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Research Document 2011/042

Document de recherche 2011/042

Maritimes Region

Région des Maritimes

Browns Bank 'North' Scallop (*Placopecten magellanicus*) Stock Assessment

Évaluation du stock de pétoncle (*Placopecten magellanicus*) du secteur nord du banc de Brown

Brad Hubley, Amy Glass, Alan Reeves, Jessica Sameoto, and Stephen J. Smith

Population Ecology Division
Bedford Institute of Oceanography
PO Box 1006, Dartmouth, Nova Scotia
B2Y 4A2

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Canada

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Correct citation for this publication:
La présente publication doit être citée comme suit :

Hubley, P.B., A. Glass, A. Reeves, J. Sameoto, and S.J. Smith. 2011. Browns Bank "North" Scallop (*Placopecten magellanicus*) Stock Assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/042: vi + 63p.

ABSTRACT

This research document describes the first analytical assessment of scallops (*Placopecten magellanicus*) on Browns Bank 'north' and the first formal assessment since 1998. There was no fishery in 2009 and a modest total allowable catch (TAC) of 200 t and interim TAC of 500 t were set for 2010 and 2011, respectively, as a large pulse of recruitment has begun to reach commercial size.

The analytical methods developed for the assessment framework of Georges Bank scallops were applied to this stock with some minor modifications (Jonsen et al. 2009). Modifications included adding a natural mortality term on the recruits and incorporating spatial and annual variability in the shell-height meat-weight relationship, expressed as a condition factor. This analysis indicated that the overall annual condition factor in 2010 of 11.05 g/dm^3 was well below the long term median (12.3 g/dm^3 from 1991-2009).

The fishery on Browns Bank north has been variable with catches that range from 0 to 2007 t and operating at different times of the year. In order to properly line up removals with the survey which occurs in late May, the fishery data was summarized by survey year (June to May) instead of calendar year.

The current scallop population on Browns Bank 'north' is dominated by a large cohort ranging is shell height between 70 - 110 mm. These scallop which straddle all three size classes (pre-recruit, recruit and fully-recruited) have begun to enter the fishery and are concentrated on the northern and southern areas of the bank.

Fully recruited biomass, estimated to be 9096 t in 2010, increased from the 2009 estimate of 5069 t due to the highest recruit biomass since 1991 estimated to be 5077 t in 2009. Continued strong recruitment in 2011 will result in a fully-recruited population dominated by younger scallops (95-105mm) and higher exploitation rates at this time could result in a loss of potential yield.

There have been three major recruitment events on Browns north since 1991, each leading to a peak in commercial biomass that has essentially sustained the fishery until the next recruitment. When the first event occurred in the mid 1990s exploitation increased sharply as these scallops reached commercial size leading to biomass falling to early 1990 levels until the next recruitment event (increases in biomass in 1999 and 2000 were largely due to improved condition at this time). As a consequence of high exploitation, landings greater than 1000 t resulting from this recruitment event lasted only two years. During the next recruitment event in the early 2000s, exploitation remained low at first giving the stock time to grow, which allowed for four years where landings were greater than 1000 t.

The 2011 interim TAC of 500 t corresponds to an exploitation rate of 0.04 and an increase in fully-recruited biomass of 43% to 13,090 t assuming no change in condition factor from 2010. Harvest scenarios ranging from 100 t to 1,000 t were examined and all were predicted to yield increases in commercial biomass for 2011 with low probability of decline.

RÉSUMÉ

Le présent document de recherche décrit la première évaluation analytique applicable au pétoncle (Placopecten magellanicus) du secteur nord du banc de Brown et la première évaluation en bonne et due forme de ce stock depuis 1998. Il n’y a pas eu de pêche en 2009 et un modeste total autorisé de captures (TAC) de 200 t ainsi qu’un TAC provisoire de 500 t ont été fixés pour 2010 et 2011, respectivement, une forte vague de recrues ayant commencé à atteindre la taille commerciale.

Les méthodes analytiques établies pour le cadre d’évaluation du stock de pétoncle du banc Georges ont été appliquées au stock considéré ici, avec quelques modifications mineures (Jonsen et al. 2009). Ces modifications ont consisté à ajouter un paramètre de mortalité naturelle parmi les recrues et à intégrer une variabilité annuelle et spatiale, exprimée en tant que coefficient de condition, dans la relation entre la hauteur de coquille et le poids de la chair. L’analyse a révélé que le coefficient de condition annuel général de 2010, soit 11,05 g/dm3, était bien inférieur à sa valeur médiane à long terme (12,3 g/dm3 de 1991 à 2009).

La pêche dans le secteur nord du banc de Brown a varié, tant pour ce qui est de la période à laquelle elle a été pratiquée que de ses captures, qui se sont situées entre 0 et 2007 t. Pour bien harmoniser les prélèvements avec le relevé, qui a lieu à la fin mai, les données de la pêche ont été résumées par année de relevé au lieu d’être présentées par année civile.

La population actuelle de pétoncles dans le secteur nord du banc de Brown est dominée par une vaste cohorte dont la hauteur de coquille s’échelonne entre 70 et 110 mm. Ces pétoncles, qui chevauchent les trois catégories de taille (prérecrues, recrues et pétoncles pleinement recrutés), ont commencé à apparaître dans la pêche et ils sont concentrés dans les secteurs nord et sud du banc.

La biomasse de pétoncles pleinement recrutés, estimée à 9 096 t en 2010, a augmenté par rapport à son estimation de 2009 (5 069 t) en raison de la présence de la plus forte biomasse de recrues depuis 1991, estimée à 5 077 t en 2009. Le maintien d’un fort recrutement en 2011 se traduira par une population de pétoncles pleinement recrutés dominée par des individus plus jeunes (95 105 mm), si bien que des taux d’exploitation qui seraient alors plus élevés pourraient aboutir à une perte de potentiel de rendement.

Depuis 1991, le secteur nord du banc de Brown a connu trois grandes vagues de recrutement, chacune se traduisant par un pic de la biomasse commerciale qui a alimenté la pêche jusqu’à la vague de recrutement suivante. Quand la première de ces vagues est survenue, au milieu des années 1990, l’exploitation a nettement augmenté tandis que ces pétoncles atteignaient la taille commerciale, ce qui a fait chuter la biomasse à ses niveaux du début des années 1990 jusqu’à la vague de recrutement suivante (les hausses de la biomasse observées en 1999 et 2000 étaient largement dues à une amélioration de la condition à ce moment-là). Par suite de la forte exploitation, les débarquements de plus de 1 000 t provenant de cet apport de recrues n’ont duré que deux ans. Lors de la vague de recrutement suivante, au début des années 2000, le taux d’exploitation est d’abord resté bas, ce qui a laissé au stock le temps de grandir et de produire pendant quatre ans des débarquements supérieurs à 1 000 t.

Le TAC provisoire de 500 t pour 2011 correspond à un taux d’exploitation de 0,04 et à une hausse de 43 % de la biomasse de pétoncles pleinement recrutés qui porte celle-ci à 13 090 t, cela dans l’hypothèse d’un coefficient de condition qui reste inchangé par rapport à 2010. Des scénarios de captures allant de 100 t à 1 000 t ont été examinés et selon les prévisions tous allaient produire des hausses de la biomasse commerciale pour 2011, avec une faible probabilité de déclin.

INTRODUCTION

The last formal assessment of the Browns Bank north scallop (*Placopecten magellanicus*) stock was in 1998 (Robert and Butler 1998). A limited (4 to 270 t) fishery occurred on Browns Bank along the southern edge at depths greater than 100 m in the 1970s and early 1980s (Robert and Butler 1998). In 1989 the fishery began to develop on the northern part of the bank where it generally occurs today. Since that time it has been managed under scallop fishing area (SFA) 26 with an initial meat count restriction of no more than 55 meats per 500 g which was reduced to 40 in 1994 (Robert and Butler 1998). In 1998 the bank was officially divided into north and south management areas (Figure 1) to reflect the differing growth regimes of the two areas. Browns Bank south is a marginal area for growth, where there is a very high meat count in the regulations (60 / 500 g), and only supports a fishery in years with exceptional growth conditions. This assessment will focus on Browns north, the more productive area and where 90% of the total landings have occurred since 1998. During this period, landings on Browns north have ranged from 0 to 2000 t. Industry-managed closure areas have been used in the recent past to protect large densities of juveniles and encourage recruitment. There was no fishery in 2009 and modest TACs of 200 t and 500 t were set for 2010 and 2011 respectively as a large pulse of recruitment has begun to reach commercial size.

Harvest advice is requested on an annual basis by Fisheries and Aquaculture Management Branch (FAM) but the lack of a population model has hindered the provision of quantitative advice until now. This year the assessment framework developed for Georges Bank scallop was applied to this stock (Jonsen et al. 2009).

DATA

SURVEY

Browns Bank north is currently covered by the joint industry/DFO spring scallop survey which generally takes place in May or June. There has been some survey coverage on the Bank since the early 1980s but coverage on Browns north has only been consistent since 1990 (Figure 2). The survey had been conducted on the government research vessel *FRV E.E. Prince* until 1994. From 1994 to present, the survey has been conducted using commercial scallop vessels; 1994-2006 *FV Cape Keltic*, 2007 *FV E.E. Pierce*, and 2008-2010 *FV Tenacity*. From 1990 until 2000 surveys used stratified random designs with strata based on the commercial catch rates of the previous 9 months (Robert and Butler 1998). With the growing awareness of the association of substrate types and scallop abundance, the stratification scheme for the survey was changed to bottom types based on analysis of multibeam data (Kostylev et al. 2001; Kostylev et al. 2003). In the 2010 survey there were 70 stations on Browns Bank north that were randomly selected and allocated proportionally to the area of the 4 bottom type strata (Figure 3). Survey gear was a 2.44 m wide New Bedford style offshore drag (75 mm ring size) lined with 38mm mesh polypropylene netting. Each survey tow lasted 10 minutes and was tracked using a global positioning system (GPS). The tracks are then used to calculate the actual distance of each tow. Catches are standardized to a common distance of 800 m.

The primary data output from the survey is the shell height frequency. All scallops caught are enumerated within 5 mm bins. Only in the cases of extreme recruitment events are subsamples of smaller scallops taken. In these cases numbers are prorated by weight. Biological samples are also taken typically one in every 10 minute square. These samples include the collection of shells for ageing, abductor muscle, gonads and the remaining soft body parts for weights. The relationship between the shell height and abductor muscle weight is particularly useful for monitoring the condition of scallops in a given place and time.

FISHERY

Landings and the associated total allowable catch (TAC) are presented in Table 1. Landings were calculated from commercial logs and separated by north and south management areas after 1998.

Commercial Logs

Every vessel in the fleet is required to fill out an offshore scallop monitoring document. This records trip details such as vessel information, area fished, number of crew (and number of crew shucking), size of gear, date sailed and date landed, as well as detailed fishing information; a position (latitude and longitude) for each six hour watch and the associated estimated catch, effort (numbers of tows, average tow time and number of rakes fished), bottom type, depth and weather conditions. For every trip (established in 1995), the actual weight of meats landed is recorded and verified by a dockside monitor. This data is entered by the dockside monitoring company following each trip and is subsequently verified by both the Science branch and Commercial Data division of DFO. In 1998, a fleet wide satellite vessel monitoring system was implemented, allowing for the collection of real time effort distribution data.

Port Sampling

In 1995 the industry assisted in the port sampling such that every trip is sampled upon landing in an effort to monitor the distribution of meat weights being landed. Samples are selected from various portions of the landed catch and the weights of individual meats are recorded from each day's catch to provide information for the locations fished throughout the trip.

ASSESSMENT

GROWTH AND CONDITION

Although shells are generally collected on each survey, age data determined from reading the growth rings on the shells were only available from 1996 to 2003. A Von Bertalanffy (VB) growth equation was fitted to these data as a nonlinear mixed effects model with random effects assigned to each year sampled.

$$L_t = (L_\infty - l_{\infty,y})\left[1 - e^{(-\kappa - k_y)(t-(t_0 - t_{0,y}))}\right]$$

where L_∞, κ and t_0 are the fixed effects model parameters and $l_{\infty,y}$, k_y and $t_{0,y}$ are the random effects for each year, y. For the purposes of this assessment the fixed effects parameters were used because data are not available for each year surveyed and the random effects do not indicate any major deviation from the fixed effects (Figure 4). The resulting fixed effect parameters were: L_∞= 154.54, κ = 0.186 and t_0 = 0.614. Although these parameters may appear to be very different from the last reported VB parameters for this stock (Robert and Butler 1998), they actually produce very similar growth curves (Figure 5). The deviation in the curves at the older ages may be the result of more large scallops from the early 2000s included in the current analysis.

Given that data comprising of paired meat weight and shell height measurements are available for all years, a closer examination of the variability in the height weight relationship was possible. Jonsen et al. (2009) estimated the relevant parameters for Georges Bank while accounting for variability between years using a linear mixed effects model:

$$\log(w_{i,t}) = \log(A - a_t) + (B - b_t)\log(h_{i,t}) + \varepsilon_{i,t}$$

where $w_{i,t}$ is the meat weight of the ith scallop in year t, A and B are the fixed effects parameters describing the common meat weight - shell height relationship over time, a_t and b_t are the random effects parameters describing the annual differences and $\varepsilon_{i,t}$ are the error terms. While this approach may account for the variability between years when fixed and random effects are compared (Figure 6), it does not explicitly account for the spatial variation that when each tow within an annual survey is set as the random effect (Figure 7). Spatial variability in growth rates are well documented in sea scallops and is likely related to both temperature and food availability (Robert et al. 1990; Kenchington et al. 1997; Smith et al. 2001). There is also a substantial amount of variability in the shell height/meat weight relationship that is likely the result of seasonal factors such as food availability (i.e. blooms) and spawning but because the survey occurs at the same time each year this variation should be minimized. Unfortunately there were not sufficient data to include both year and location as random effects so it was necessary to simplify the model in order to account for both spatial and annual variability.

One way to simplify the meat weight/shell height model is to assume an isometric length weight relationship where the weight is divided by the cube of the shell height. This ratio is commonly referred to as the condition factor (CF).

$$CF = \frac{W}{L^3}$$

Condition factors are commonly used in finfish fisheries and aquaculture to denote the relative health of individuals and have been used in other scallop species such as *Argopecten gibbus* (Quinn et al. 2005)*, Argopecten irradians* (Bricelj et al. 1987) and *Psychrochlamys patagonica* (Gutiérrez and Defeo 2005), to evaluate general health. In these studies total round weight was used but here, the length/weight relationship applies only to the abductor muscle. Also, decimetres (dm) were used for shell height units so that the condition factor will be relative to the meat weight of a scallop with a 100 mm shell (roughly commercial size).

