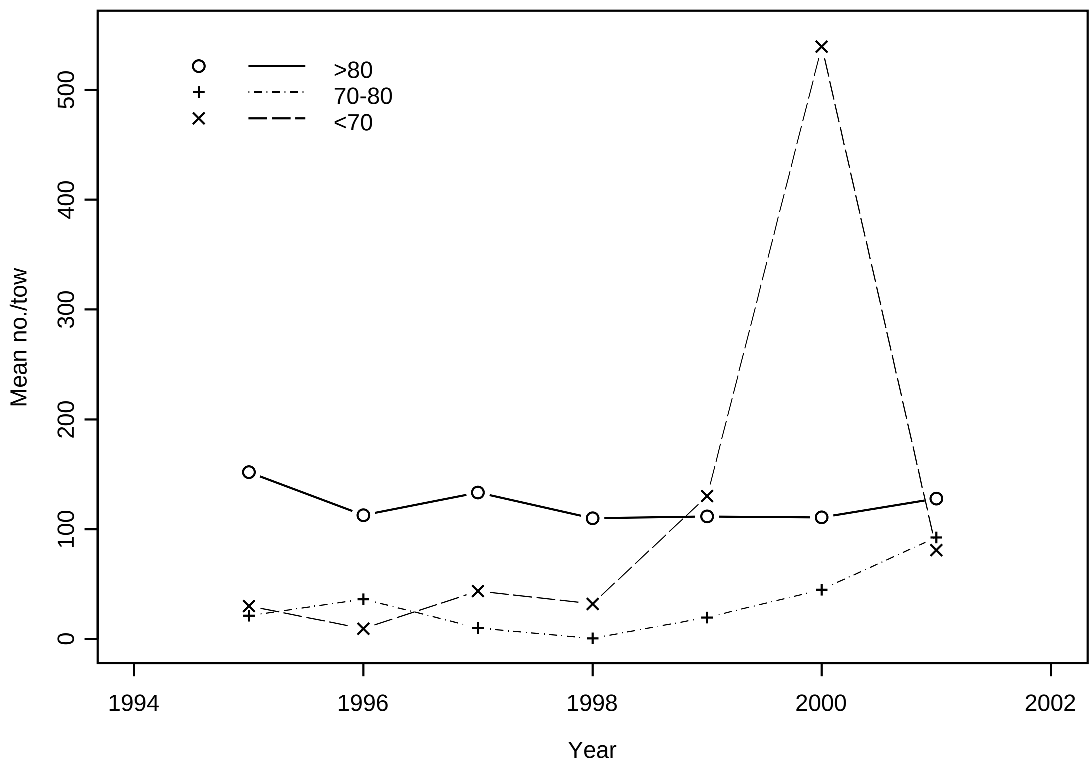


Fig. 11. Estimates of mean number of scallops per tow by size range for the Lurcher Shoal Area from August annual research surveys.

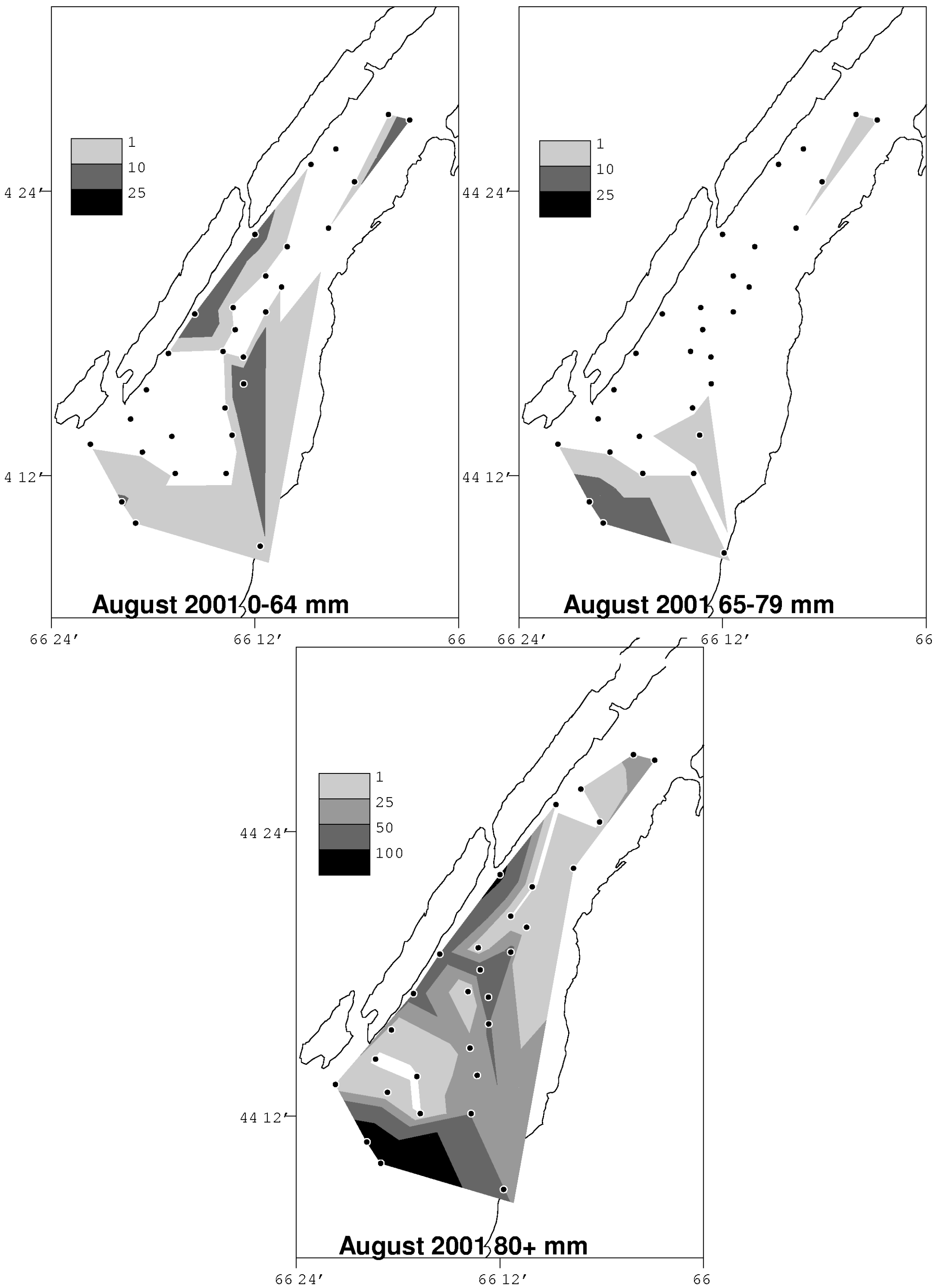


Fig. 12. Spatial distribution of scallops for shell heights less than 65 mm, between 65 and 80 mm, and greater than 80 mm caught during the 2001 research survey in St. Mary's Bay. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

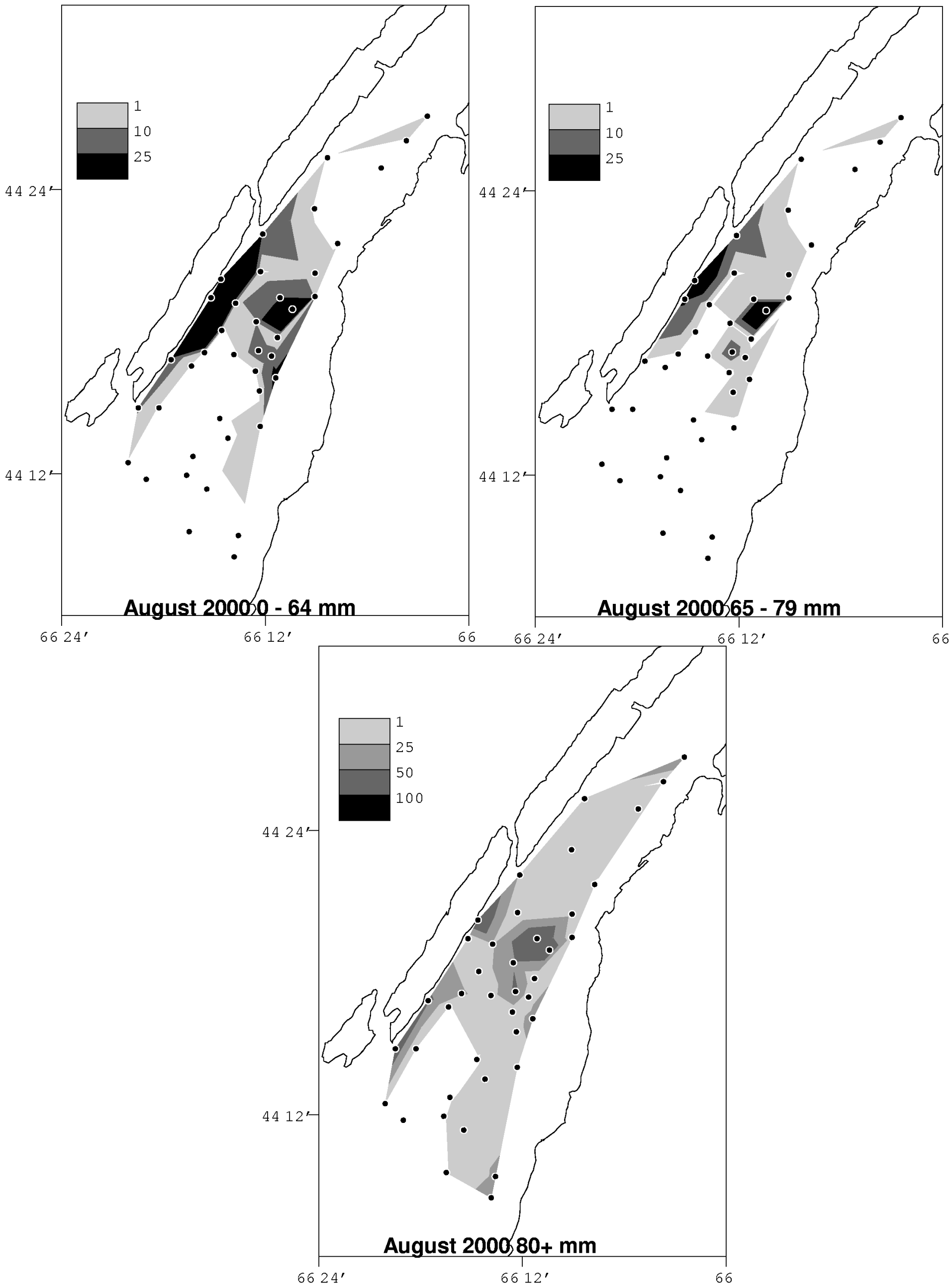


Fig. 13. Spatial distribution of scallops for shell heights less than 65 mm, between 65 and 80 mm, and greater than 80 mm caught during the 2000 research survey in St. Mary's Bay. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