Fixed and random effects need only be estimated for the condition factor in this simpler model allowing for estimates of random effects for each sample location (l).

$$w_{i,l} = (A - a_l)(h_{i,l})^3 + \varepsilon_{i,l}$$

The resulting fits of this model to all the meat-weight shell-height data available is shown in Figure 8, where the blue line represents the fixed effect (A) or the overall condition factor and the red lines represent the random effect (a_l) or the sample specific condition factor. Condition factors for sample locations l were then plotted spatially on the bank with inverse distance weighted interpolation (Figure 9). Food availability and temperature are the likely factors that have the most effect on condition factor but detailed data for these variables are not available for each sample location. However, depth was available and generally serves as a proxy for these other variables. The relationship between depth and condition is evident from its correlation with the estimated condition factors for each location (correlation coefficient = -0.56, p<0.001; Figure 10). Depth data were also available for a wider area than the meat/shell samples and thus could be used to predict condition factor for tows where no meat weight sampling occurred. If we assume depth is a good predictor of the spatial variation in condition we can estimate its effects along with the annual variability by fitting a generalized linear model with depth and year as a factor predicting condition for a given sample.

$$CF_{l,y} = aD_l + b_y + c + \varepsilon_{l,y}$$

Where the condition factor for a given location (l) and year (y) is a function of the depth at the location (D_l), an annual factor (b_y) that may represent variability in food availability and temperature, and intercept (c). By using this model to predict condition factors for each tow, more accurate estimates of biomass per tow could be estimated instead of just using the same parameters for every station. Overall annual condition factors can also be calculated using the annual factors and mean depth weighted by abundance (Figure 11). This analysis indicates that the current overall condition factor is well below the long term median and at is lowest point of the time series.

SIZE AT RECRUITMENT TO FISHERY

Although there is some variability around size at recruitment to the fishery, knife-edge recruitment was assumed for the delay difference model in this assessment. In order to select the most appropriate shell height for the knife-edge cut-point, the port sampling data were examined to determine what sizes were being retained in the catch. As was done in Jonsen et al. (2009), the shell/meat samples where used to convert meat weights in the port sampling data to shell heights using a linear mixed effects model where the month sampled was the random effect to account for seasonal variability in the relationship (Figure 12). The resulting catch distribution by shell height demonstrates the variability around size at recruitment (Figure 13). When determining the appropriate cut-point for size at recruitment the general rule-of-thumb used here was to select a shell height that is near the bottom 5th percentile of the size composition of the catch (Figure 14). For Browns north, shell height-at-recruitment was determined to be 95 mm. Another cut-point was also required to define next year's recruitment from the current year's survey data. To arrive at the recruitment interval the growth parameters were used to age back one year giving a pre-recruit shell height of 85 mm. Thus, the scallops on Browns north with shells ranging from 85 mm to 95 mm are expected to recruit to the fishery in the following year.

SURVEY BIOMASS INDICES

The standardized numbers of scallops per tow were divided into three size classes (pre-recruits, recruits and fully-recruited) based on the recruitment interval (85-95mm). The stratified mean numbers per tow in a given year for each size class were calculated using the population estimate from a stratified random design,

$$\hat{P}_{st} = \sum_{h=1}^{H} N_h \, \overline{C}_h$$

where,

A_h = area within stratum h
a = area of a towable unit
N_h = A_h/a = number of towable units in stratum h

$\overline{C_h} = \sum_{j=1}^{n_h} C_{hj}$ = mean number of scallops per tow in stratum h, where n_h is the number of tows sampled in stratum h.

The variance of the population estimate from a stratified random design is,

$$Var\left(\hat{P}_{st}\right) = \sum_{h=1}^{H} N_h^{\ 2}\ Var\left(\overline{C}_h\right)$$

This estimate of variance can be used to produce standard errors for each point estimate. This measure of uncertainty can be carried forward into the model such that it will be represented in the final biomass estimates. The stratified population estimate was scaled up for the whole survey area. We also present the time series of mean numbers per standard tow with their standard errors for each size class (Figure 15). Mean biomass per tow was calculated in much the same way but with numbers first converted to biomass using the tow specific condition factor (Figure 16). It is these stratified population biomass estimates and their coefficients of variation for fully-recruited and recruit size scallops that will serve as biomass indices (I) for the assessment model (Figure 17).

Detailed information about the size structure of the population comes from the shell height frequency and may be relevant in characterizing the nature of the fishable biomass. When there is a dominant cohort it is also possible to track relative growth and mortality over time, as was the case for Browns north for the last four years (Figure 18). Here we can clearly see how the dominant cohort has decreased in abundance as it has increased in shell height. In 2010 the cohort is straddling all three size classes so that some are commercially exploitable now, some will become commercially exploitable in a year and others at a later time. It would be useful to determine if there was spatial segregation between these size classes and whether it is possible to specifically target scallops greater than 95 mm. The data collected from the survey also allows for the distribution of scallops at the various size classes to be represented spatially over the survey area. The highest abundances of fully-recruited scallops are found predominantly in the northern part of the bank near the former industry-managed closure area known as "Happy Valley" (Figure 19). Recruits were also abundant here and in the southern part of the bank (Figure 20). The pre-recruit size class actually consists of two cohorts, the lower portion of the dominant cohort and a new smaller cohort less than 50 mm (Figure 18). These cohorts they were plotted separately to examine differences in the spatial distribution. The distribution of pre-recruit scallops between 50 and 85 mm was similar to recruit scallops where the highest abundances were found at the northern and southern edges of the bank (Figure 20, Figure 21), while pre-recruit scallops less than 50 mm were found in their highest abundances in the central and north-eastern areas (Figure 22).

FISHERY INPUTS

The important inputs to the assessment from the fishery are the annual removals or catch (C) and an index of relative abundance or catch per unit effort (CPUE). The level of catch on Browns north has been variable over time although the CPUE time series generally matched the survey index of commercial size scallops with the exception of 2001 and 2002 (Figure 23). The CPUE index (U) was calculated using a Jackknife estimator (Smith 1980) on class 1 data from the commercial logbooks. Class 1 data are the daily logbook records that include prorated catch (kg), effort (hm) and position (longitude, latitude). The Jackknife estimator is a robust method for estimating CPUE and also provides the means for calculating standard errors.

$$U_{-j} = n\left(\frac{C}{E}\right) - (n-1)R_{-j}$$

where,

> n = the number of records in a year
> C = the sum of the catch in a year
> E = the sum of the effort in a year
> $R_{-j} = \left(\frac{\sum C_{ij}}{\sum E_{ij}}\right)$ with the j^{th} observation removed

The value of U for a given year is the average of all U_{-j} for that year. The variability around these estimates was used in carrying through uncertainty in the model. The time series of the CPUE index with standard errors from the Jackknife estimator are shown along side the fishing effort in Figure 24. A period of high catch rates with low effort occurred from 2001 to 2003, since then catch rates have returned to near the long-term median around 20 kg/hm. Fishing effort was zero in 2009 so it was not possible to calculate CPUE in that year and not having a value for U causes problems if it is to be used as a biomass index in the model. This and other problems concerning timing were solved by defining the fishery in the year between surveys instead of the calendar year.

Catch is an important component of the model and it is necessary to define or assume how the timing of the removals relates to the biomass index in the model. The model can be written such that removals occur before or after the survey index but not both. Unfortunately the timing of the fishery on Browns north has not been consistent over time (Figure 25). In some years the fishery occurs before the survey and in some years it occurs after it and this caused some problems when initially fitting the model to the calendar year catch. For instance there were substantial catches in 2006 (912 t) and 2007 (1198 t) however there was much less catch (367 t) between the surveys in 2006 and 2007 (Figure 23, 25 and 26). Also there was no catch in 2009 but there was catch between the 2008 and 2009 survey. Depending on the timing assumption there would no catch to account for a decline in the biomass index. The solution to this problem was to consider catch and CPUE for the survey year (June – May), not the calendar year (Jan. – Dec.). Not only did this approach solve the issue of timing but it also filled in the missing point in the CPUE index, thus allowing for it to be included in the model as an additional biomass index (Figure 26). The new values for U are also more similar to the survey index with the exception of one point in 2007 where very little effort was expended between surveys such that there were high catch rates before any depletion effect occurred. Fortunately the estimates of variability around this point are sufficiently large to allow for the model to compensate when it is fit to these data (Figure 27).

NATURAL MORTALITY

The dominant cohort of recruitment is clearly visible in the shell height frequency of the last 4 years (Figure 18). What is also clear is the decline in the absolute abundance of scallops over this period. High levels of natural mortality are to be expected for juveniles especially when they are present in high densities.

For the purposes of the assessment, natural mortality was only considered for the recruit and fully-recruited size classes. Dead scallops with both shells still attached are assumed to have died from natural causes and are identified in the survey as clappers. Clappers were examined to determine if there are any indications of higher than normal levels of natural mortality among recruit and fully-recruited sizes (Figure 28). To get a sense of the mortality rate, the abundance of clappers must be examined relative to live abundance i.e., the percentage of dead scallops per tow (Figure 29). The percentage of clappers relative to live scallops was highest at times when abundance is high but was relatively low overall with the median 1.4% dead scallops per tow. The proportion of dead scallops was also examined spatially to see if there are any spatial patterns present (Figure 30). The percentage of dead scallops was higher in the northern portion of the bank where abundance of live scallops was high but was low in the southern portion where abundance of live scallops was also high, suggesting that there are factors other than density which are affecting natural mortality (Figure 30, 19 and 20). To get estimates of mortality from these data, the popcorn model presented in Smith et al. (2002) was used and yielded estimates of M for fully-recruited scallops that ranged from 0.07 to 0.27 with a mean of 0.15 (Figure 31) and for recruit scallops that ranged from 0.05 to 0.37 with a mean of 0.16 (Figure 32). There are some concerns with estimating natural mortality using clapper data as many factors (i.e. bottom type) may affect the separation of shells. The popcorn model considers the length of time since the scallop died as the only factor that affects the separation of shells. It is also possible to estimate mortality within the population model itself and some attempts have been made to do so using hyperpriors or a random walk. However, all these various methods have not been sufficiently evaluated to the point where one will be presented here. For this assessment M was assumed to be 0.1, similar to the Georges Bank assessment.

DELAY-DIFFERENCE MODEL

The delay difference model that is being used for this assessment was reviewed at the assessment framework meeting and applied to subsequent assessments for Georges Bank (Jonsen et al. 2009; DFO 2009a; DFO 2009b; DFO 2010) The model formula presented in Jonsen et al. (2009) was:

$$B_t = \left[e^{-M} \left(\rho + \frac{\alpha}{\overline{\omega}_{t-1}} \right) \left(B_{t-1} - C_{t-1} \right) + R_t \right]$$

where B_t is biomass at time t, M is the instantaneous rate of natural mortality, C_{t-1} is the observed annual catch, R_t is the biomass of recruits, α and ρ are growth parameters and $\overline{\omega}$ represents the average weight of fully-recruited scallops.

Some adjustments have been made to this formulation mainly to incorporate the estimate of annual variability in condition factor. In the previous formulation of the model the growth potential of the population was a function of the average meat weight of fully-recruited scallops ($\overline{\omega}$) where a population with a lower average meat weight would have a higher potential for growth. The analysis of the annual variability in condition factor demonstrates that $\overline{\omega}$ is affected by more than just the growth of the shell (Figure 33). This may become a problem in older populations that experience a poor condition year, because if condition declines $\overline{\omega}$ will decrease suggesting a greater growth potential than may actually exist. It would make more sense to relate growth potential to the average shell height ($\overline{h}$) and not meat weight ($\overline{\omega}$) so that a variable condition factor does not have unintended effects on growth potential (Figure 33). To resolve this issue and more accurately represent the growth dynamics of the population we have replaced the theoretical growth component ($\rho + \alpha / \overline{\omega}_{t-1}$) with an observed growth component g_t that incorporates the annual variability in condition. The observed growth component is simply the ratio between the observed average meat weight of fully-recruited scallops and the observed average meat weight of the same scallops the following year. To calculate g, the average shell height of fully-recruited scallops is converted to a meat weight using the annual condition factor:

$$\overline{\omega}_{t-1} = CF_{t-1} \times \overline{h}_{t-1}^{3}$$

Then the average height of those scallops a year later ($\overline{h}_t$) is calculated using the VB parameters: L_∞,= 154.54 and κ = 0.186,

$$\overline{h}_t = 154.54\left(1 - e^{-0.186}\right) + e^{-0.186}\overline{h}_{t-1}$$

and then,

$$\overline{\omega}_t = CF_t \times \overline{h}_t^{3}$$

so that,

$$g_{t-1} = \frac{\overline{\omega}_t}{\overline{\omega}_{t-1}}$$

The resulting annual observed growth potential is much more variable than the original theoretical growth potential (Figure 34).

A natural mortality term was also added to the recruits part of the model such that the new delay-difference model equation becomes:

$$B_t = \left[e^{-M} g_{t-1}\left(B_{t-1} - C_t\right) + R_t e^{-M}\right]$$

Other aspects of this model are the same as was presented in Jonsen et al. (2009). Biomass was rescaled by a constant (K, $P_t = B_t/K$) to improve convergence. The model includes both process error (η_t) and observation error for the fully-recruited (τ_t) and recruit (ε_t) survey indices as well as the CPUE index (v_t). However unlike the model presented in Jonsen et al. (2009), observation error includes both estimated and measured components in the form of coefficients of variation (cv) for each index such that the observation equations become:

$$I_{f(t)} = qP_t K \tau_t$$

$$I_{r(t)} = qP_t K \varepsilon_t$$

$$U_t = q_U P_t K \nu_t$$

where τ, ε and v are random variables with a mean of zero and a variance equal to the coefficients of variation plus an estimated fixed variance, i.e. $cv_{f(t)} + \sigma^2_\tau$. The model presented for Georges Bank also contained a variable size-at-recruitment whereas knife-edge recruitment was fixed for Browns. Therefore, there is only one survey catchability (q) being estimated here along with the proportionality coefficient for the CPUE index (q_{U}).

The priors remain largely unchanged from the model accepted at the framework and subsequent assessments for Georges Bank (Jonsen et al. 2009, DFO 2009, DFO 2010). Uninformative priors were used for q_U, K and process error. A vaguely informative beta prior based on scallop survey dredge studies conducted by the National Marine Fishery Service

(NMFS) was used for the catchability (q). The priors on the estimated observation error were the same informative gamma prior on the precision terms (σ^{-2}_{τ}, $\sigma^{-2}_{\varepsilon}$, σ^{-2}_{v}) used in Jonsen et al. (2009) (Figure 35). The data used to fit the model are presented in Table 2.

Biomass Estimates

Fully-recruited biomass was increasing in the early 1990s until 1995 when it fell by 37% from 8922 t in 1995 to 5648 t in 1996 (Table 3, Figure 36). It then began to slowly increase until 2001 when it increased sharply due to a large biomass of recruits. Recruit biomass remained high (1636 t to 3505 t) from 2000 to 2002 which eventually lead to the highest estimated biomass of 22 680 t in 2003 (Table 3, Figure 36). From that high water mark the fully-recruited biomass declined until it fell to nearly 5000 t in 2009 where it had not been since 1993. Fortunately the largest recruit biomass was observed that same year ensuring an increase of over 4000 t in 2010 to a fully-recruited biomass estimate of 9096 t with a 95% credible interval from 5544 t to 15,441 t. (Table 3, Figure 36). The recruit biomass time series indicates three major recruitment events about nine years apart with the most recent being the largest beginning in 2009 (Figure 36). A predicted fully-recruited biomass for May 2011 is shown as a boxplot where the box is the 50% credible range and the whiskers give the bounds for the 80% credible range (Figure 36). The median prediction represents an increase of 44% to 13,090 t assuming a catch of 500 t and no change in the average condition factor in 2011. The estimates of exploitation derived directly from biomass estimates and reported catch suggest that exploitation on Browns north has been relatively low compared to estimates of exploitation on Georges Bank and in the Bay of Fundy (DFO 2010, Smith et al. 2009). The highest exploitation occurred in 1995 and 1996 when biomass had recently increased but then fell, potentially due to these higher than average rates (Figure 37). Exploitation was low from 1999 to 2003, a period that saw a dramatic increase in biomass. The current rates of exploitation are also low with exploitation from June 2009 to May 2010 estimated at 0.02.