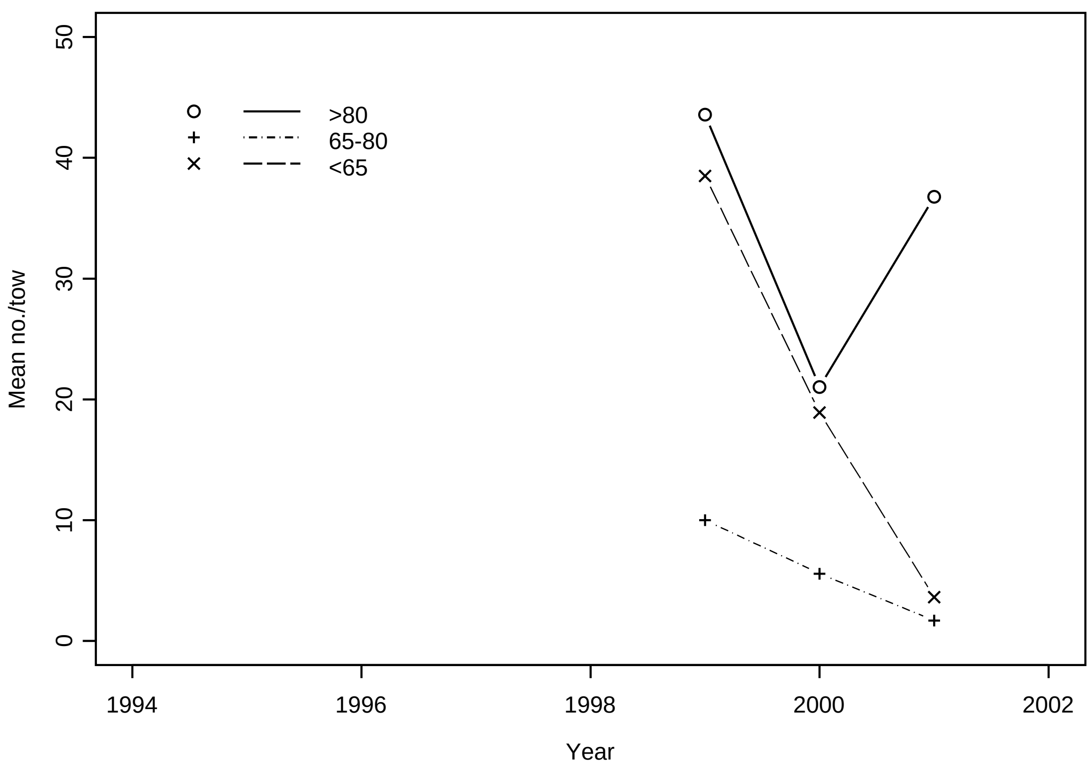


Fig. 14. Estimates of mean number of scallops per tow by size range for the St. Marys Bay Area from August annual research surveys.

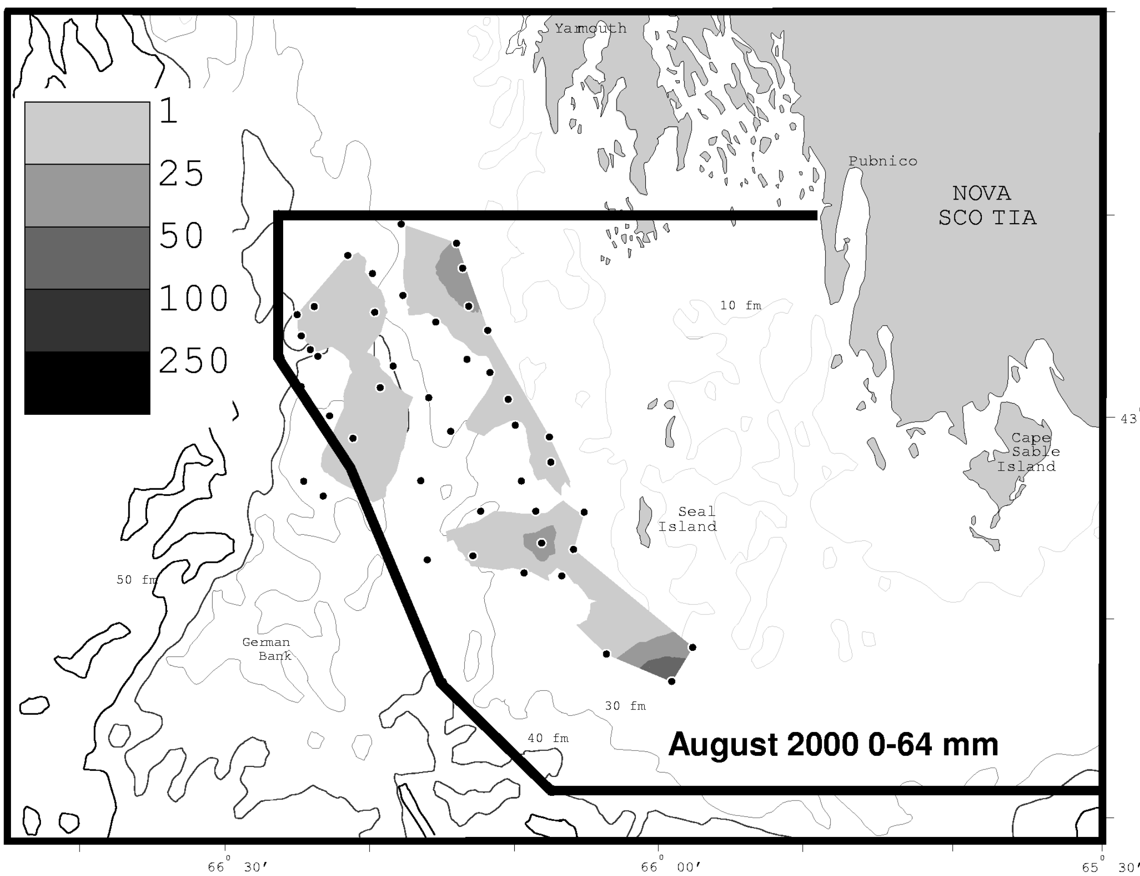


Fig. 15. Spatial distribution of scallops for shell heights less than 65 mm caught during the 2000 research survey with the J. L. Hart in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

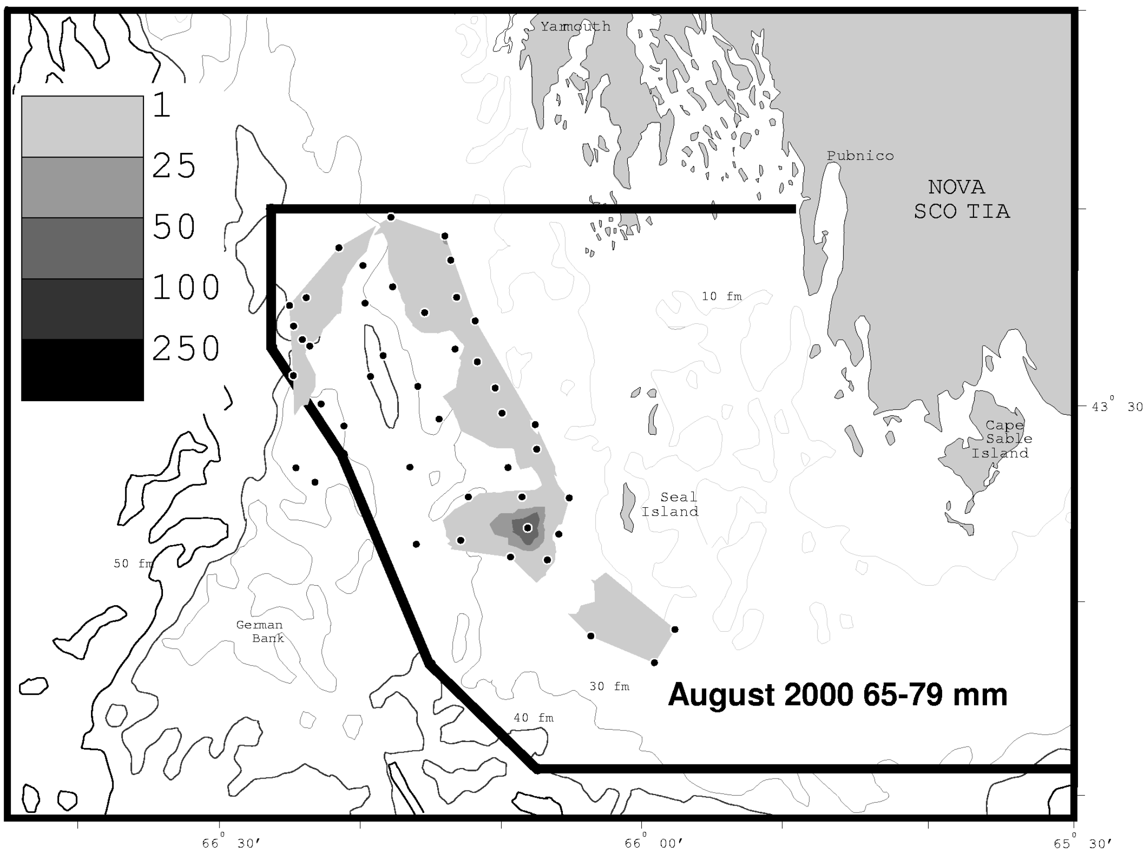


Fig. 16. Spatial distribution of scallops for shell heights betweem 65 and 80 mm caught during the 2000 research survey with the J. L. Hart in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

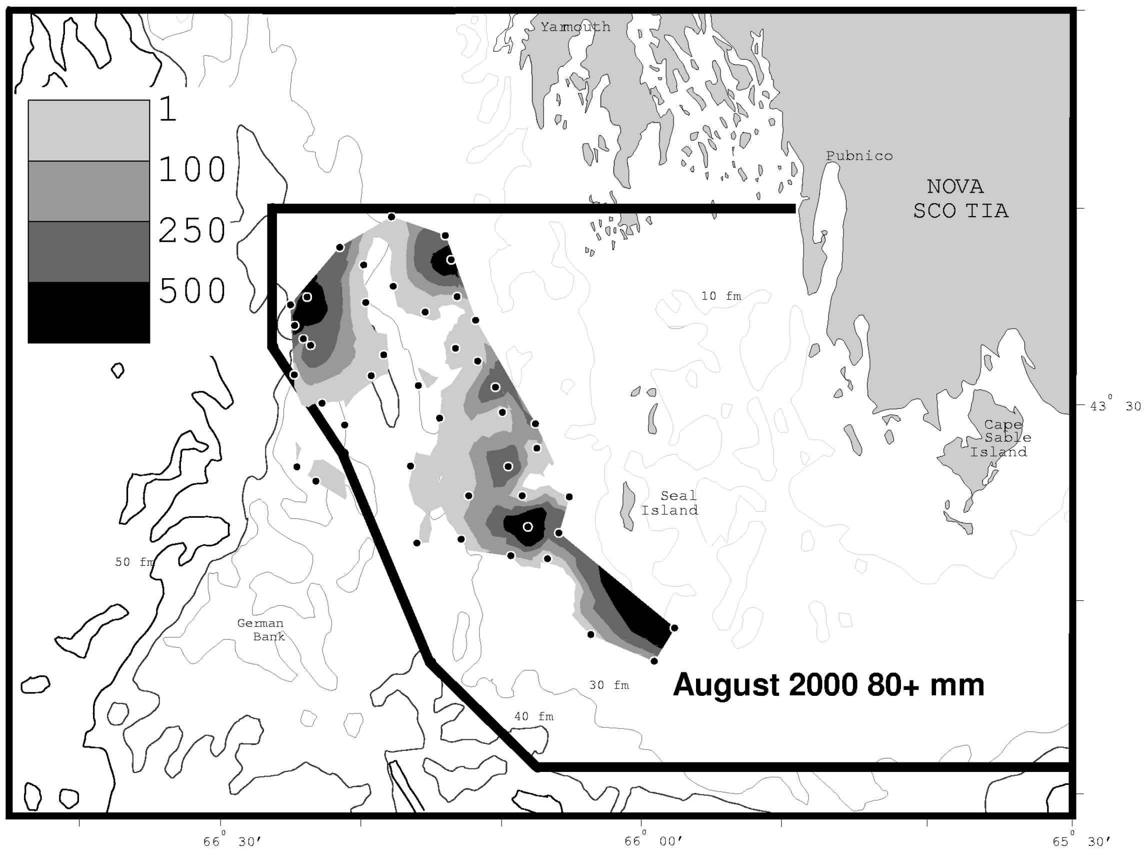


Fig. 17. Spatial distribution of scallops for shell heights greater than 80 mm caught during the 2000 research survey with the J. L. Hart in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