Diagnostics

The same diagnostics as were presented at the framework meeting, were performed on this model to test performance using data from Browns north. The posteriors for several parameters of interest indicate considerable information in the data particularly where priors are uninformative (Figure 35). The posteriors for the estimated component of the observation error for the survey biomass indices closely resemble the prior distributions but the posteriors for CPUE observation error indicate greater precision than the prior suggested. This may be compensation for large coefficients of variation associated with a CPUE index that actually tracks closely with the survey fully-recruited biomass index. The fits of the model predictions to the observed biomass indices are generally quite good (Figure 38). There was a strong residual in the CPUE index in 2007 because the model fits more strongly to the survey index (Figure 39).

The retrospective analysis (data systematically removed from end of time series) suggests a tendency to overestimate biomass when the biomass is declining (Figure 40). The discrepancy is strongest when the time series ends in 2007, which is the year with the extraordinarily high CPUE index. However if this assessment methodology was used to provide advice in 2007 it is likely that the model would have been fit to the survey index only given the large difference between the biomass indices and the large standard error of the CPUE index. The prospective analysis (data systematically removed from start of time series) suggest that when fit to Browns Bank north there is much less sensitivity in the model to the starting conditions then there was for Georges Bank (Figure 41; Jonsen et al. 2009). An evaluation of model predictions was made by comparing the one year-ahead biomass predictions to the biomass estimates for those same years (Figure 42). The model tends to over-predict when biomass is declining except for 2007 where it is prediction was close to next year’s estimate, but then the prediction for 2008 was strongly over-predicted. In order to determine if this unusual behaviour was related to the disagreement between the CPUE and survey index in 2007 the analysis was repeated without fitting the model to CPUE in 2007. The resulting evaluation of predictions was closer to the expectations: modest over-predictions when biomass is declining and slight under-prediction when biomass is increasing (Figure 43).

DISCUSSION AND ADVICE

The third and possibly largest major recruitment event since 1990 is beginning to reach commercially exploitable size on Browns Bank north. Concurrent with this event the scallop condition has declined with respect to the size of the meats at a given shell height. These factors complicate the provision of advice for this stock. On the one hand, the commercially exploitable biomass has increased and the recruit biomass is sufficiently large that biomass is essentially ensured to increase over the short term. However, exploitation that is too high, particularly at a point when condition is poor, may result in a shortened period of high biomass and subsequent loss in potential yield.

Looking at the time series of fully-recruited and recruit biomass (Figure 36), the three periodic recruitment events that led to peaks in commercially exploitable biomass are obvious (1995, 2003 and upcoming). If we compare the two previous periods with estimates of exploitation at the time we see that in survey year ending 1995 and 1996 exploitation was the highest in the time series (0.2) while exploitation was the lowest (0.02 - 0.06) in the time series from 1999 to 2003 and then increased to moderate levels (0.10 - 0.14) from 2004 to 2006 (Figure 37). The difference in terms of the fishery between these two periods was that the higher biomass of fully recruited scallops in the 2000s sustained high catches for longer with less effort than in the 1990s. In the current period exploitation has been kept low in the last few years as the large pulse of recruitment has increased in shell height. The high exploitation for survey year 2008 in Figure 37 was the result of fishing in the later part of 2007 (Figure 25) targeted at large scallops, remnant of the recruitment in the early 2000s, while the large cohort of juveniles were protected with industry managed closure areas (Figure 18). Now as the recruitment begins to enter the fishery it becomes important to prevent exploitation from increasing to levels observed in 1995-96 in order to ensure that this recruitment event will sustain the fishery for years to come.

The other consideration that was not previously mentioned was the meat count regulations in the current poor condition year. Although it is unlikely that any of the examined catch levels between 100 and 1000 t will result in a decline in next year’s biomass (Table 4), the current fully-recruited biomass is susceptible to be fished over the meat count restriction. A breakdown of the estimated fully-recruited biomass for May 2010 by shell height illustrates this point (Figure 44). The distribution of fully-recruited biomass is skewed such that most was just over the knife edge shell height of 95 mm. From the observed meat weights at shell height in this poor condition year scallops less than 105 mm are likely less than 12.5 g which would put them over the meat count regulation of 40 meats per 500 g. In others years this would not be an issue but in 2010 a young stock of fully-recruited scallops with a low average shell height and with an overall poor condition factor has lead to low average meat weight for scallops >95 mm. That is, a large portion of the fully-recruited biomass estimated in the model could have meat counts greater than the limit (Figure 44, Table 5). The silver lining in this is that there remains a large potential for growth both due to the age of the stock as well as possible improvement in condition during 2011 (Table 5). However, improved condition factor is not assured and for the purposes of this assessment, condition is assumed to remain the same in 2011.

Currently, it is not possible to predict what condition will be ahead of time. Research is currently underway to examine the effect of various environmental factors on annual variability in scallop condition factor but this work remains in the early stages. Spatial variability also comes into play as size composition and condition factor vary over the bank. Unfortunately due to the nature of the size distribution of fully-recruited scallops, the areas of high meat count are generally the same areas where the abundance of fully-recruited scallops were high (Figure 45; Figure 19). Given these factors and the fact that there remains a large abundance of scallops just below the knife-edge shell height recruitment level that are part of the same cohort it makes sense to keep exploitation low to allow for growth in the fully-recruited biomass.

REFERENCE POINTS

The establishment of biological reference points is a priority for DFO in implementing the precautionary approach to managing important commercially exploited stocks. The challenge for the scallop stock is establishing meaningful biomass based biological reference points. Traditional methods developed for finfish fisheries such as maximum sustainable yield (MSY) and yield-per-recruit (YPR) have been attempted, but the differences in biology associated with invertebrates, particularly bivalve molluscs, have made such estimates extremely uncertain at best (Caddy 1978; Robert et al. 2000; Hart 2001). A production analysis was even less fruitful for Browns north than it was for Georges ‘a’ (Jonsen et al. 2009) as there was no evidence of relationships in the production, yield and stock-recruit plots (Figure 46). The phase plot of fishing mortality and biomass does suggest that there are two different regimes in the fishery and this plot may be useful in formalizing the precautionary approach. Some progress has been made in estimating removal reference points where exploitation is plotted against the change in biomass with the intercept of the regression line being the removal reference (Figure 47; Jonsen et al. 2009). This exploitation reference can then be plotted on the phase plot where it helps to define the current regime of lower exploitation that sustains a high biomass for longer than in the past regime of the 1990s where higher exploitation lead to a more rapid decline in biomass (Figure 48).

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Table 1. Landings of sea scallop meats from Browns Bank and total allowable catch (TAC), in metric tons. Since 1998, Browns Bank has been divided into north and south management areas

Year	Catch (t)		TAC (t)	
1981	25		--	
1982	156		--	
1983	106		--	
1984	28		--	
1985	16		--	
1986	5		--	
1987	0		--	
1988	5		--	
1989	337		400	
1990	207		200	
1991	215		220	
1992	454		450	
1993	575		600	
1994	1403		1400	
1995	2002		2000	
1996	743		750	
1997	500		500	
Year	Catch (t)		TAC (t)	
	north	south	north	south
1998	500	98	500	100
1999	200	293	200	300
2000	748	200	750	200
2001	999	99	1000	100
2002	649	98	650	100
2003	1003	97	1000	100
2004	2007	185	2000	200
2005	1068	38	1075	100
2006	912	14	1050	100
2007	1198	1	1200	50
2008	393	0	400	0
2009	0	0	0	0
2010	201	0	200	0

Table 2. Data used to fit Delay-Difference model for Browns Bank north.

Year	Fully-Recruited			Recruit	CPUE	Catch
	Biomass (t)	Avg Height (mm)	CF (g/dm^3)	Biomass (t)	(kg/hm)	(t)
1991	608	104	11.11	252	9.04	195
1992	918	104	11.84	647	9.56	201
1993	1142	103	12.71	354	12.84	454
1994	3546	109	14.77	579	16.45	840
1995	4187	110	12.59	221	27.85	2233
1996	1126	111	11.84	235	15.69	1414
1997	2223	111	12.83	190	16.82	540
1998	1649	114	11.63	34	14.98	378
1999	2759	117	14.18	52	17.39	181
2000	3832	112	15.19	881	25.51	551
2001	2684	114	12.11	504	32.12	541
2002	4611	108	12.59	1169	38.49	930
2003	8689	112	13.11	251	70.16	634
2004	5031	115	11.40	65	38.66	2486
2005	4044	119	10.83	70	28.67	1093
2006	3451	114	11.62	288	21.71	1104
2007	3085	122	12.16	8	60.28	367
2008	1128	127	10.94	18	19.93	1080
2009	1688	109	11.77	1924	10.07	210
2010	2666	106	11.05	1190	22.63	187

Table 3. Delay-difference model estimates of fully-recruited biomass and recruit biomass for Browns Bank north. Posterior medians are labelled 0.5, columns labelled 0.025 and 0.975 are the lower and upper limits of the 95% credible interval.

Year	Fully-Recruited Biomass (t)			Recruit Biomass (t)		
	0.025	0.5	0.975	0.025	0.5	0.975
1991	1536	2571	4533	393	844	1866
1992	2109	3417	5740	923	1950	3935
1993	3195	5105	8460	575	1223	2755
1994	5309	8415	14250	897	1901	3901
1995	5274	8922	15741	330	720	1605
1996	3460	5648	9711	380	812	1827
1997	4075	6620	11110	308	661	1467
1998	3866	6055	10130	69	145	331
1999	5287	8224	13720	100	219	535
2000	6397	10330	17900	1197	2643	5522
2001	6919	10920	18180	778	1636	3579
2002	9107	14635	25141	1628	3505	7442
2003	14010	22680	39232	395	842	1816
2004	9828	15650	26740	121	271	700
2005	7693	12180	20531	129	280	636
2006	6538	10440	17750	413	951	2221
2007	7020	11310	19970	19	42	113
2008	3596	5766	9656	39	83	205
2009	3078	5069	8602	2482	5078	10160
2010	5544	9096	15441	1655	3494	7253

Table 4. Posterior probabilities of a decline in biomass Pr(Δ < 0) from 2010 to 2011, for various harvest levels. The corresponding posterior median exploitation rate μ and percent change % Δ in fully-recruited biomass associated with harvest levels are also provided.

Catch (t)	μ	Pr(Δ < 0)	% Δ
100	0.01	0.10	47.46
200	0.02	0.10	46.06
300	0.02	0.11	44.23
400	0.03	0.11	44.15
500	0.04	0.11	42.64
600	0.05	0.13	41.52
700	0.05	0.13	40.17
800	0.06	0.13	39.97
900	0.07	0.15	37.69
1000	0.08	0.16	35.75

Table 5. Breakdown of the 2010 fully-recruited biomass by meat count and the predicted growth.

Meat Count	Biomass (t)	Percent of Total	Predicted Growth (%)
40+	4005	44	31
40-30	2704	30	23
30-20	1379	15	14
20-10	996	11	5
under 10	13	<1	0

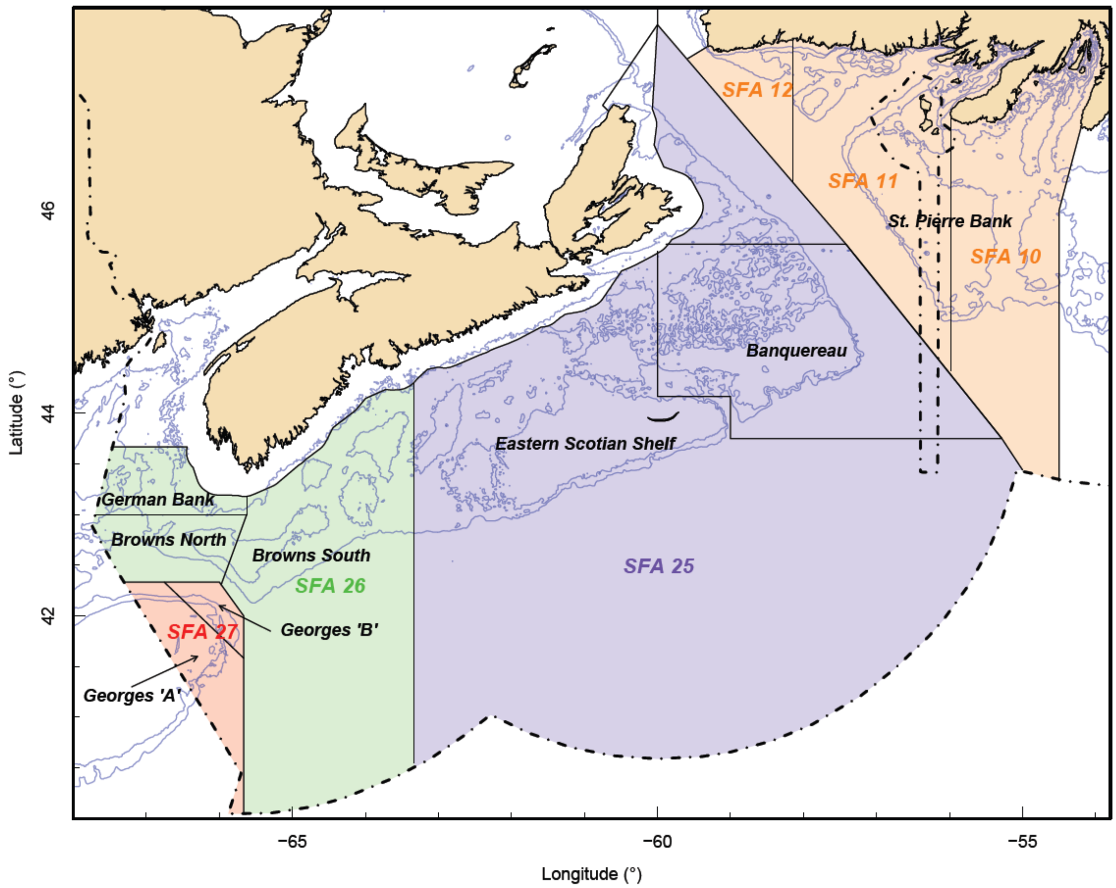

Figure 1. Offshore scallop fishing areas (SFA) used for management purposes in the Maritimes region. Note the division of Browns north as a subarea of SFA 26.

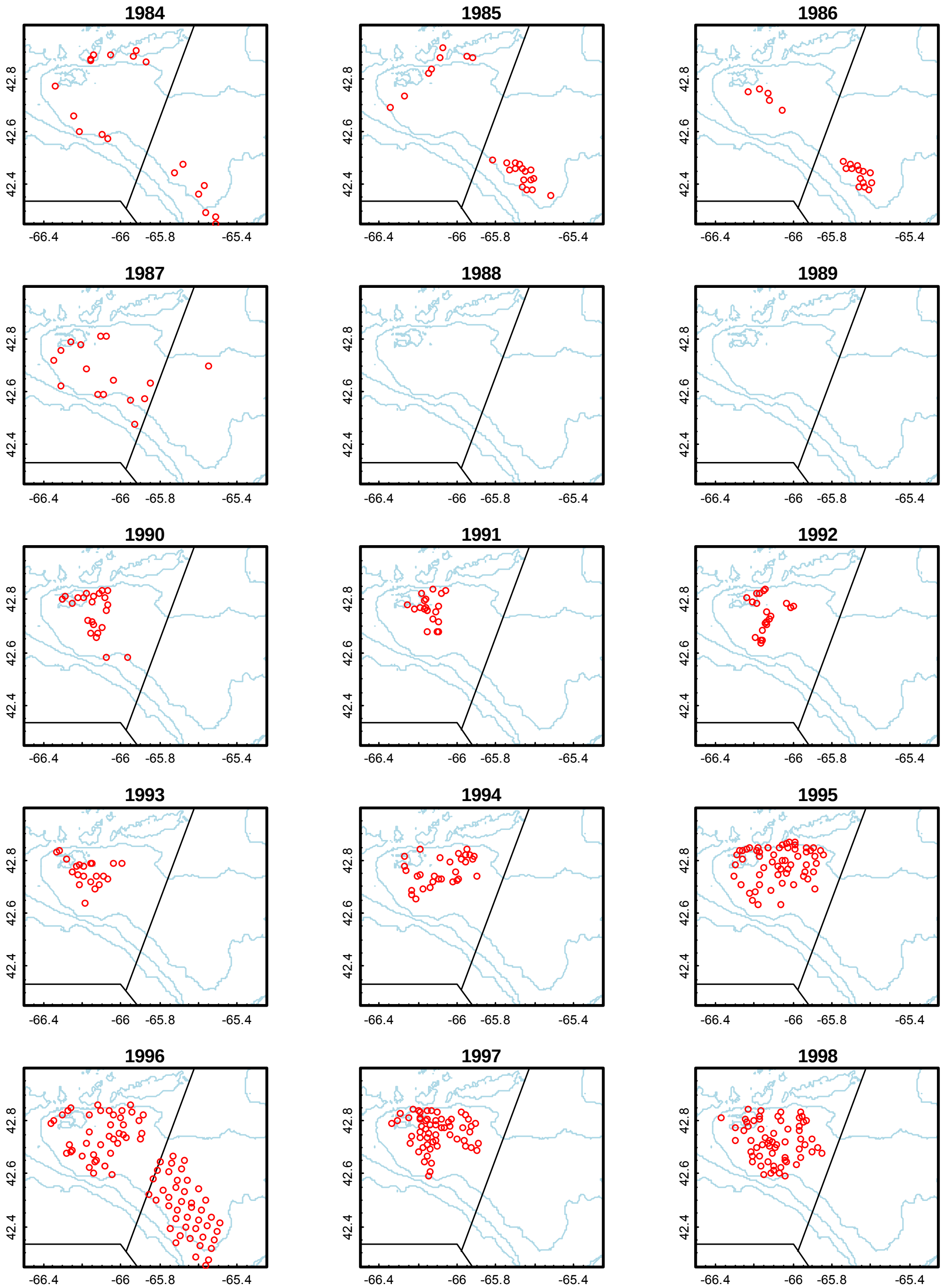

Figure 2. Positions of survey tows on Browns Bank from 1984 to 2010.

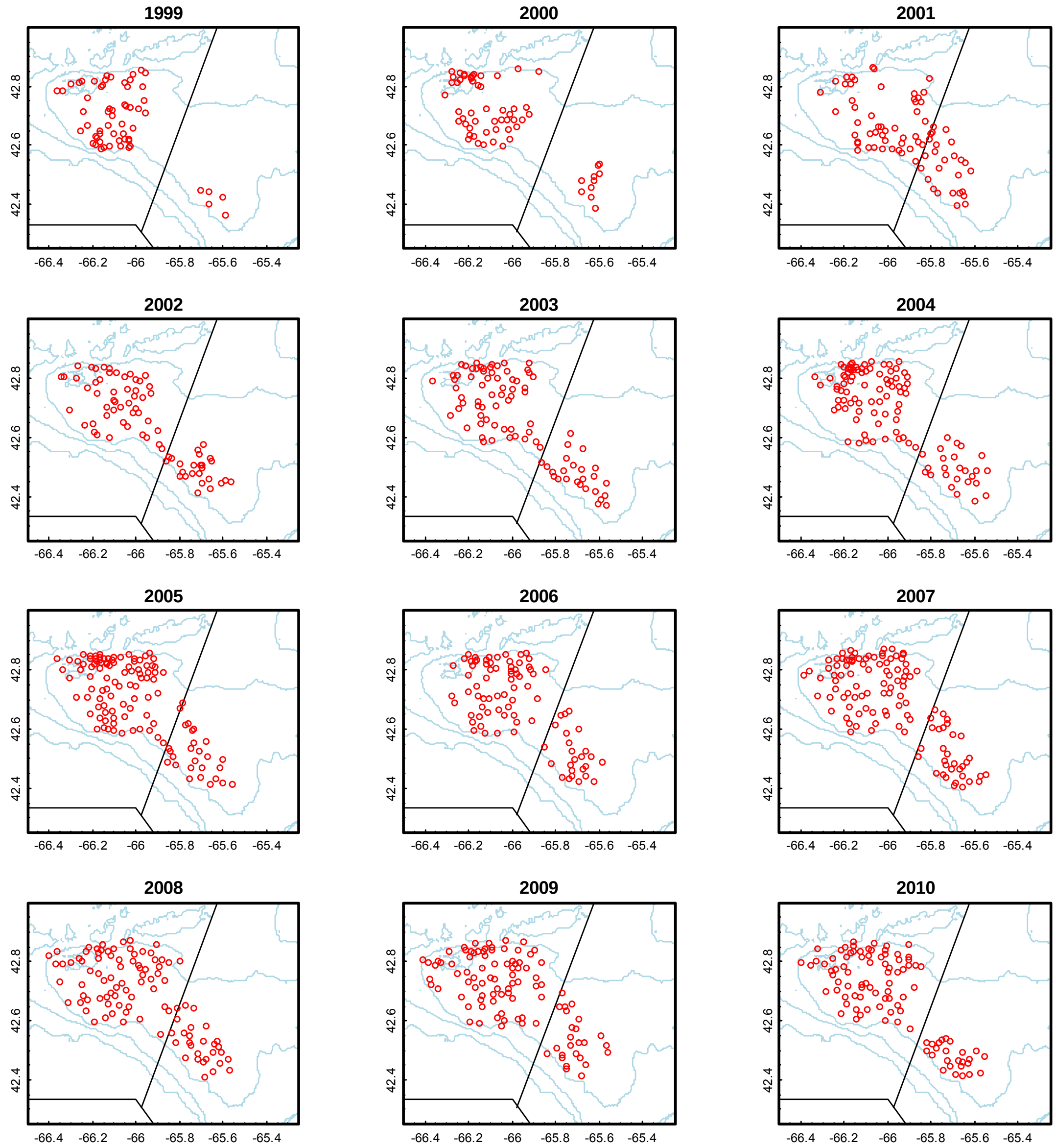

Figure 2 continued. Positions of survey tows on Browns Bank from 1984 to 2010.

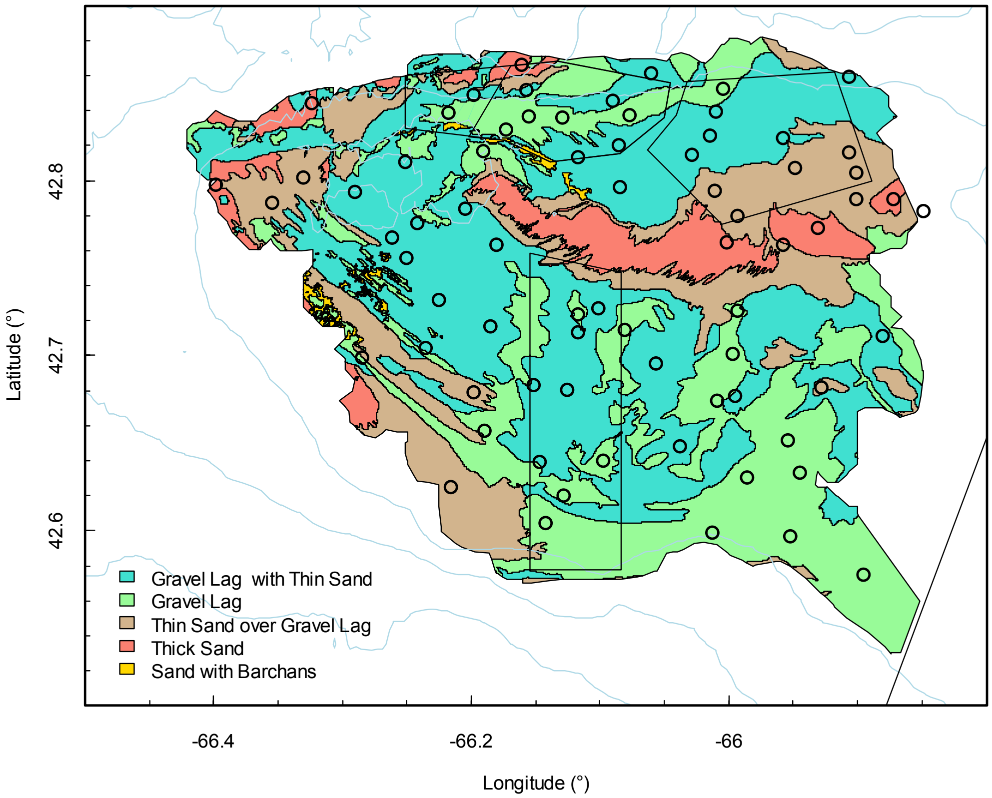

Figure 3. Browns Bank north scallop survey in May 2010. Stations (○) were allocated using a random stratified design based on bottom type (see legend). Biological samples including meats, gonads, shells and soft parts of 30 scallops were taken for one tow in each 10 minute square. Recent industry managed closure areas are provided for spatial reference only.

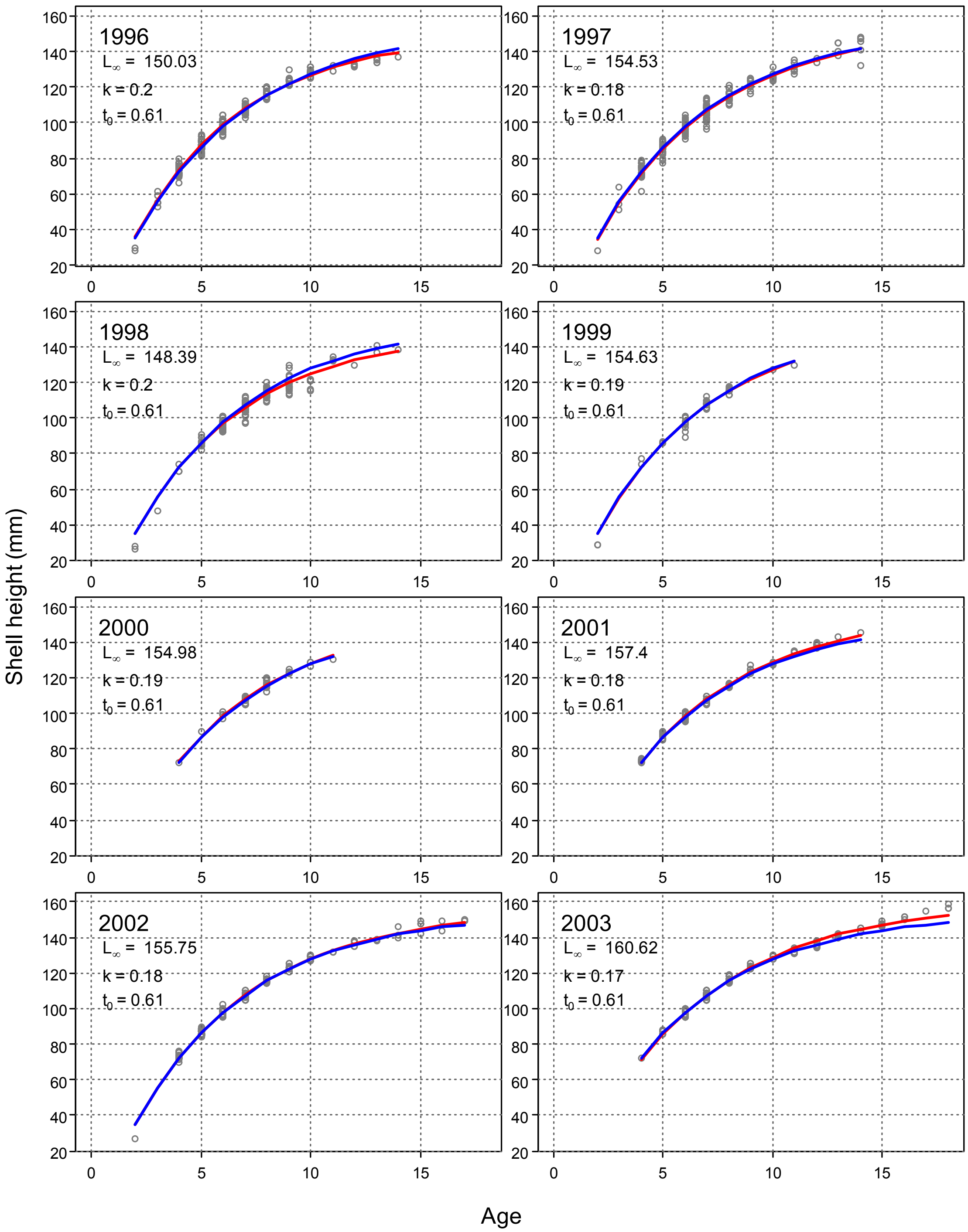

Figure 4. Von Bertalanffy growth model fit to Shell height at age data from Browns Bank north with year as a random effect (red line), for which the annual parameters are given in each panel. The blue line represents the fixed effect or overall mean relationship.

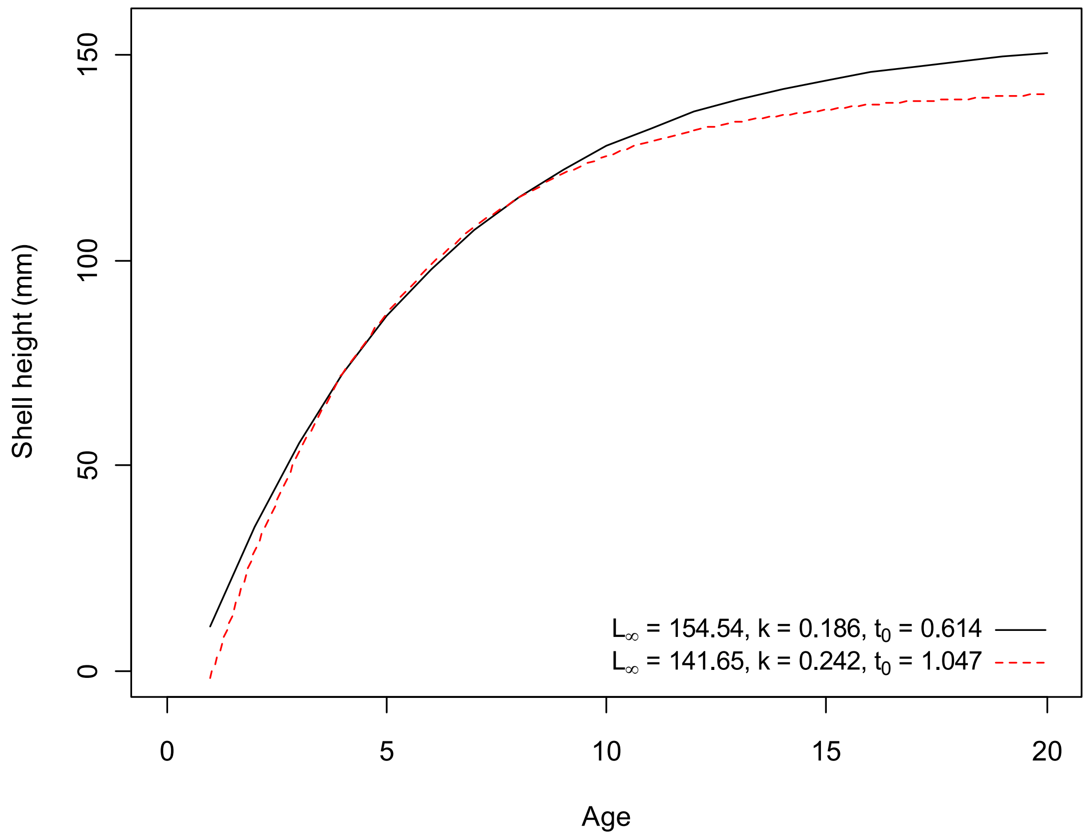

Figure 5. Comparison of growth curves resulting from LVB parameters estimated using the most recent data available (—) and those reported in Robert and Butler (1998) (- - -).