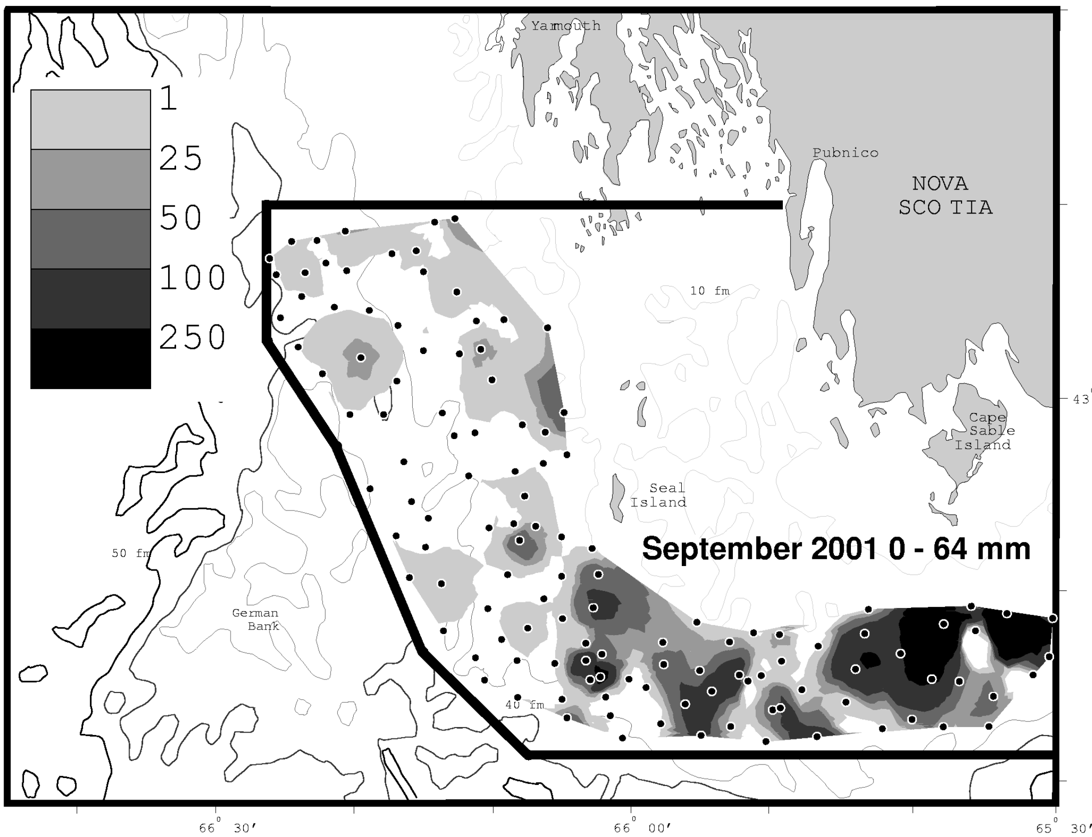


Fig. 18. Spatial distribution of scallops for shell heights less than 65 mm caught during the 2001 research survey with the Julie Ann Joan in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

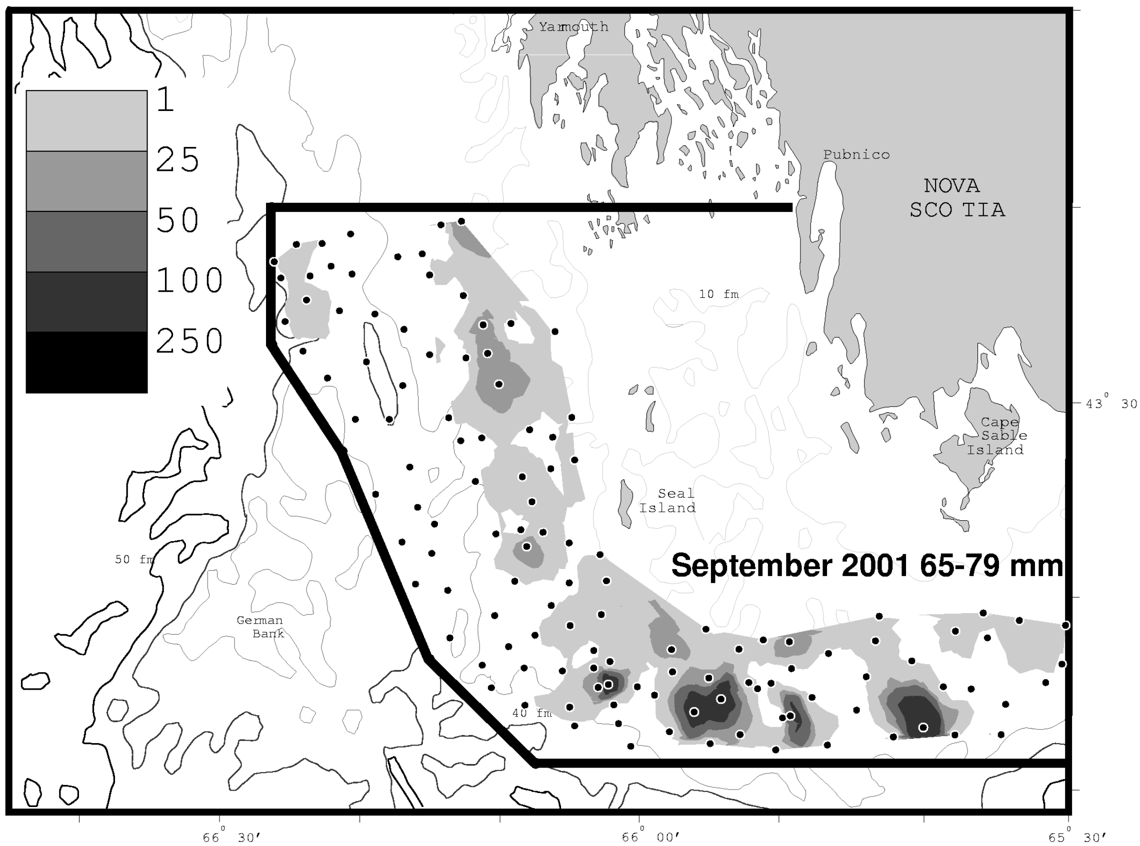


Fig. 19. Spatial distribution of scallops for shell heights betweem 65 and 80 mm caught during the 2001 research survey with the Julie Ann Joan in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

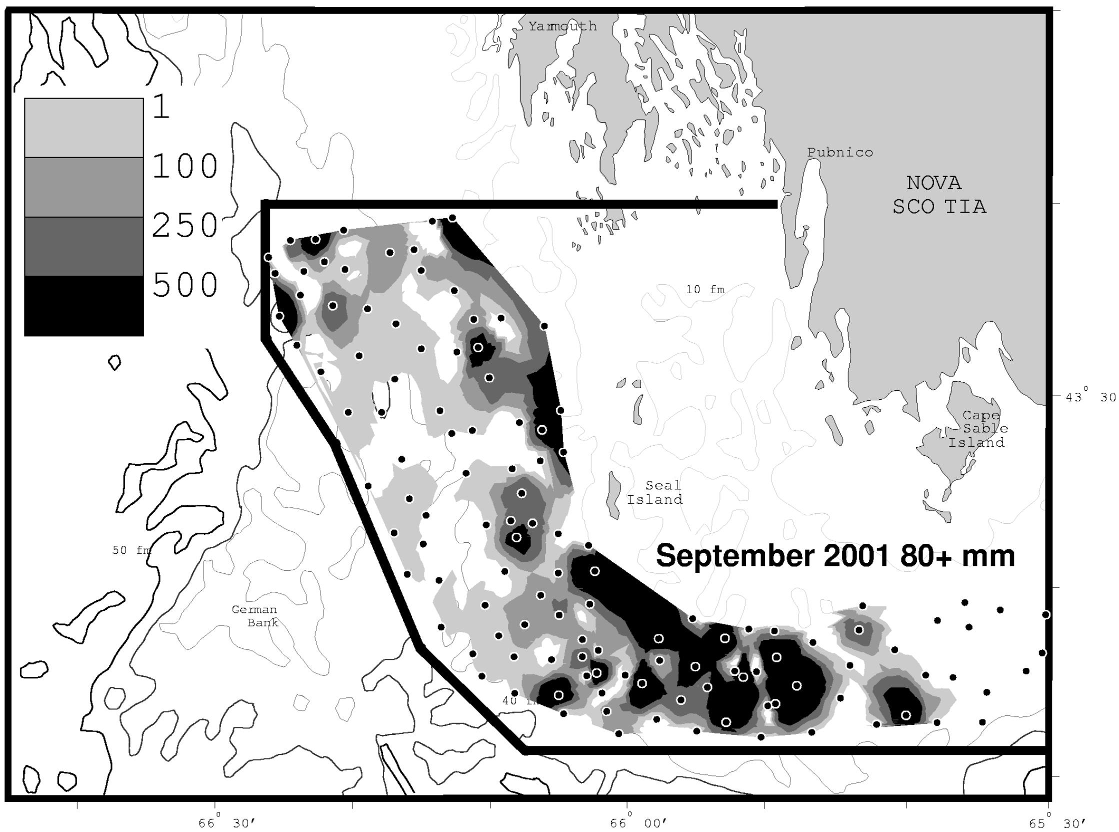


Fig. 20. Spatial distribution of scallops for shell heights greater than 80 mm caught during the 2001 research survey with the Julie Ann Joan in Scallop Fishing Area 29. Darkening shades of grey within isopleths refer to increasing numbers of scallops per standard tow. Dots depict tow locations.

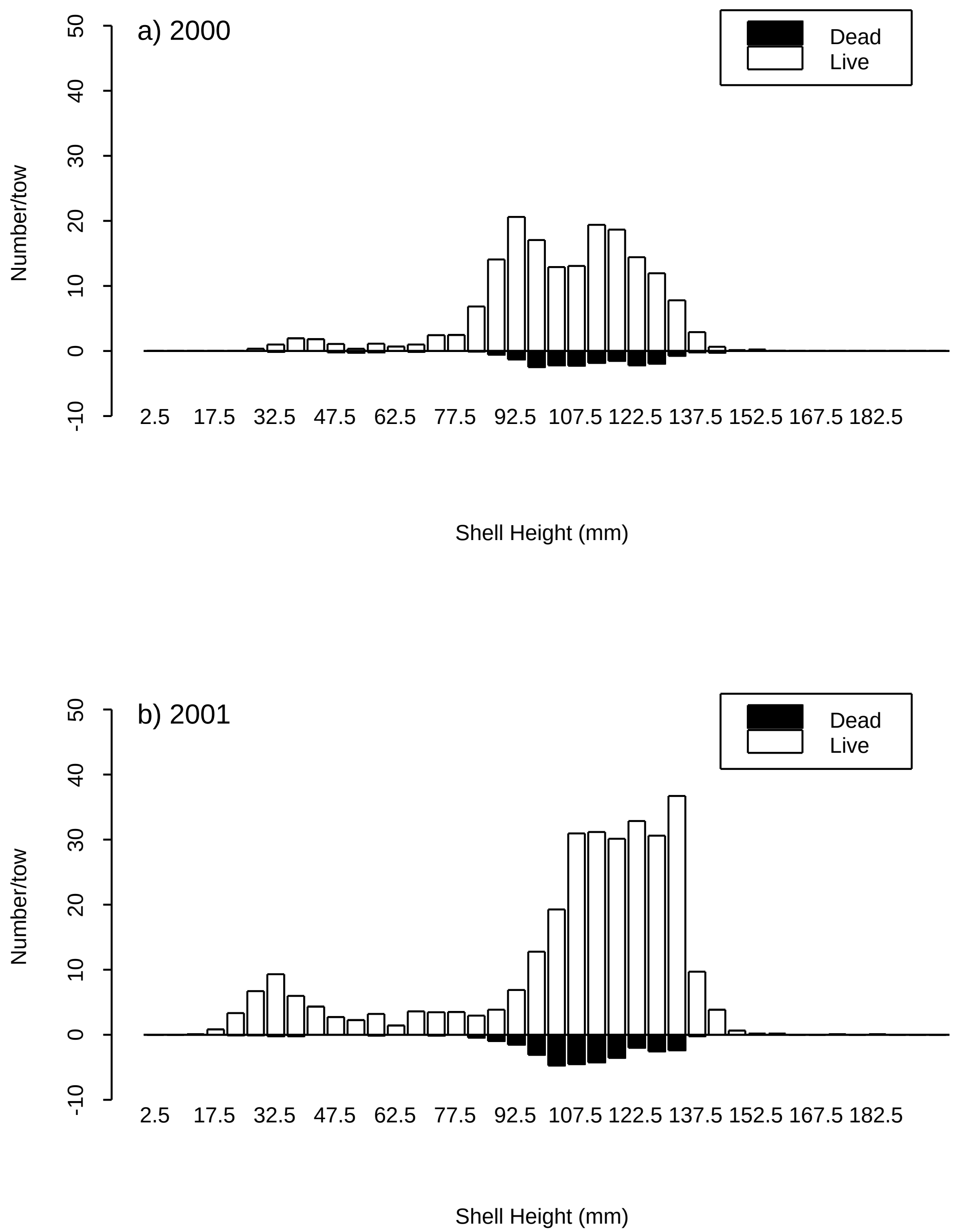


Fig. 21. Comparison of shell height frequencies from the 2000 and 2001 research survey of Scallop Fishing Area 29. Note that the coverage of the area was more extensive in 2001 than in 2000. Shell height frequencies for live and dead (clappers) are shown for each year.