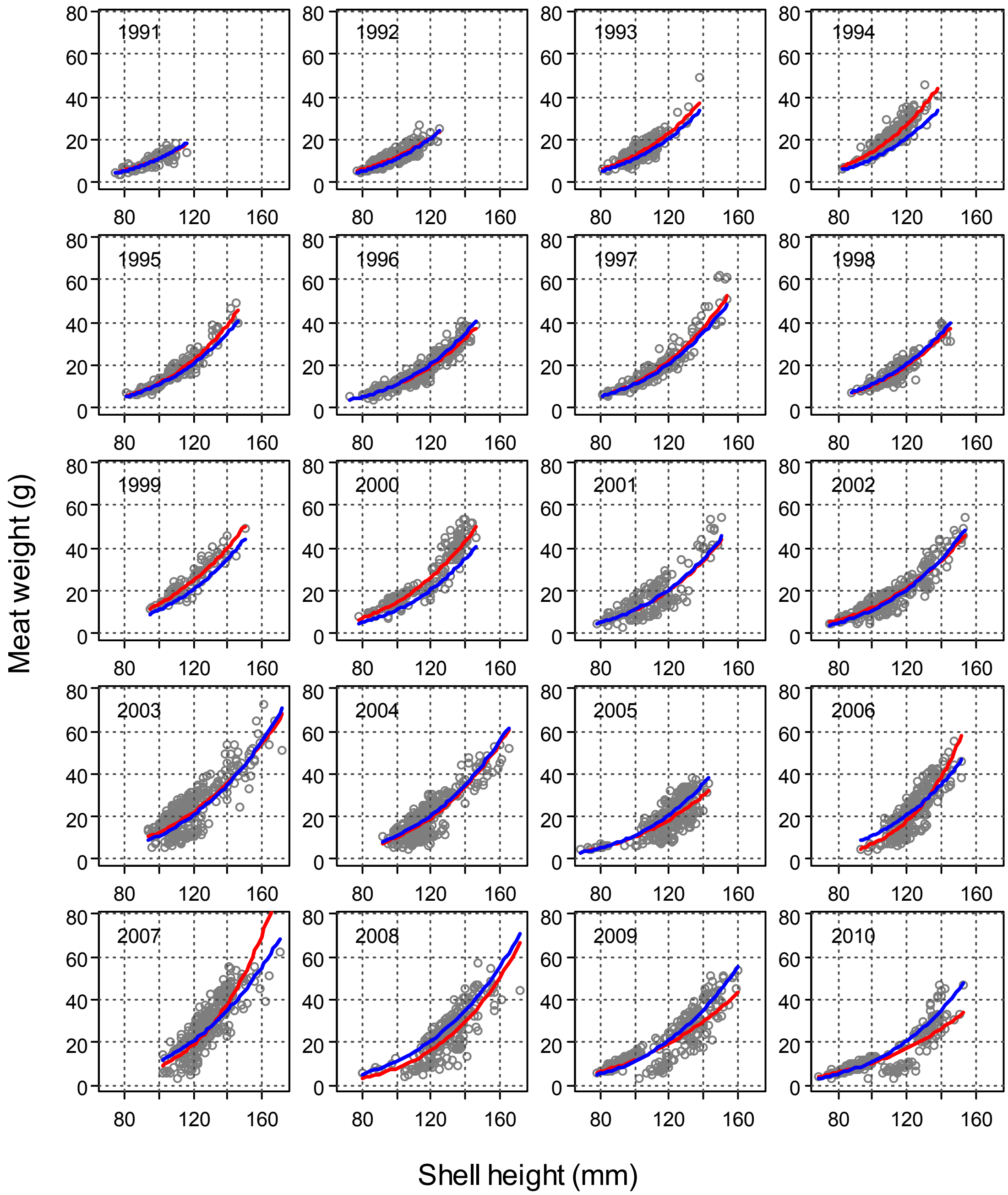

Figure 6. Shell height meat weight relationship for scallops on Browns Bank north with year as a random effect (red line). The blue line represents the fixed effect or overall mean relationship.

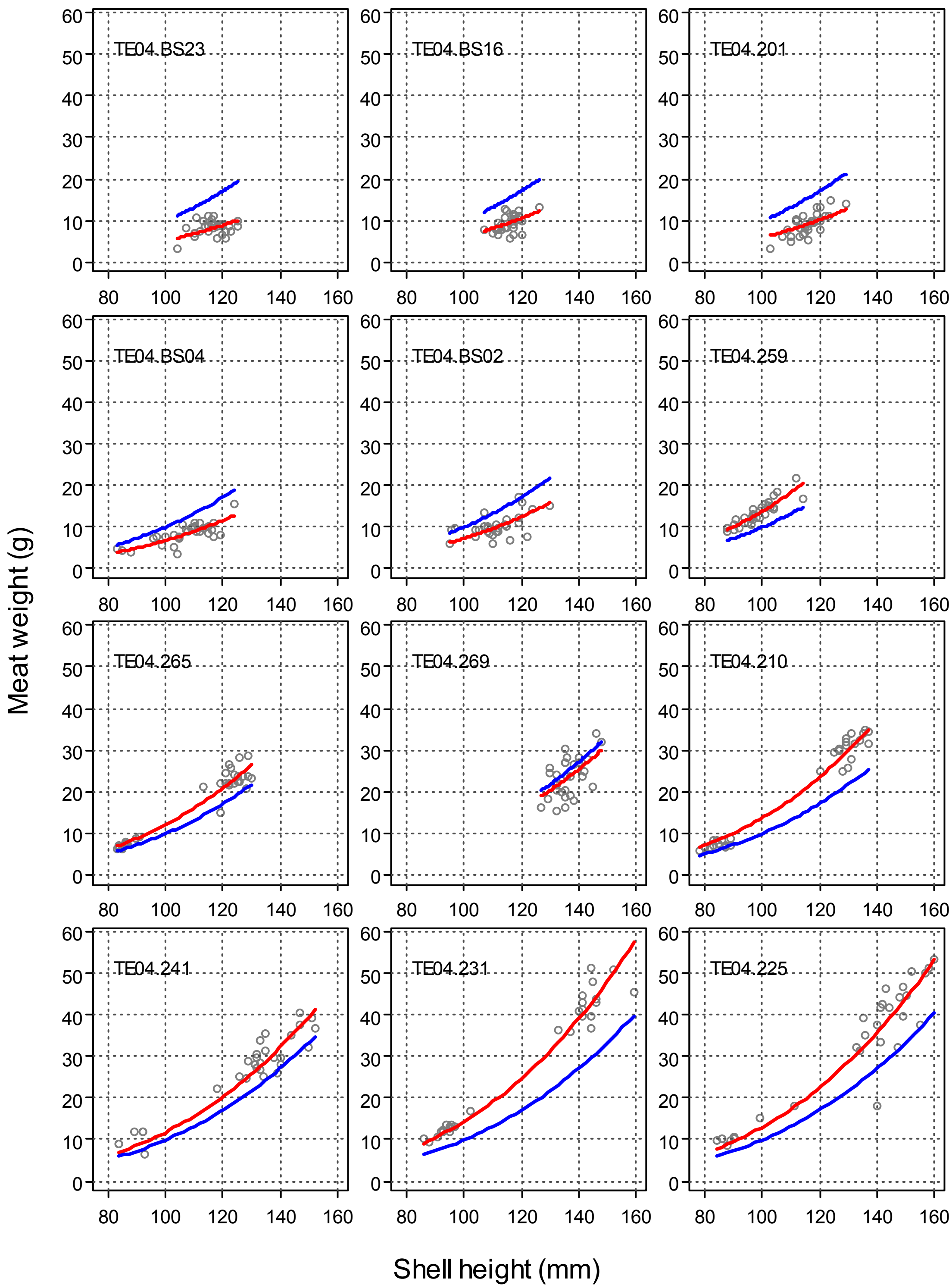

Figure 7. Shell height meat weight relationship for scallops sampled on Browns Bank north in 2009 with survey station as a random effect (red line). The blue line represents the fixed effect or overall mean relationship.

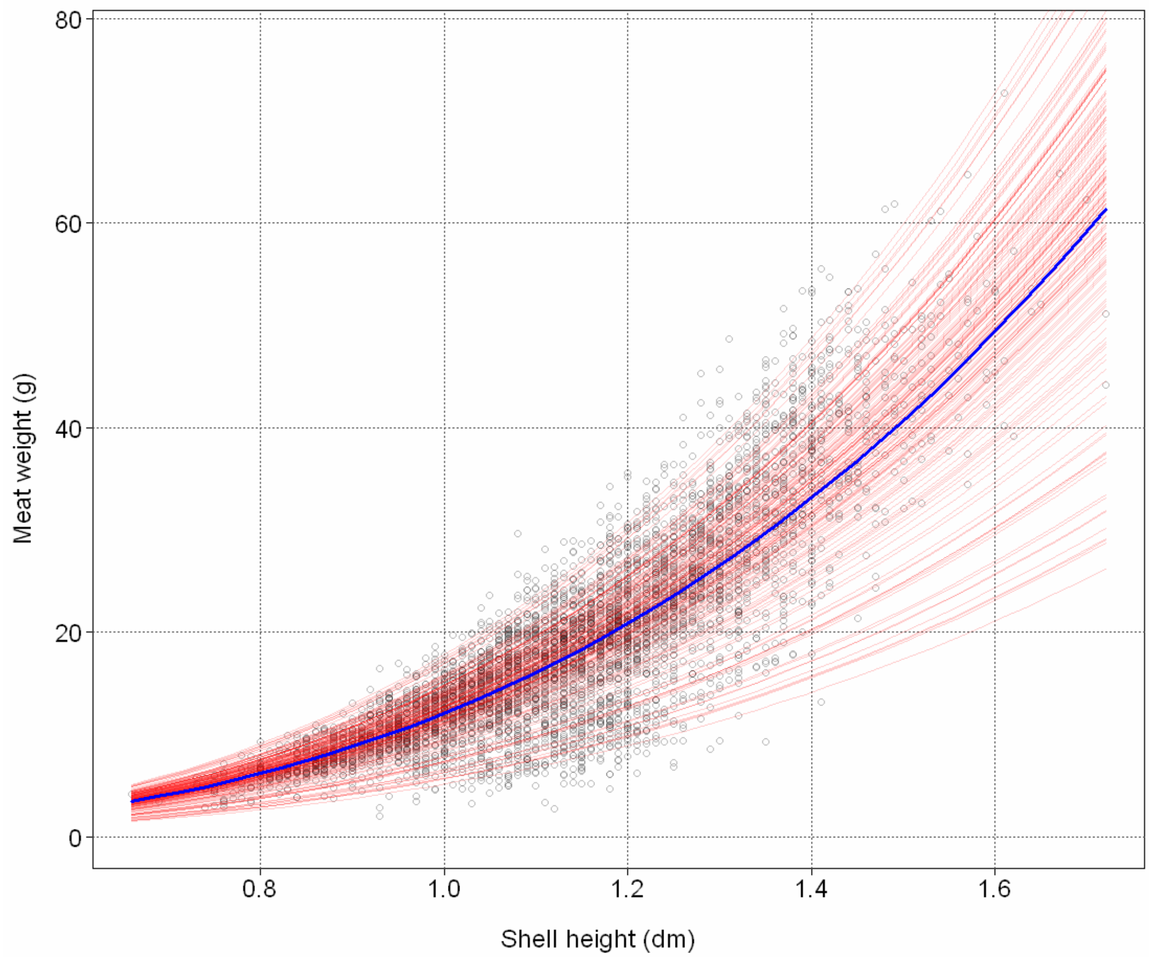

Figure 8. Isometric shell height meat weight relationship for scallops on Browns Bank north with survey station as a random effect (red lines).

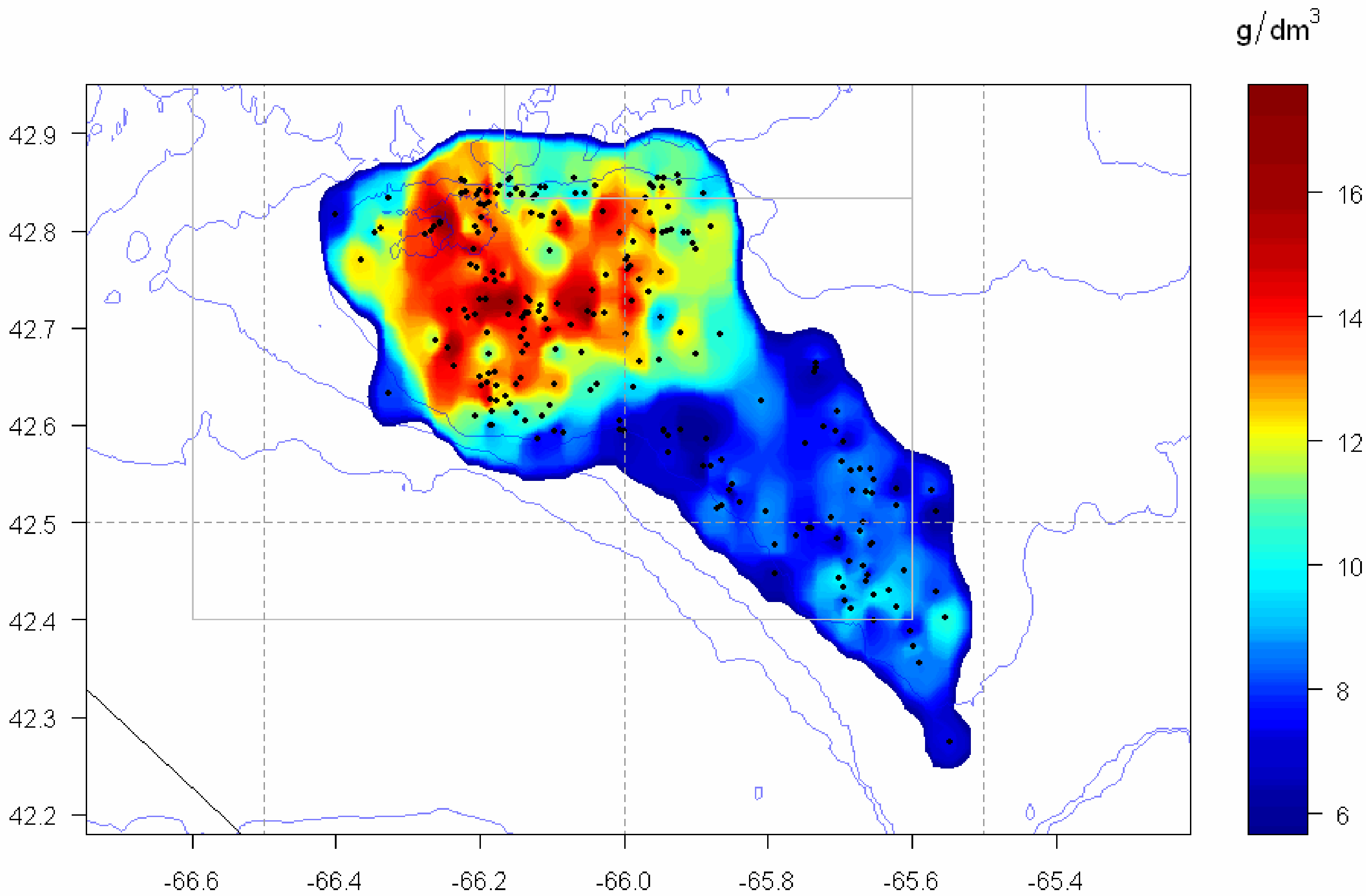

Figure. 9. Inverse distance weighted interpolation of the condition factor of scallops sampled on Browns Bank. Points represent sampling locations. The condition factor is in grams of meat per dm^3 of shell height so that the scale on the right represents the meat weight (g) of 100mm scallop).