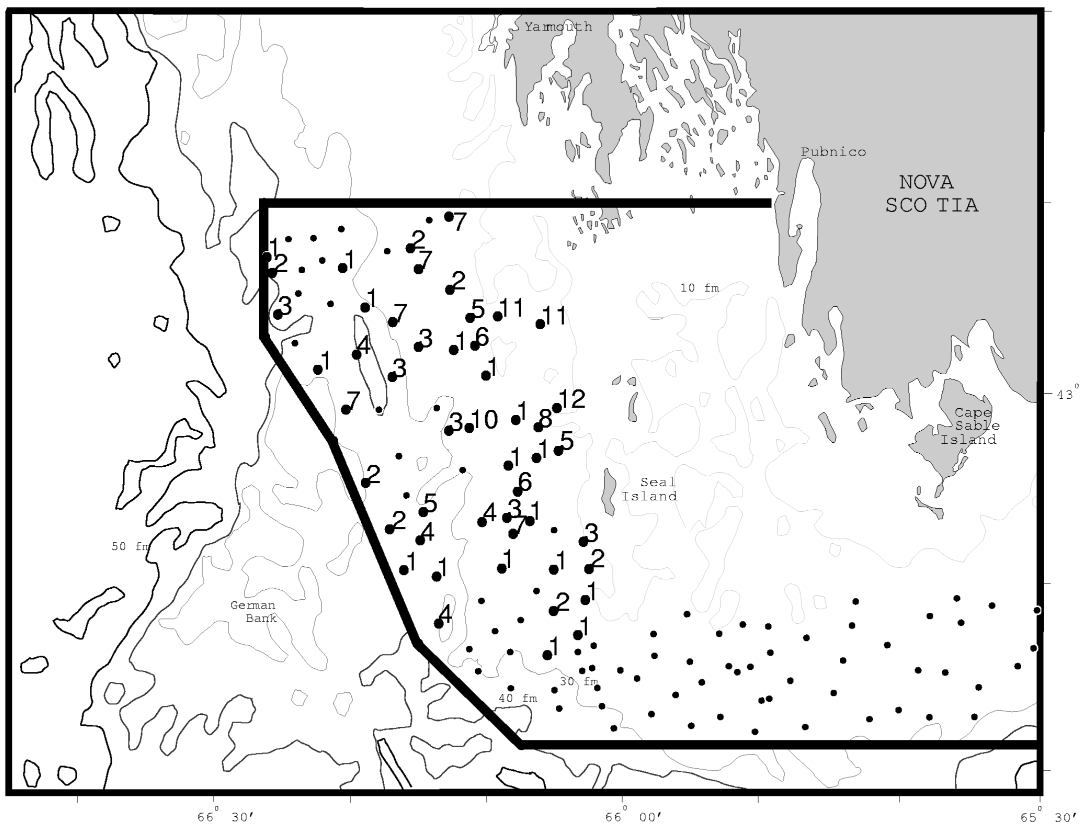


Fig. 22. Location and catch of lobsters during the 2001 research survey of Scallop Fishing Area 29. The number of lobsters caught are given by the tow locations.

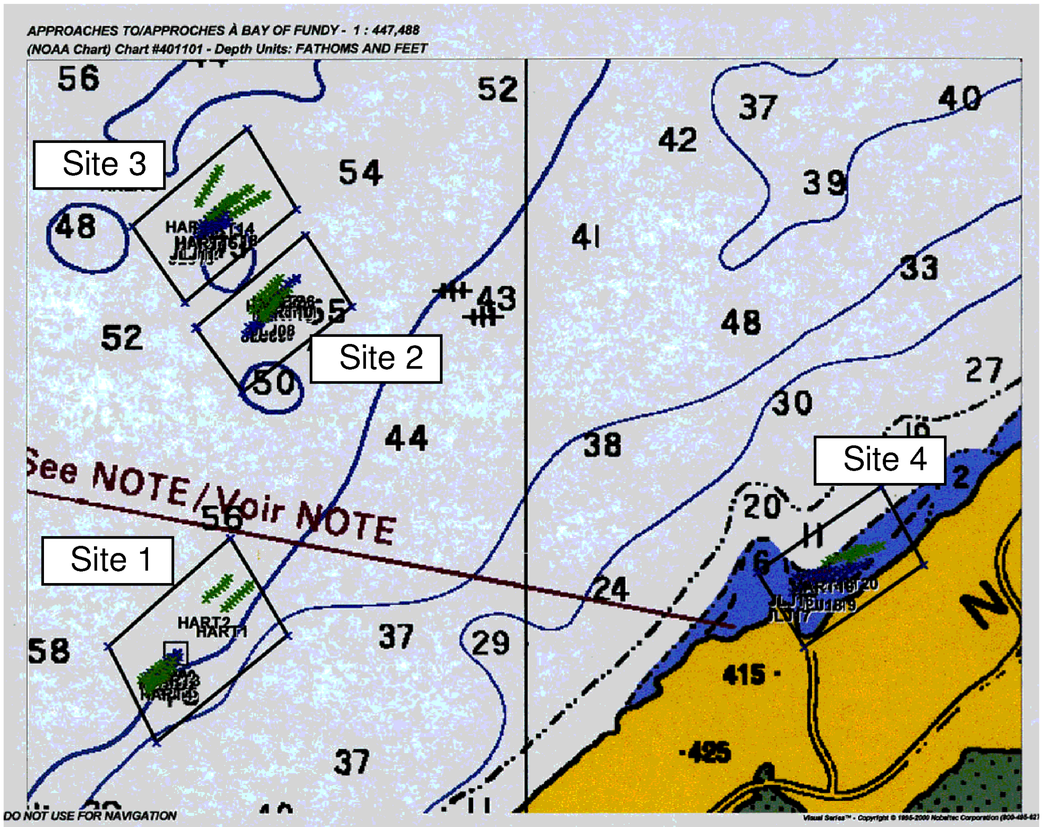


Fig. 23. Locations of the comparative tows by the J. L. Hart and Julie Ann Joan.

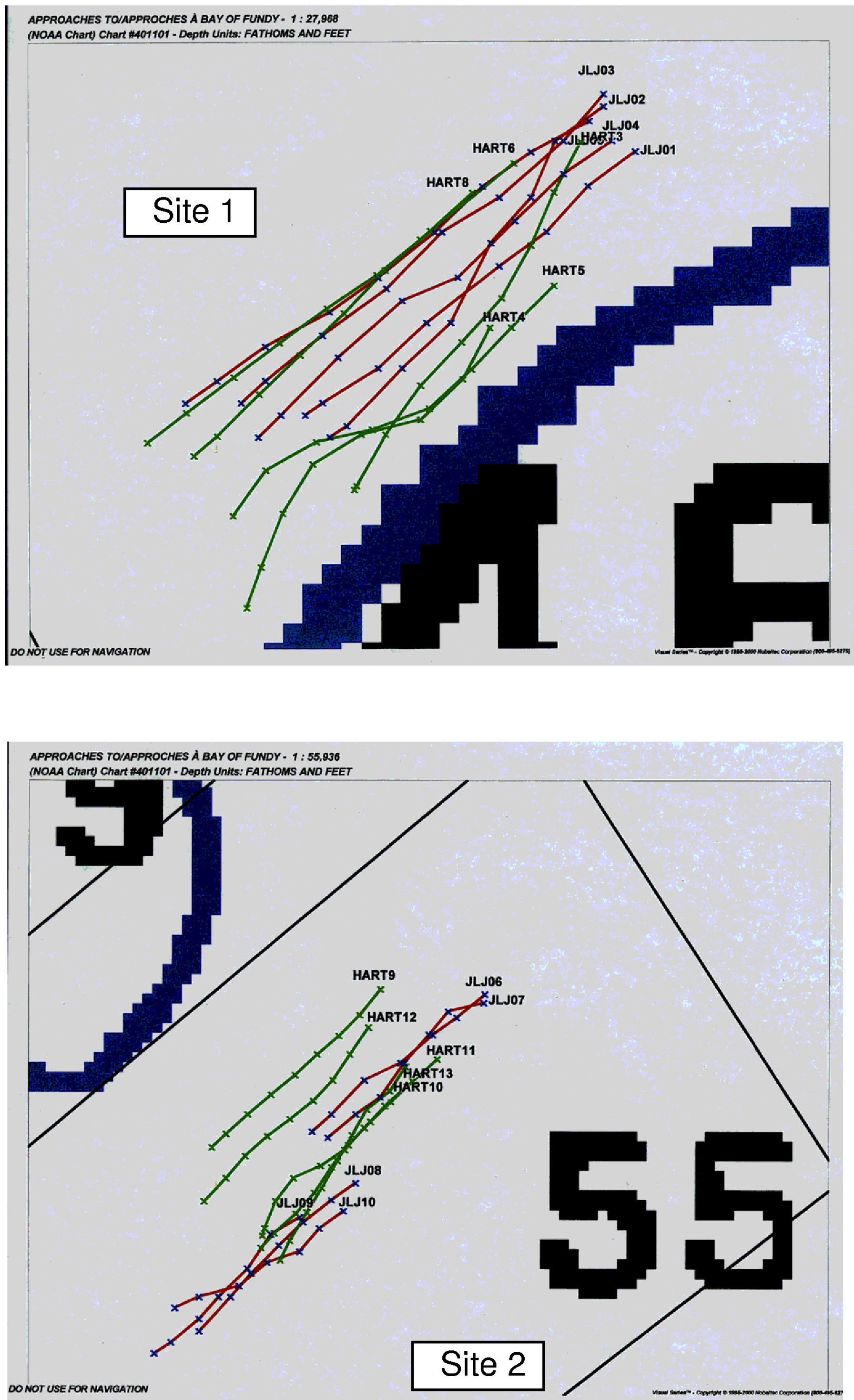
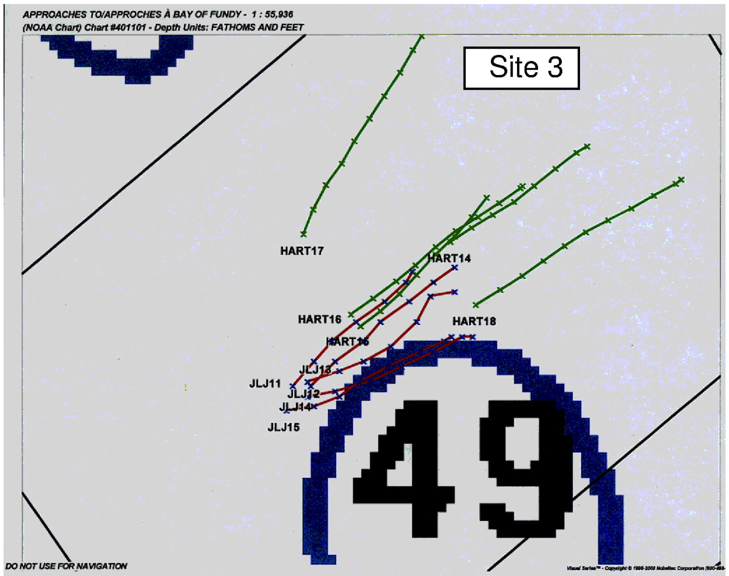


Fig. 24. Detailed locations of the comparative tows by the J. L. Hart and Julie Ann Joan for sites 1 and 2.



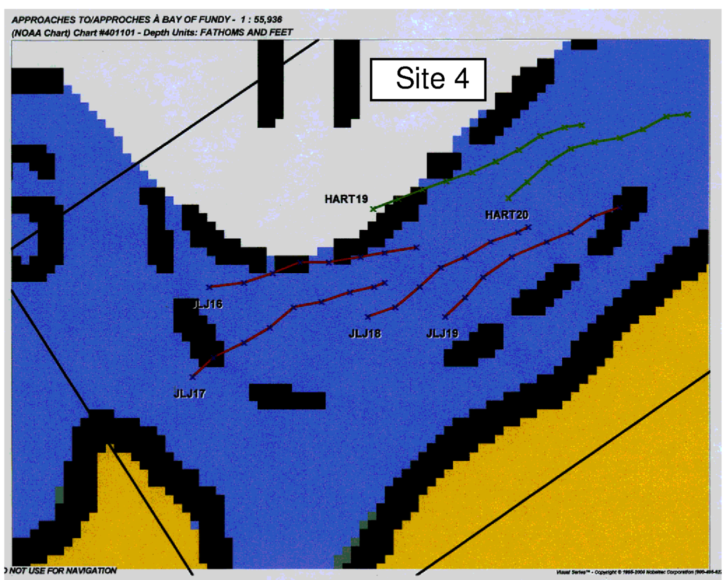


Fig. 25. Detailed locations of the comparative tows by the J. L. Hart and Julie Ann Joan for sites 3 and 4.

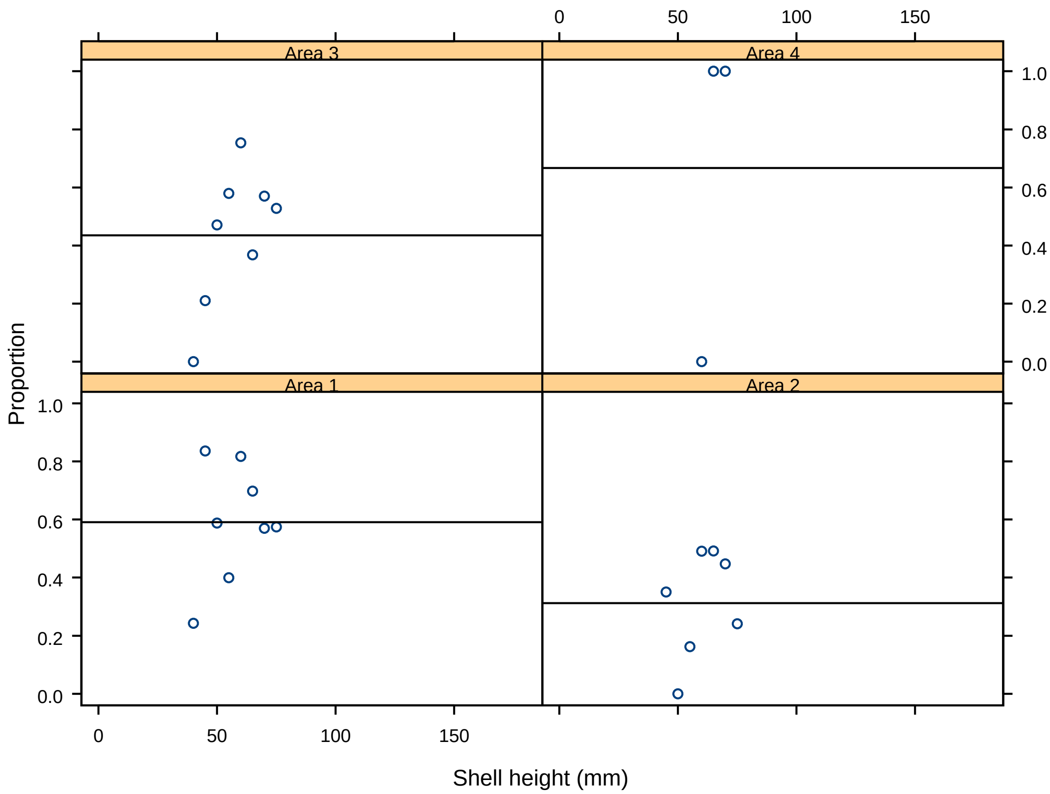


Fig. 26. Proportion of Julie Ann Joan catch of total catch by both vessels in 1999 comparative survey experiment for lined gear. Horizontal line refers to mean proportion for each area.

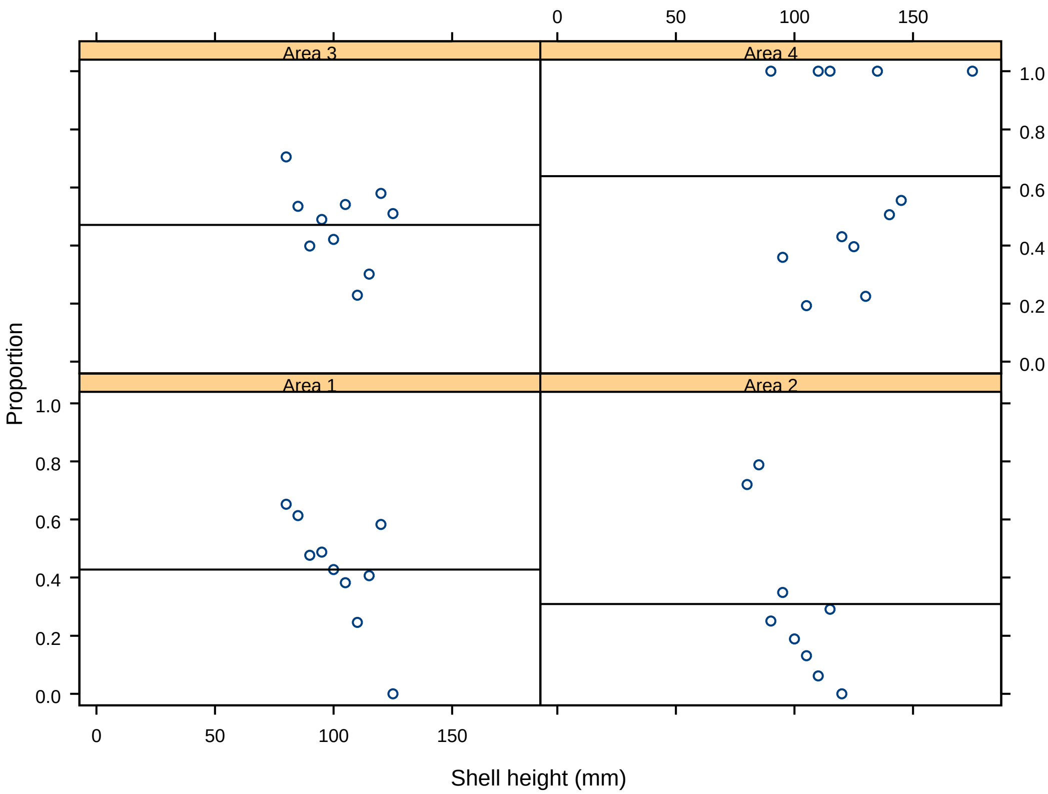


Fig. 27. Proportion of Julie Ann Joan catch of total catch by both vessels in 1999 comparative survey experiment for unlined gear. Horizontal line refers to mean proportion for each area.

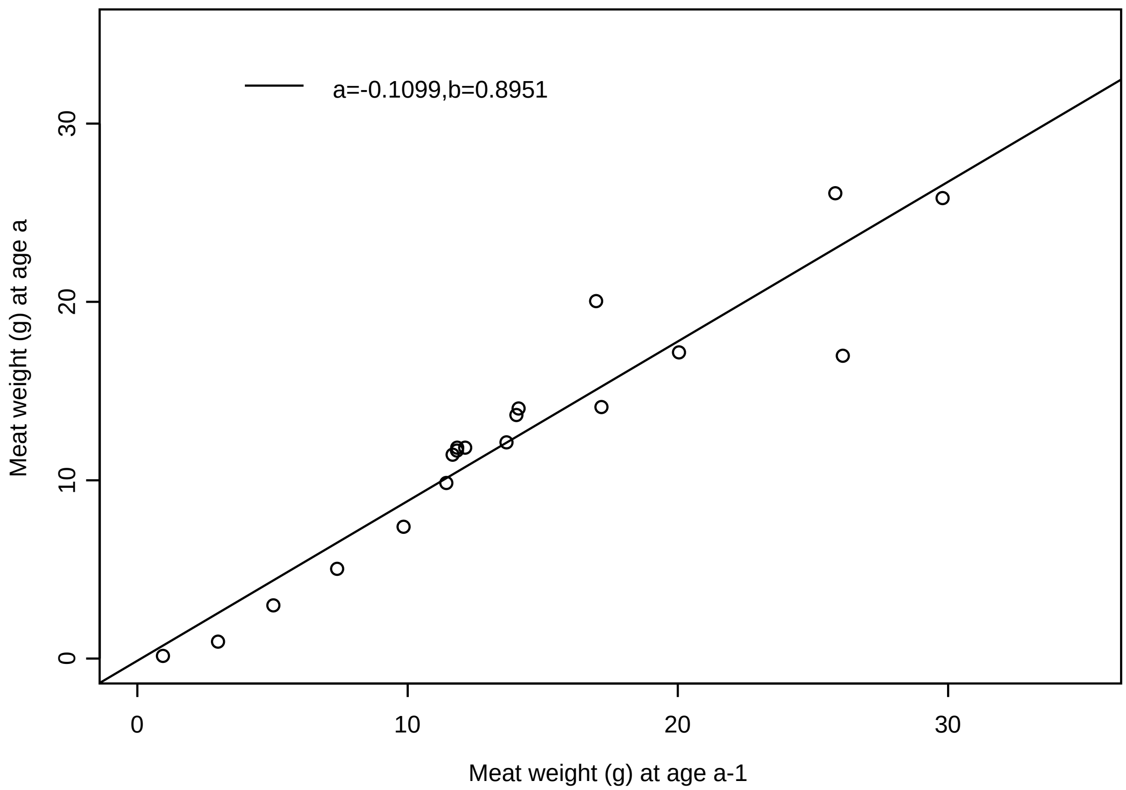


Fig. 28. Relationships between meat weights at age t and $t+1$ August 1996 research survey of Scallop Production Area 3.