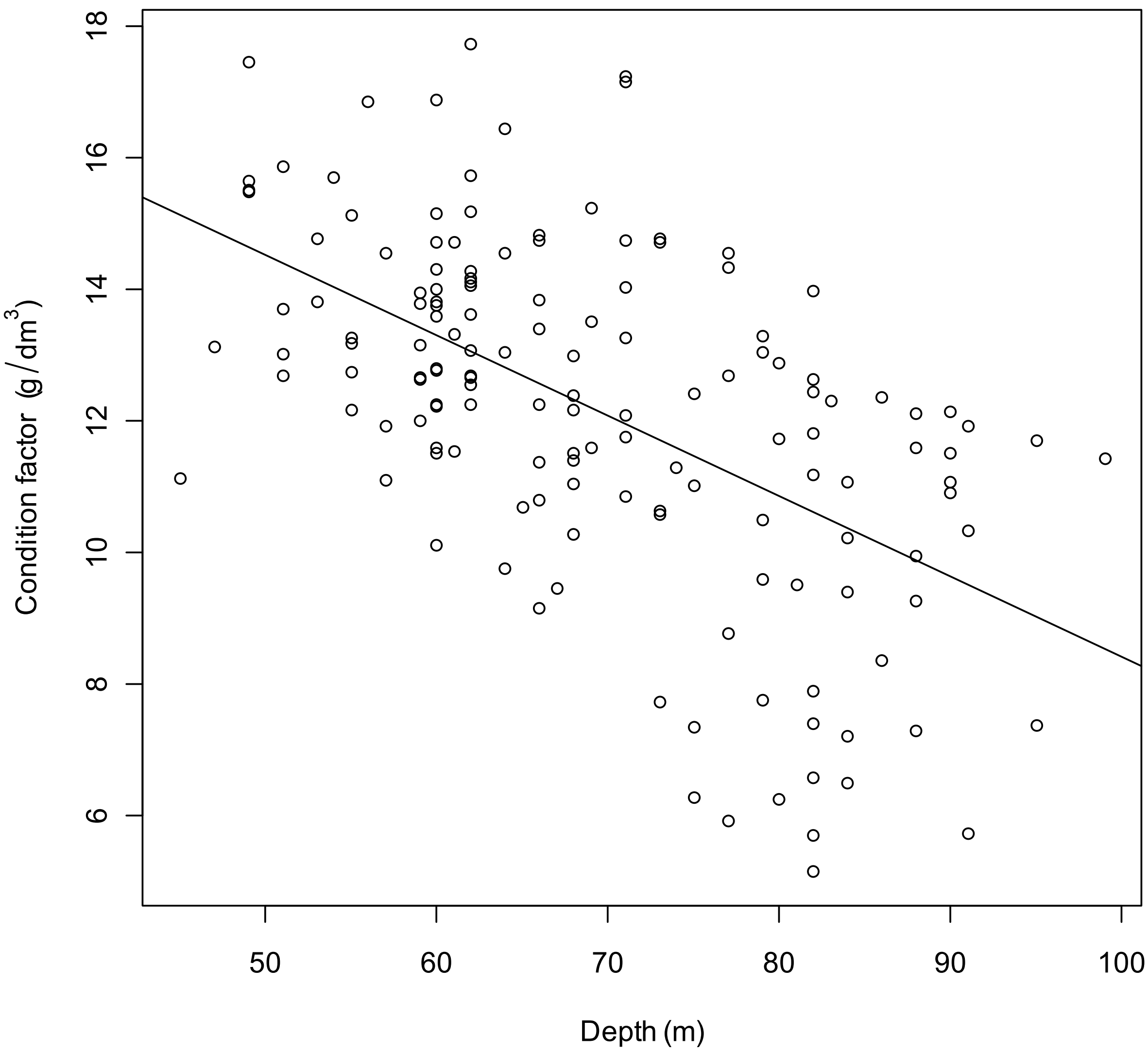

Figure 10. Linear relationship between condition factor and depth between 50 and 100 m.

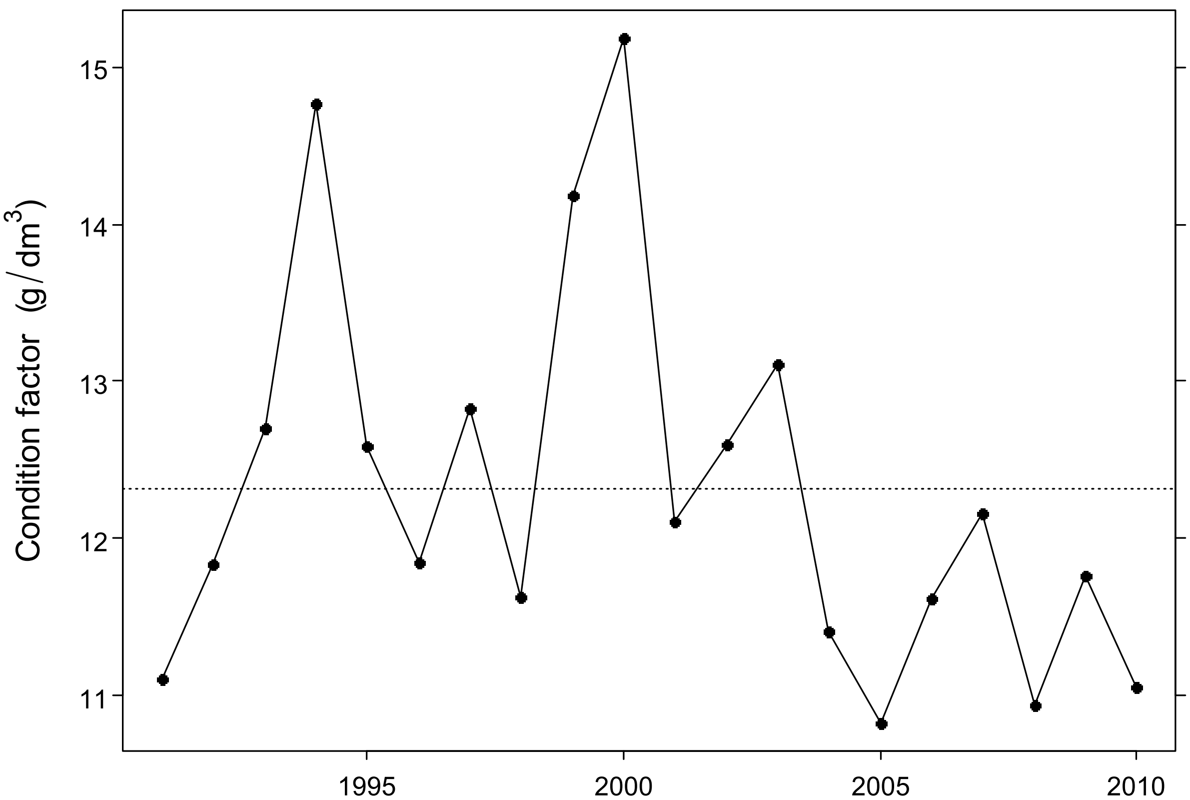

Figure 11. Overall annual condition factor calculated using estimated annual factors and the mean depth weighted by abundance. Horizontal dashed line is the long-term median.

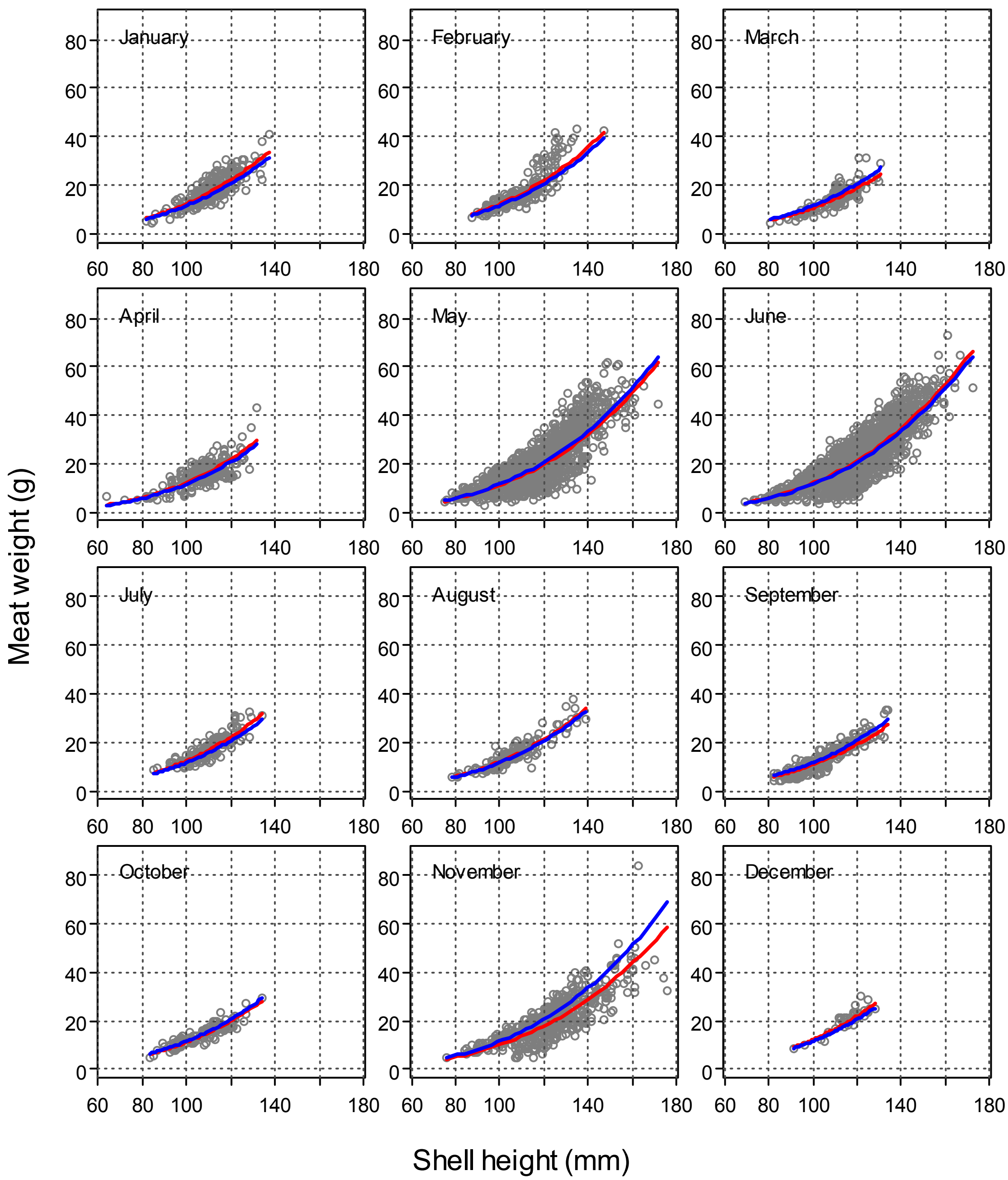

Figure 12. Shell height meat weight relationship for scallops on Browns Bank north captured from 1993 - 2010 with month as a random effect (red line).

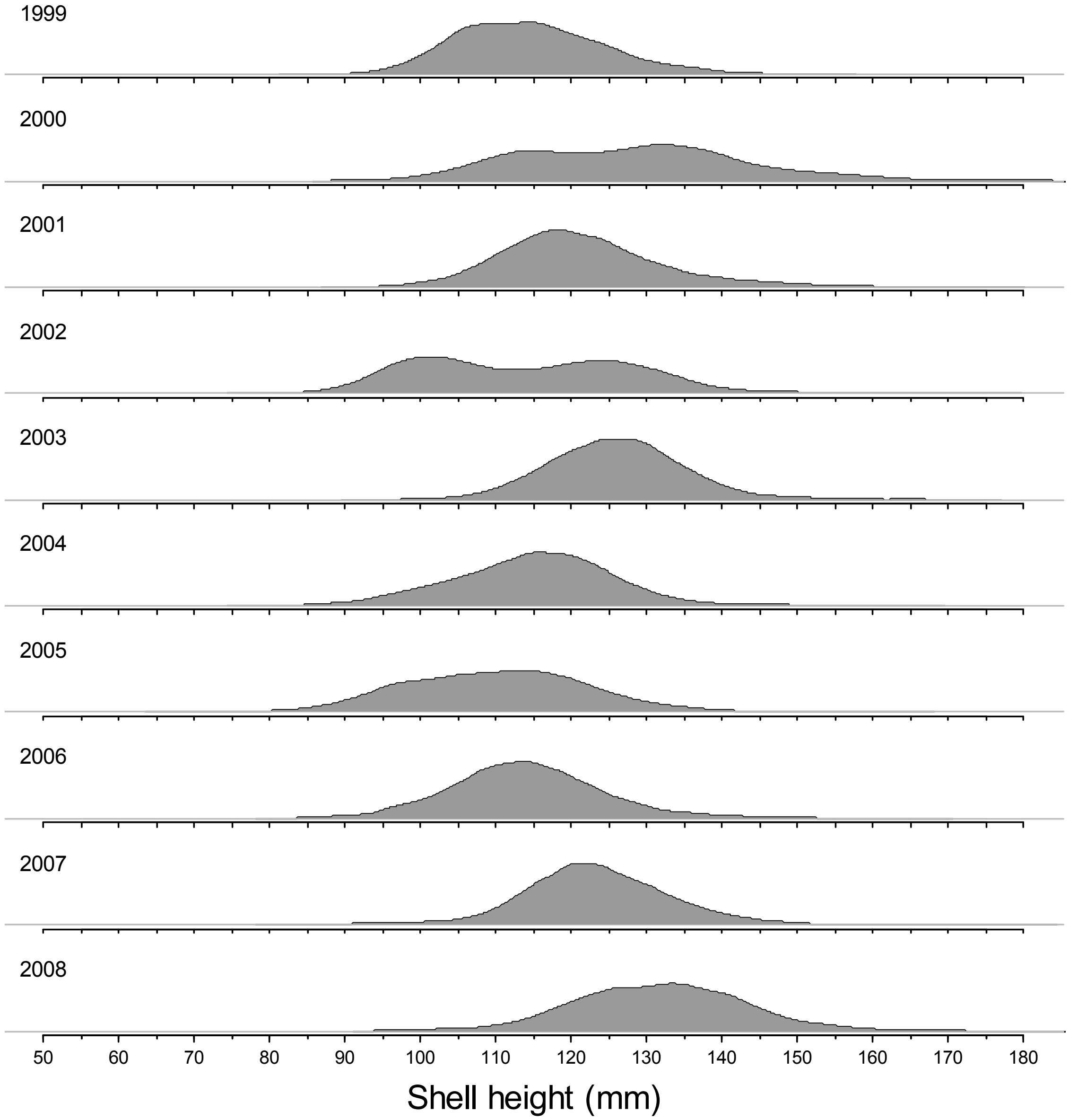

Figure 13. Shell height frequency from port sampling of catch from Browns Bank north.