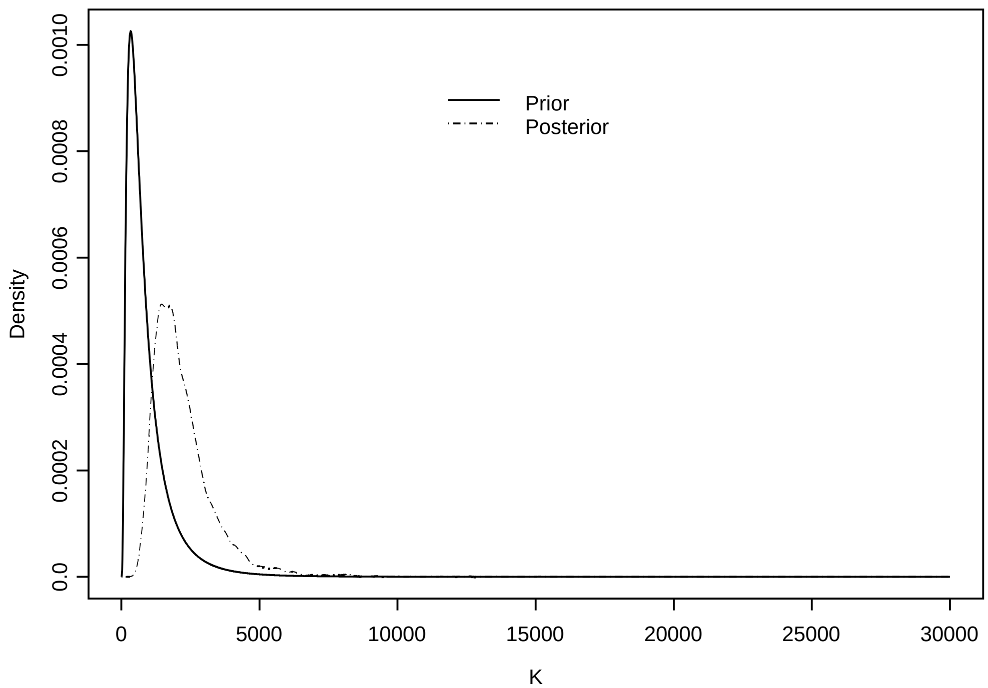


Fig. 29. Relative density functions for prior and posterior distributions for the parameter K.

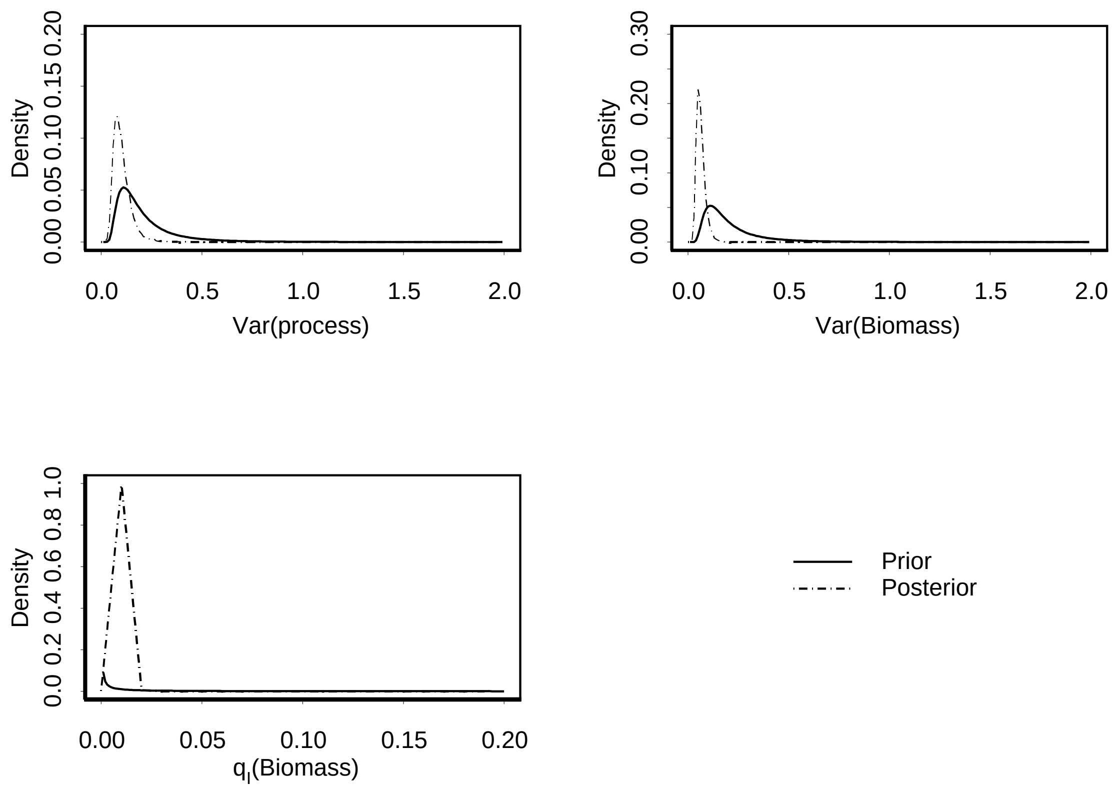


Fig. 30. Relative density functions for prior and posterior distributions for the variance terms and catchability in the delay-difference model. Solid line indicates prior and dashed line the posterior.

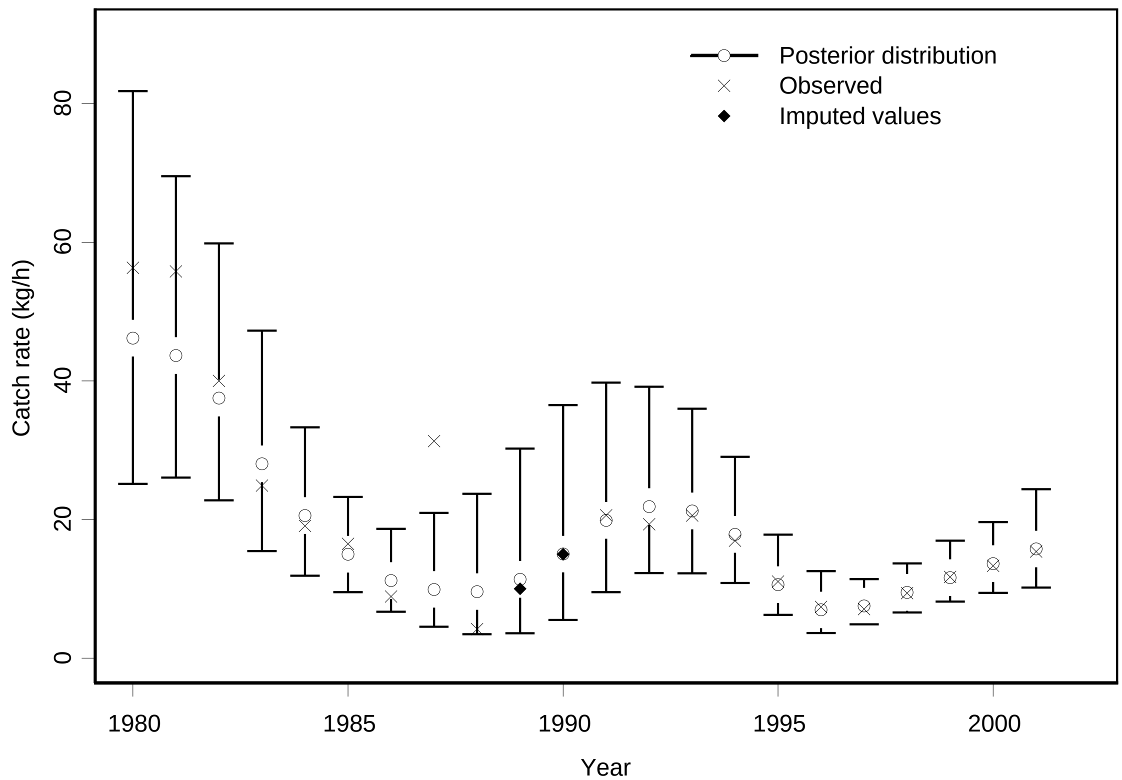


Fig. 31. Predicted and observed commercial catch rate with 95 percent credible regions for Scallop Production Area 3.

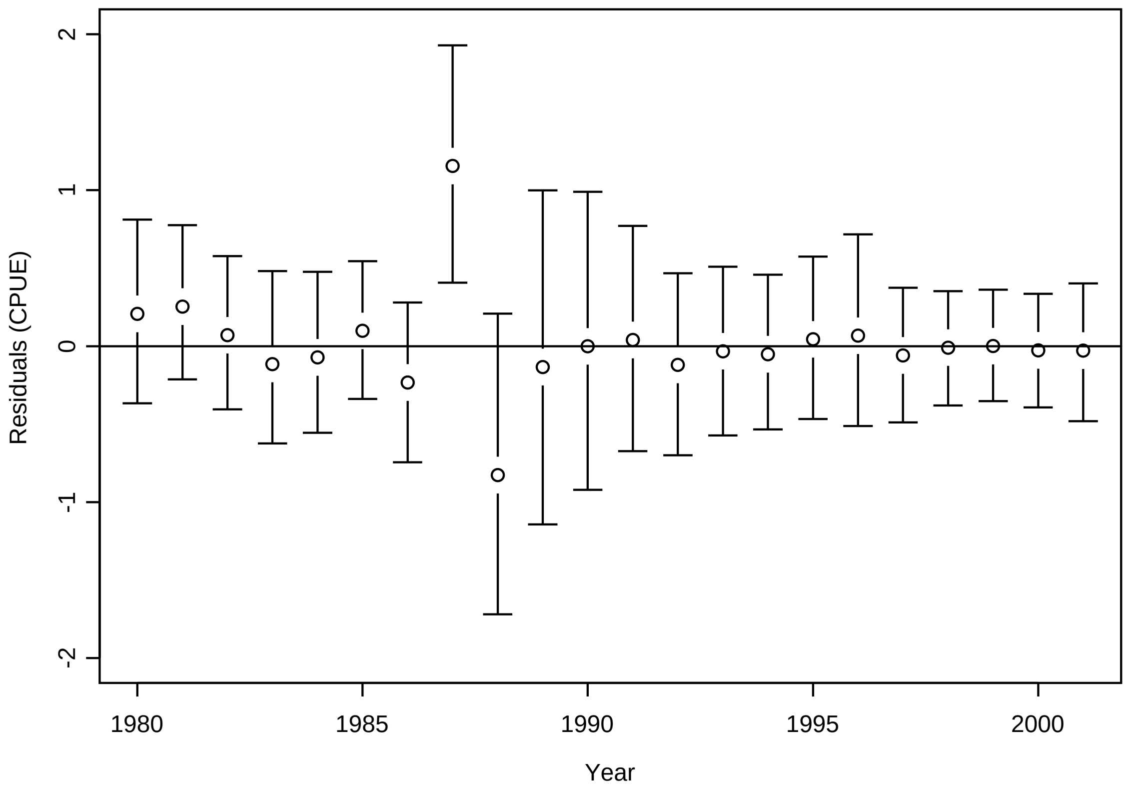


Fig. 32. Residuals for the commercial catch rate with 95 percent credible regions.