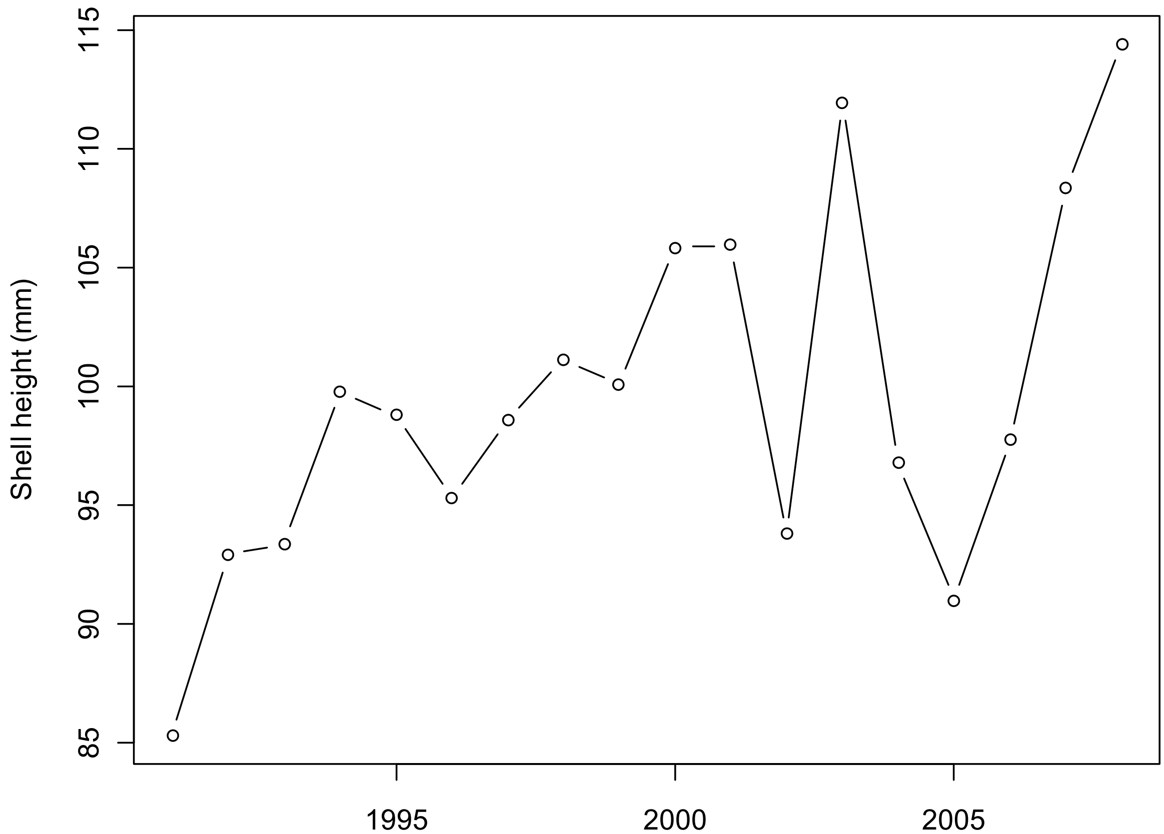

Figure 14. The lower 5th percentile for shell height in the landings from Browns Bank north.

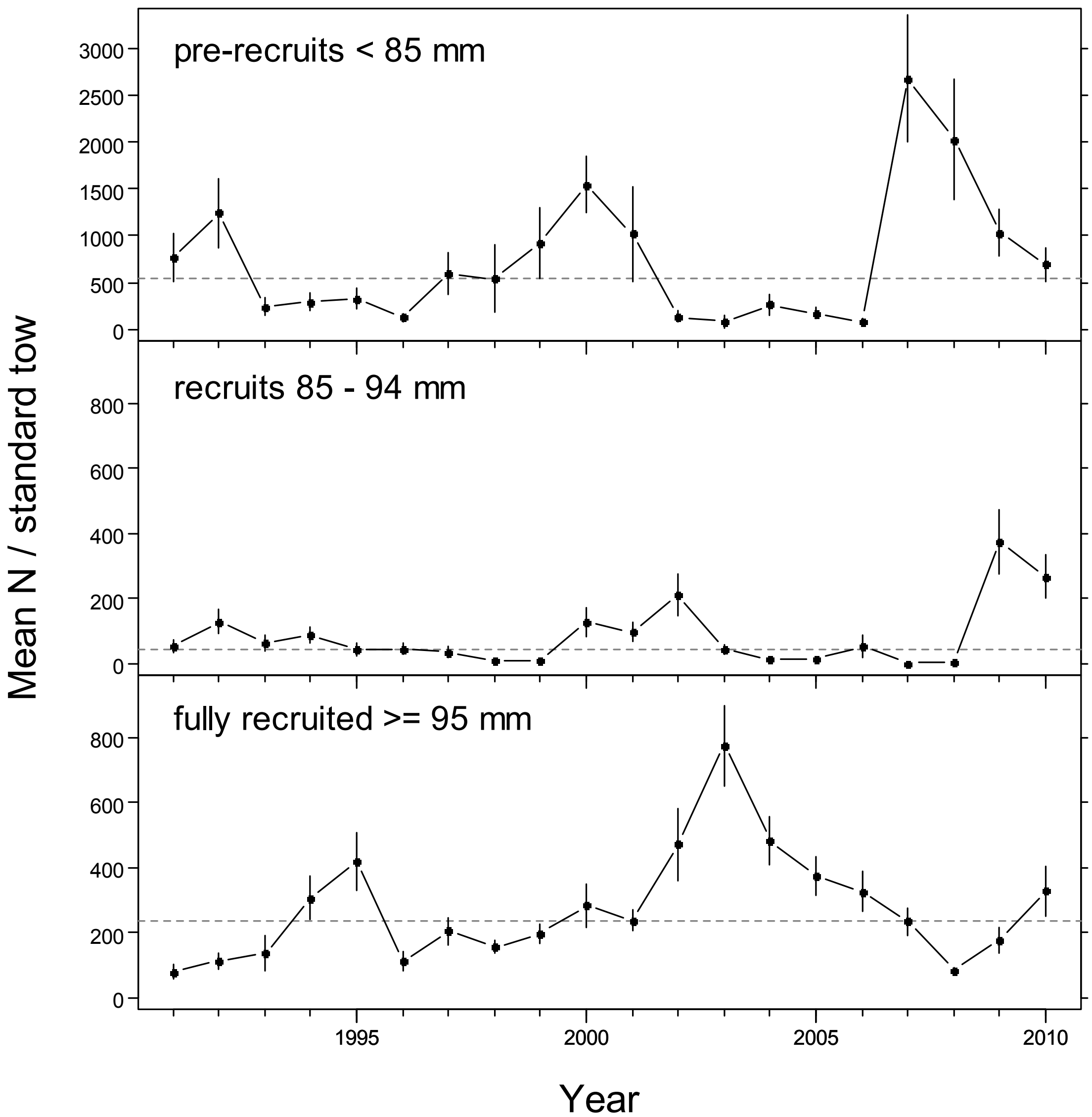

Figure 15. Stratified mean abundance per standard tow (800 m x 2.44 m drag) of scallops from spring survey of Browns Bank north (1991-2010). Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error.

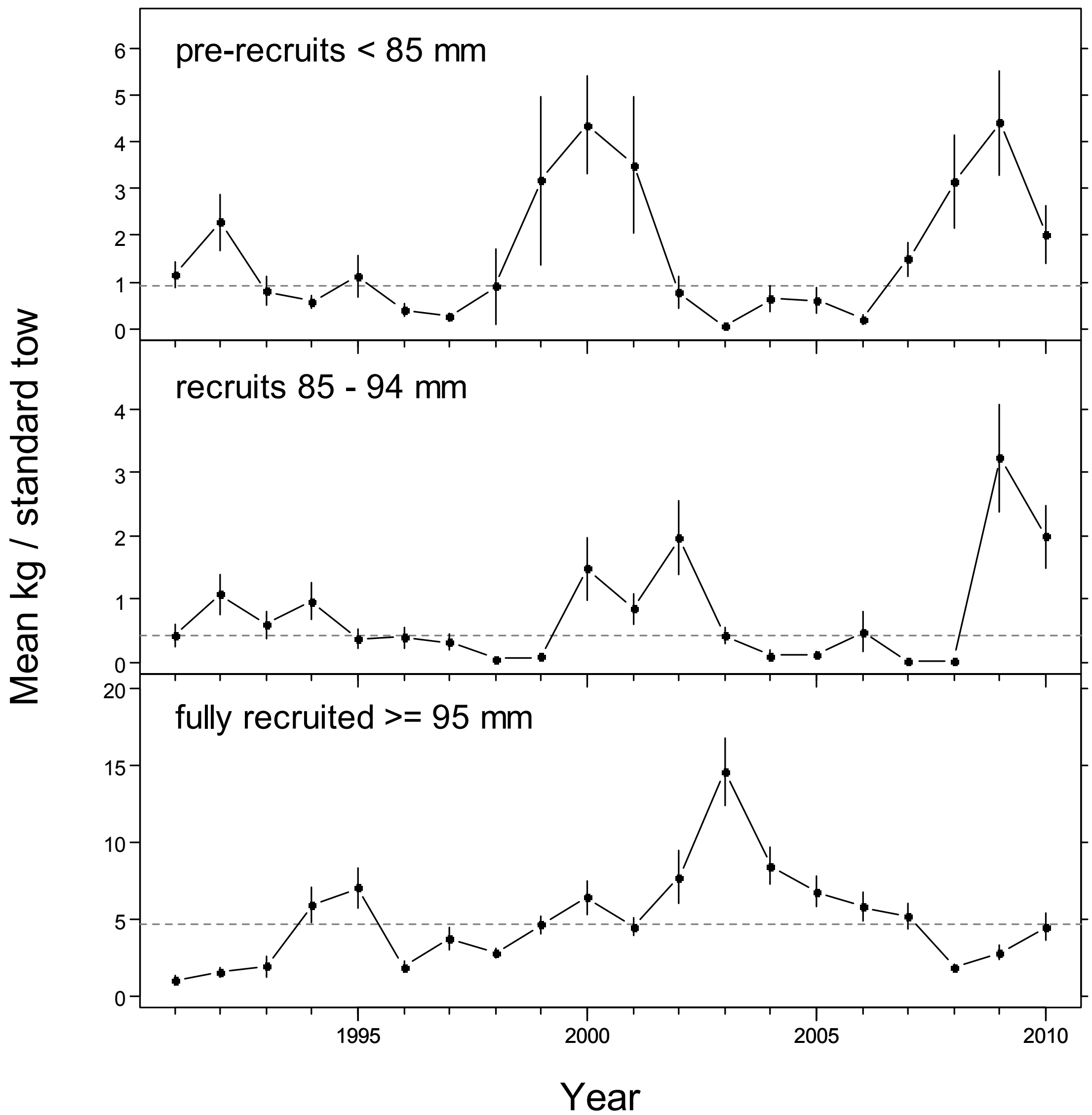

Figure 16. Stratified mean biomass per standard tow (800 m x 2.44 m drag) of scallop abductor muscles (Placopecten magellanicus) from spring survey of Browns Bank north (1991-2010).Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error.

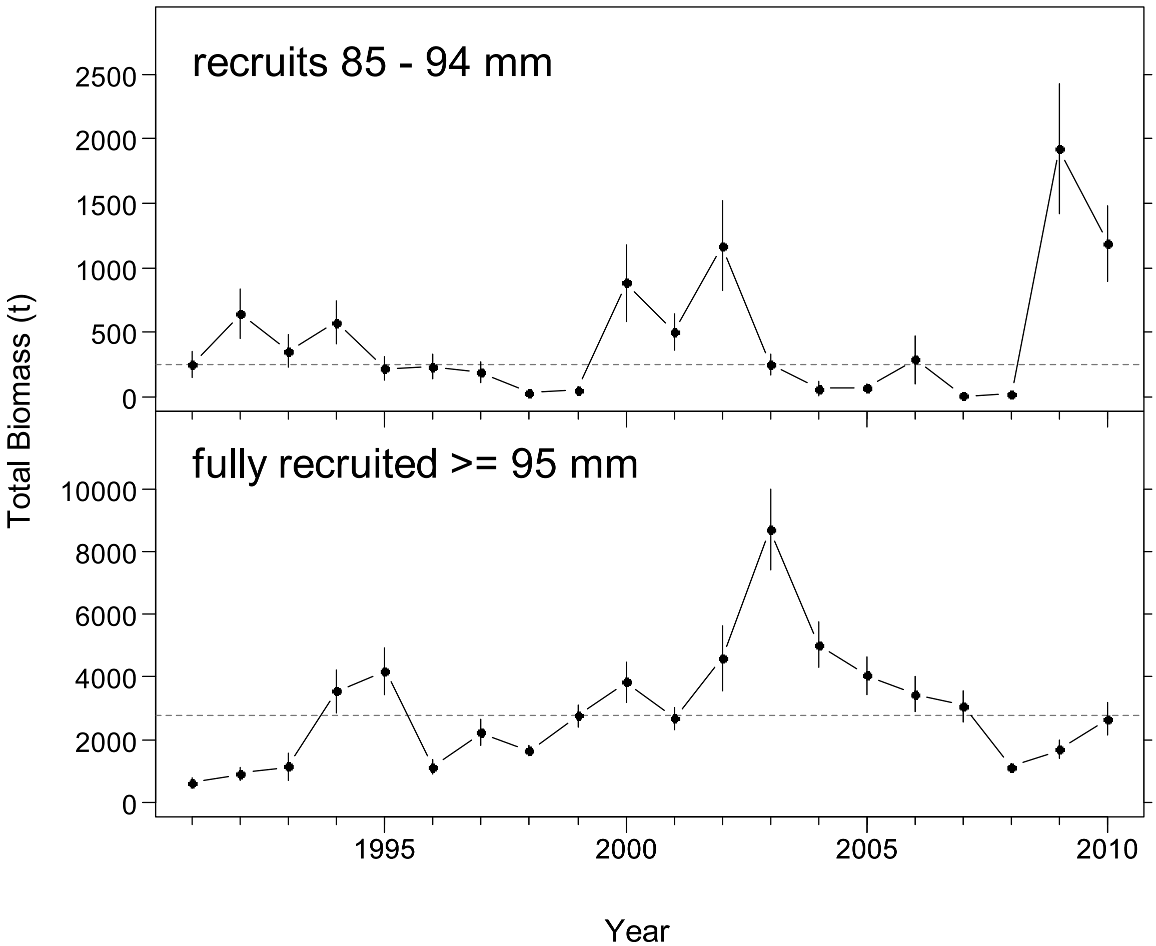

Figure 17. The stratified population biomass of scallop abductor muscles used as biomass indices for recruit and fully-recruited scallop in the assessment model. Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error.