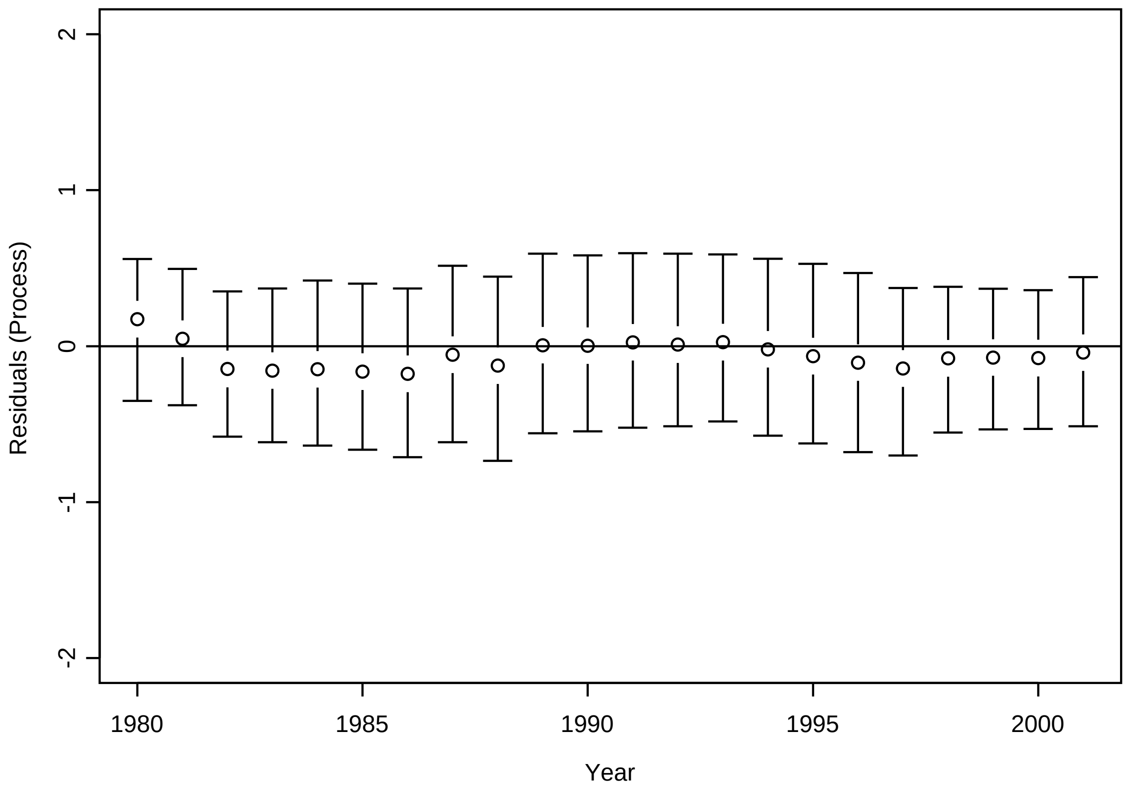


Fig. 33. Residuals for the process error with 95 percent credible regions.

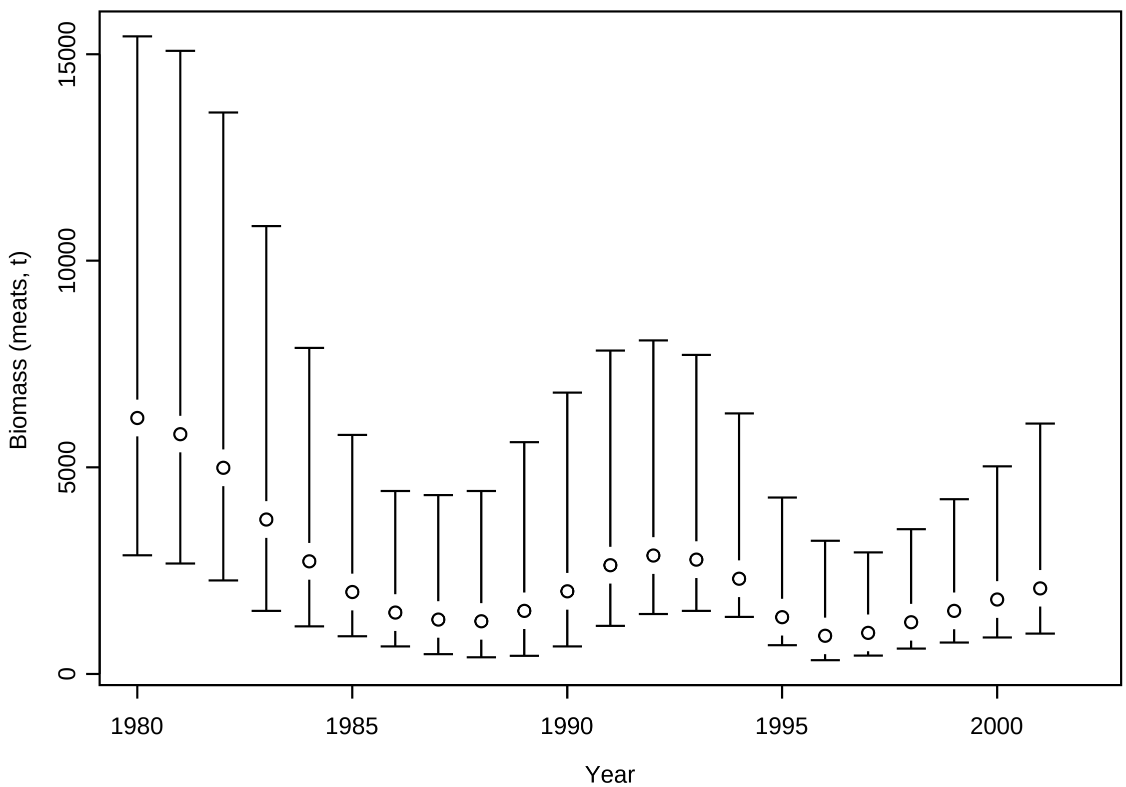


Fig. 34. Predicted biomass for fully-recruited scallops in Scallop Production Area 3 with 95 percent credible regions.

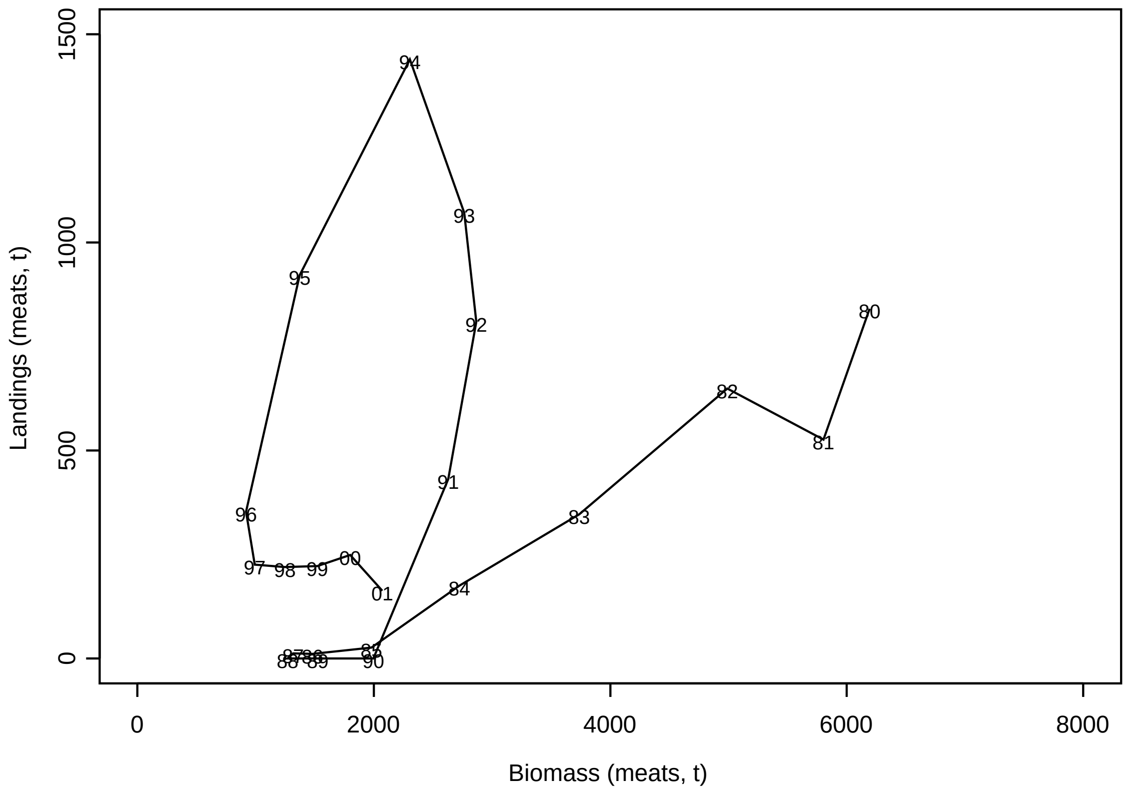


Fig. 35. Landings versus biomass estimates for Scallop Production Area 3.

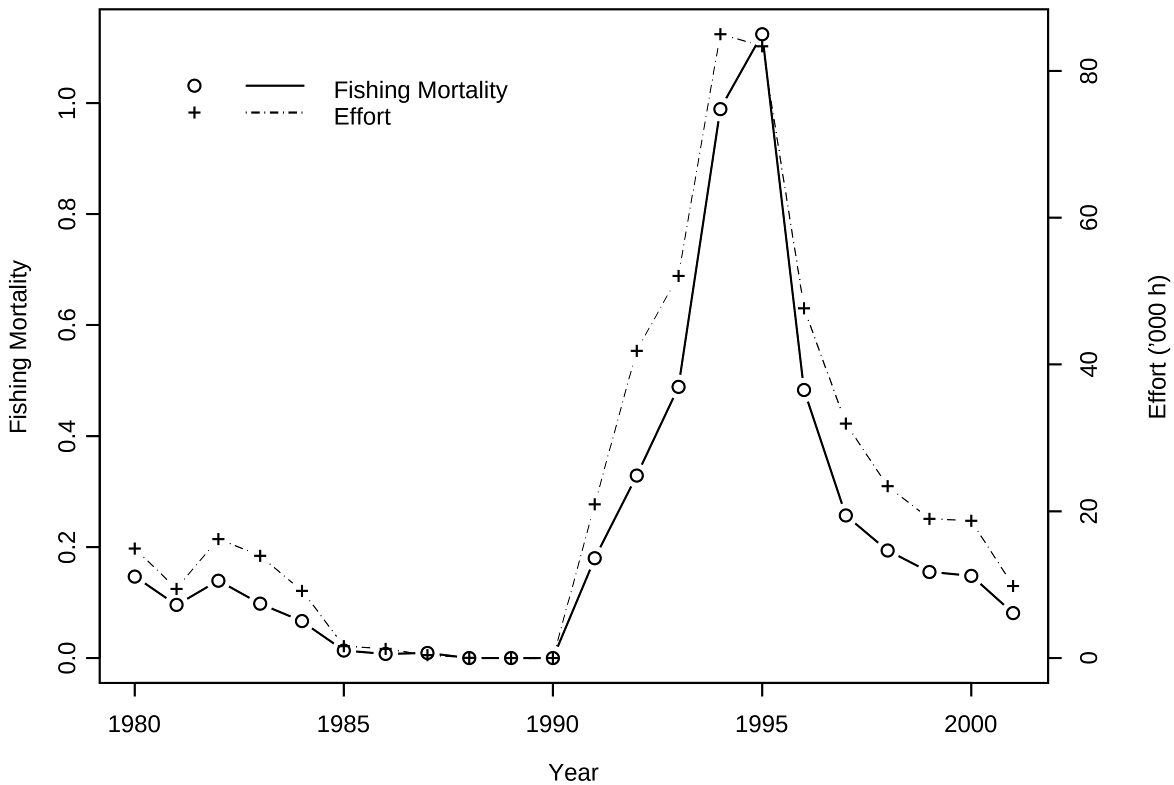


Fig. 36. A comparison of the trends in fishing mortality with those of Effort in Scallop Production Area 3.

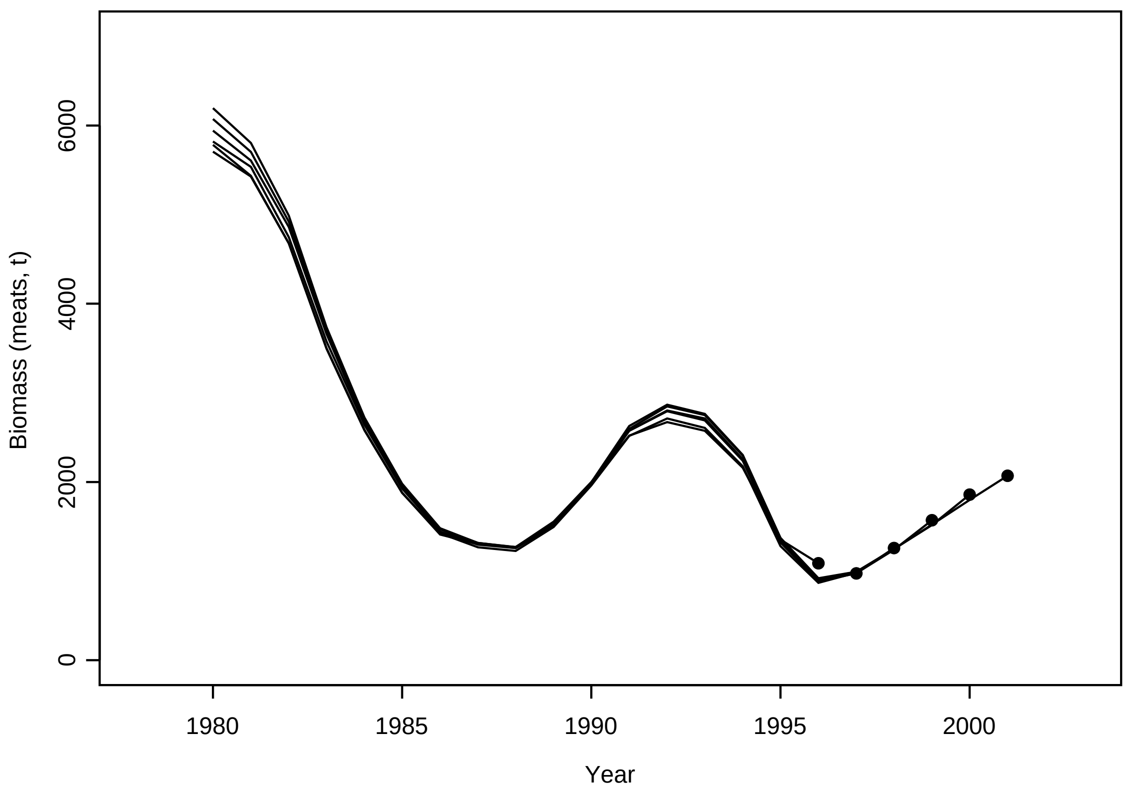


Fig. 37. Retrospective plot for biomass estimates from model fits of the delay difference model using data only up to and including 1996, 1997, 1998, 1999, 2000 and 2001.

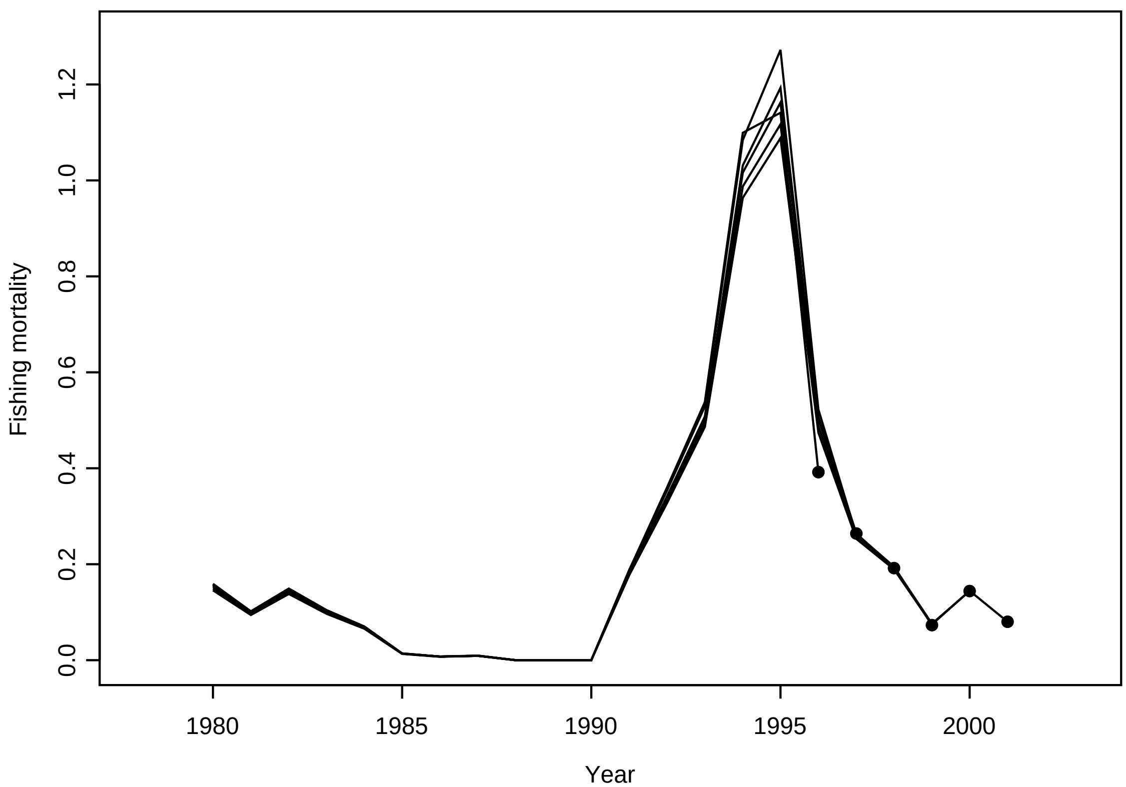


Fig. 38. Retrospective plot for fishing mortality estimates from model fits of the delay difference model using data only up to and including 1996, 1997, 1998, 1999, 2000 and 2001.

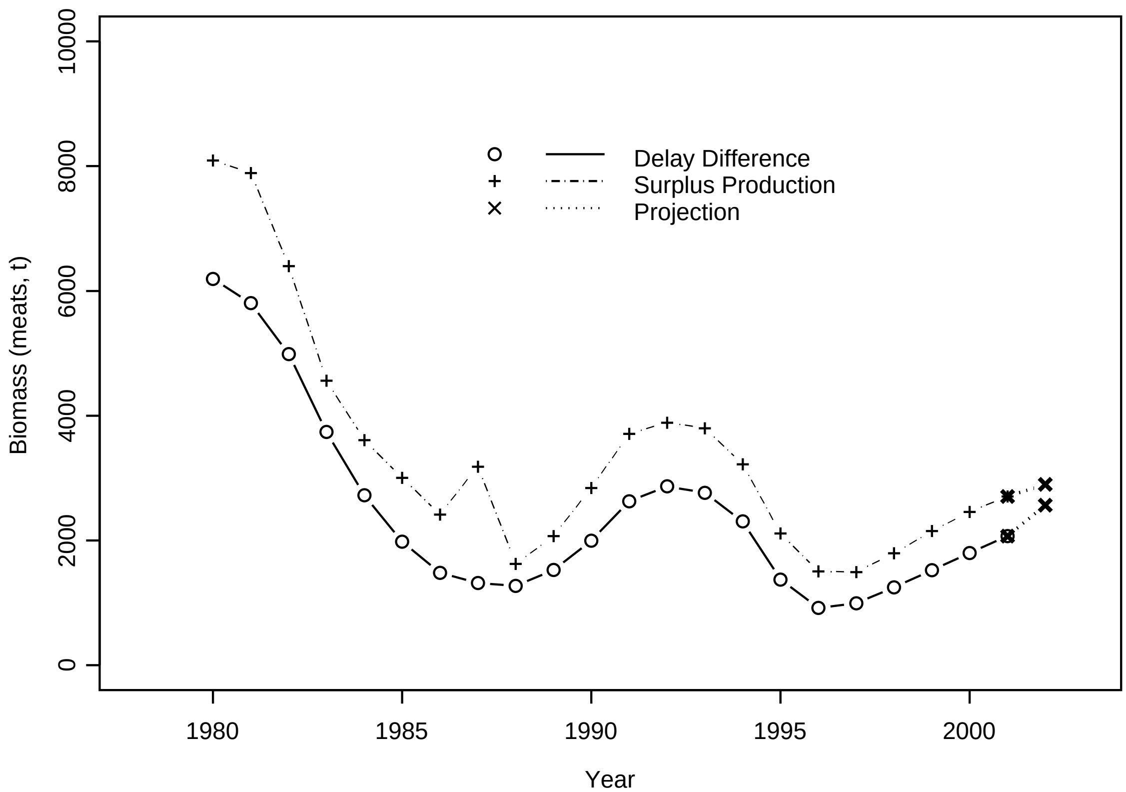


Fig. 39. Comparison of biomass estimates (median of posterior distribution) for scallop meats in Scallop Production Area 3 from the delay difference and surplus production models. See text for details.

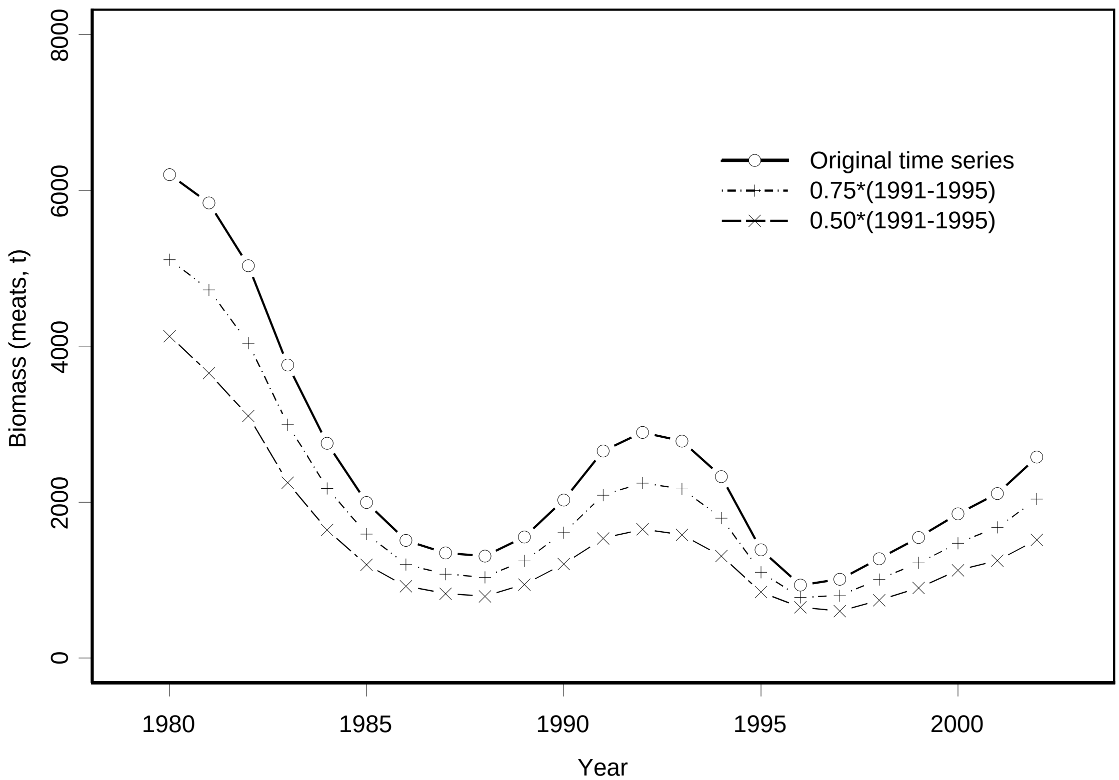


Fig. 40. Comparison of biomass estimates (median of posterior distribution) for scallop meats in Scallop Production Area 3 from the delay difference model. Original series refers to the landings as given in Table 1 with the catch in 1999 cut in half. The other two series in this graph are the original series with the landings for 1991–1995 reduced by 1/4 and 1/2. The 2002 estimates are predictions. See text for details.