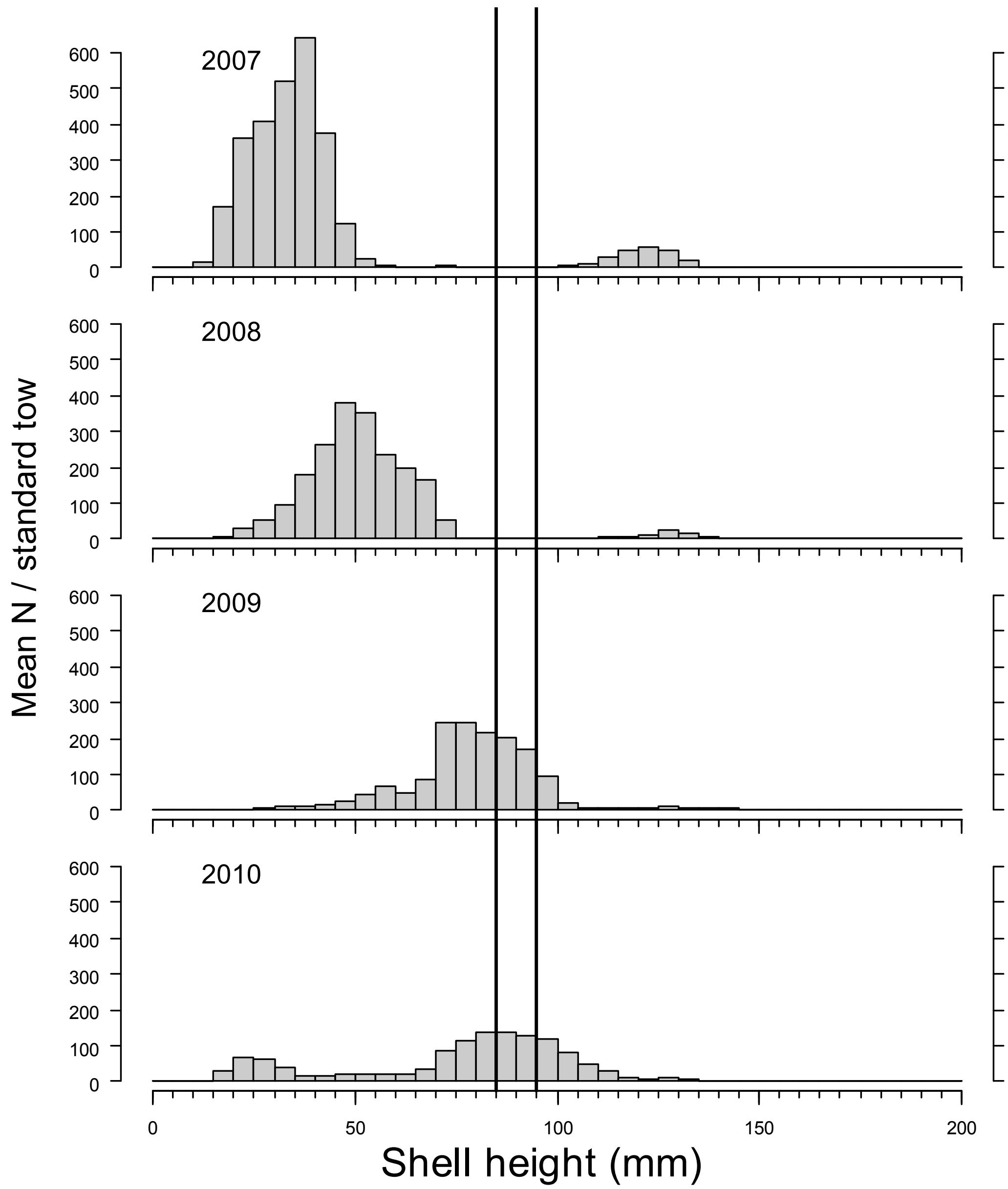

Figure 18. Shell height frequency plot showing the mean number of scallops per standard tow (800 m x 2.44 m drag) from spring survey of Browns Bank north (1991-2010) for each 5 mm bin. Vertical lines divide the pre-recruit, recruit and fully-recruited size classes.

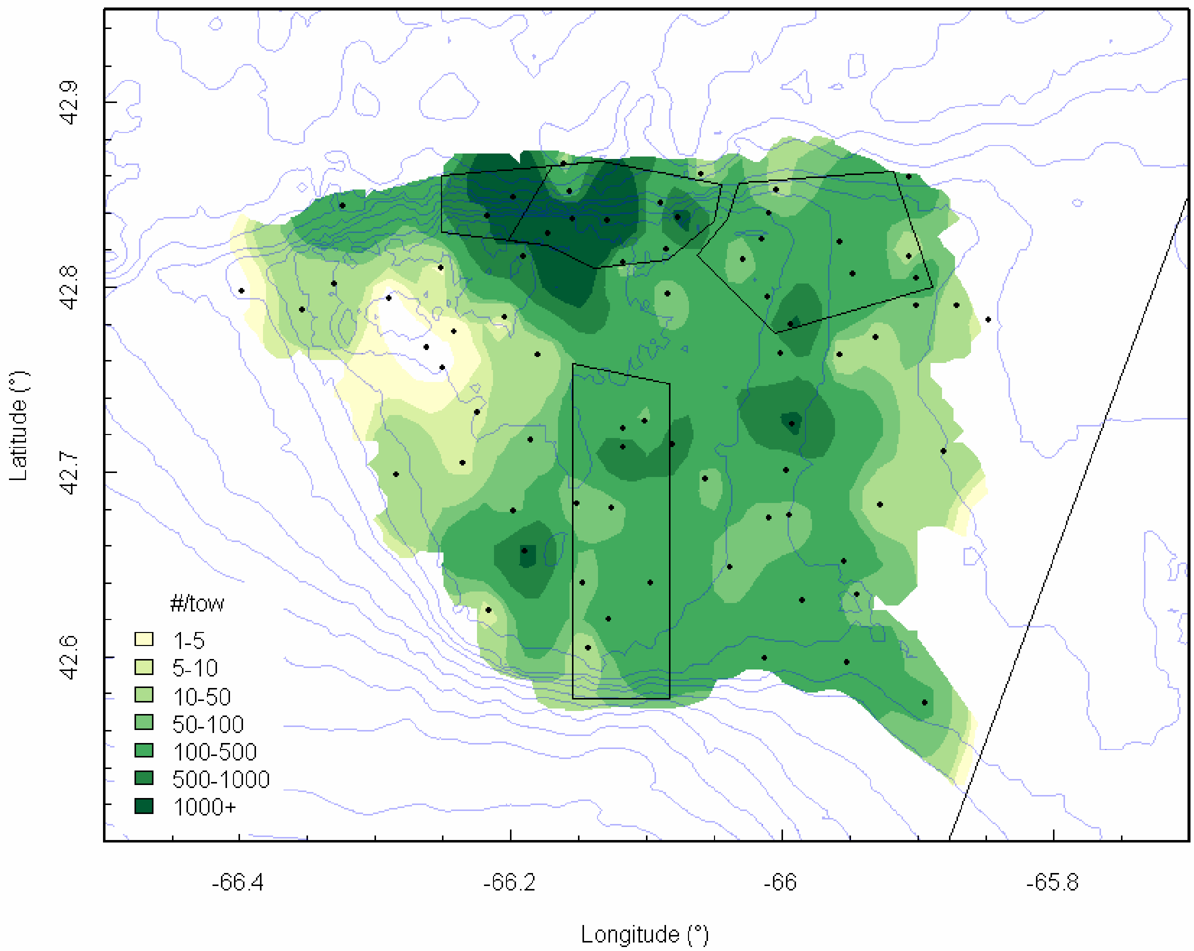

Figure 19. Distribution of fully recruited (≥95 mm shell height) scallops from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

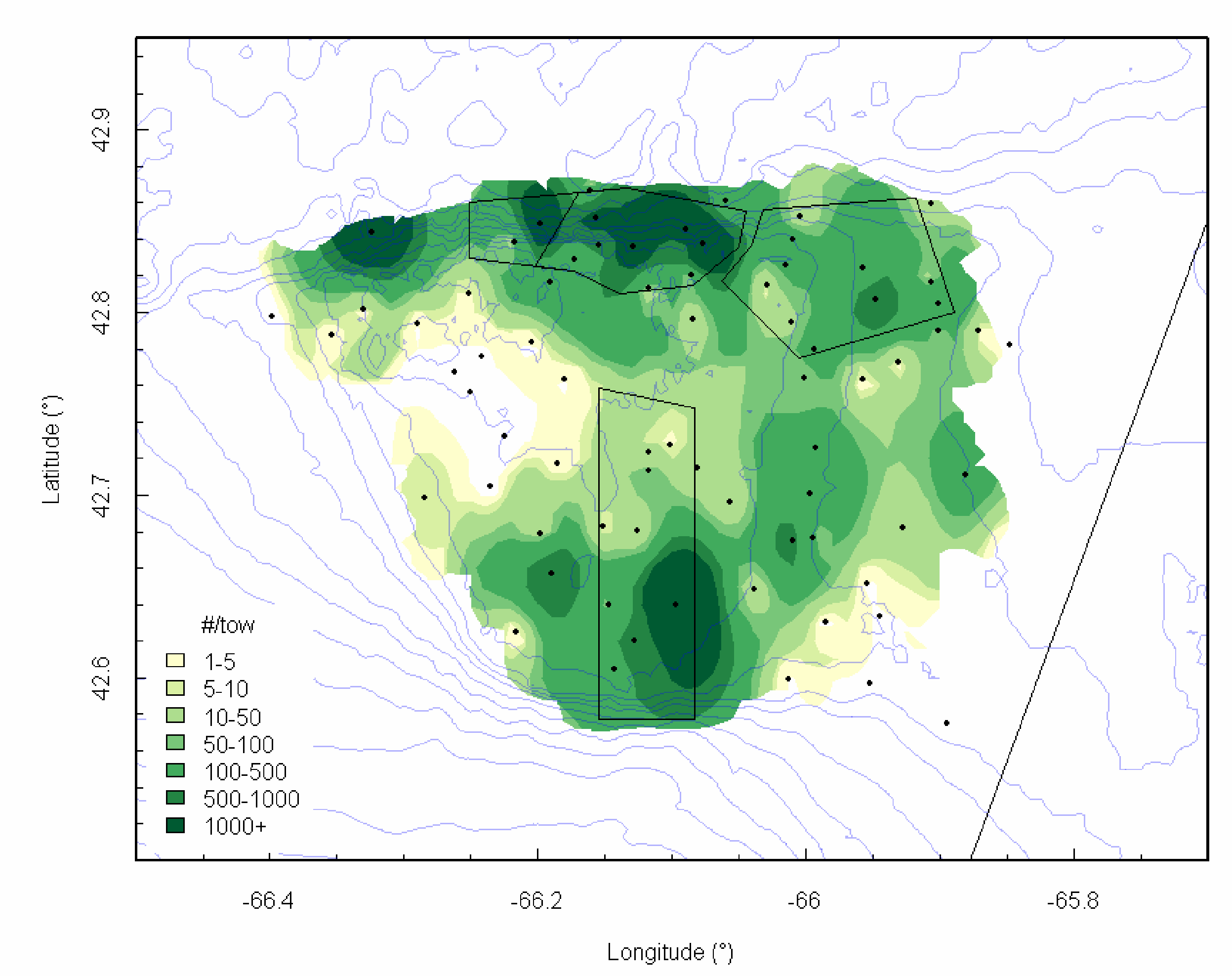

Figure 20. Distribution of recruit (85 - 95 mm shell height) scallops from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

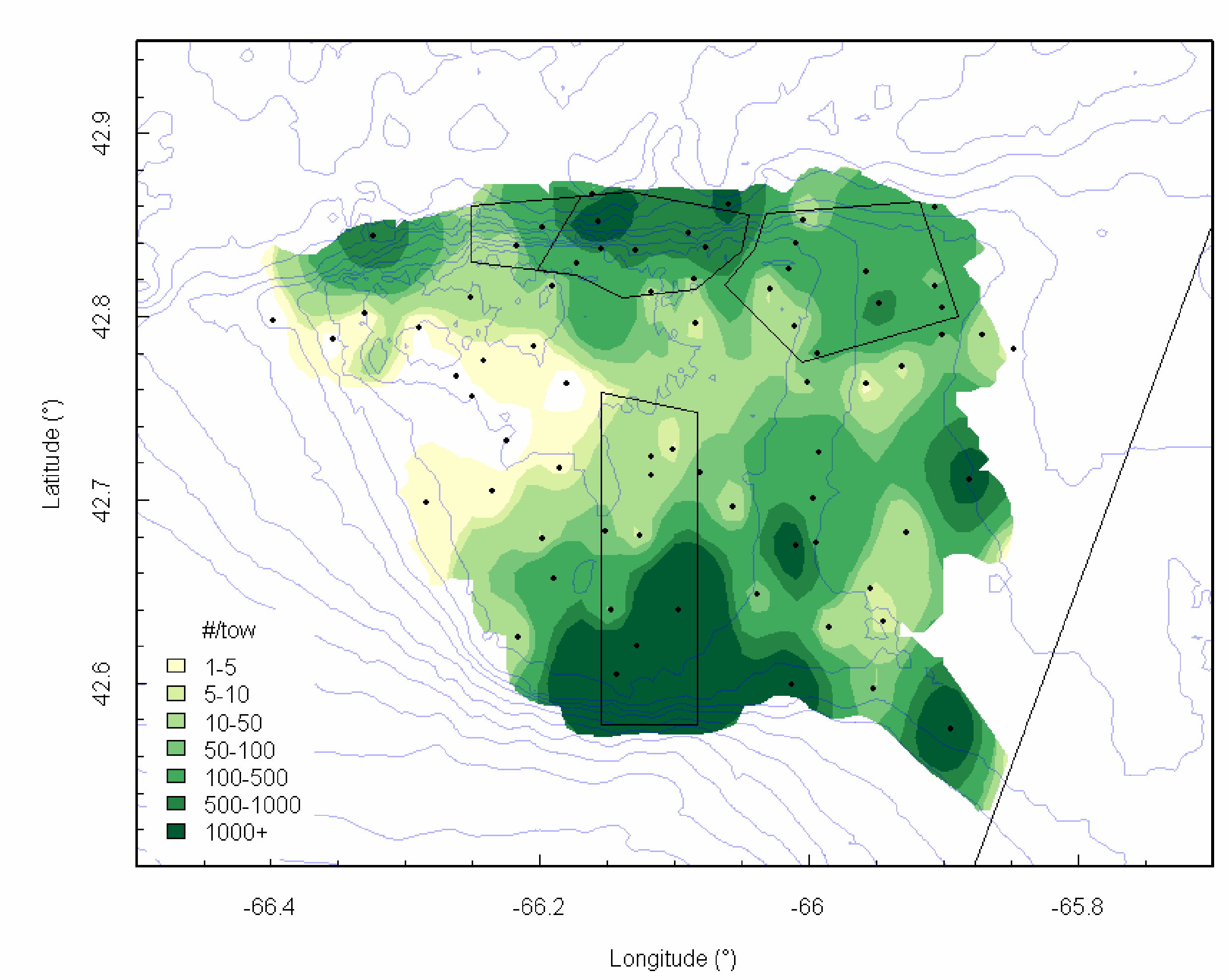

Figure 21. Distribution of pre-recruit (50 - 85 mm shell height) scallops from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

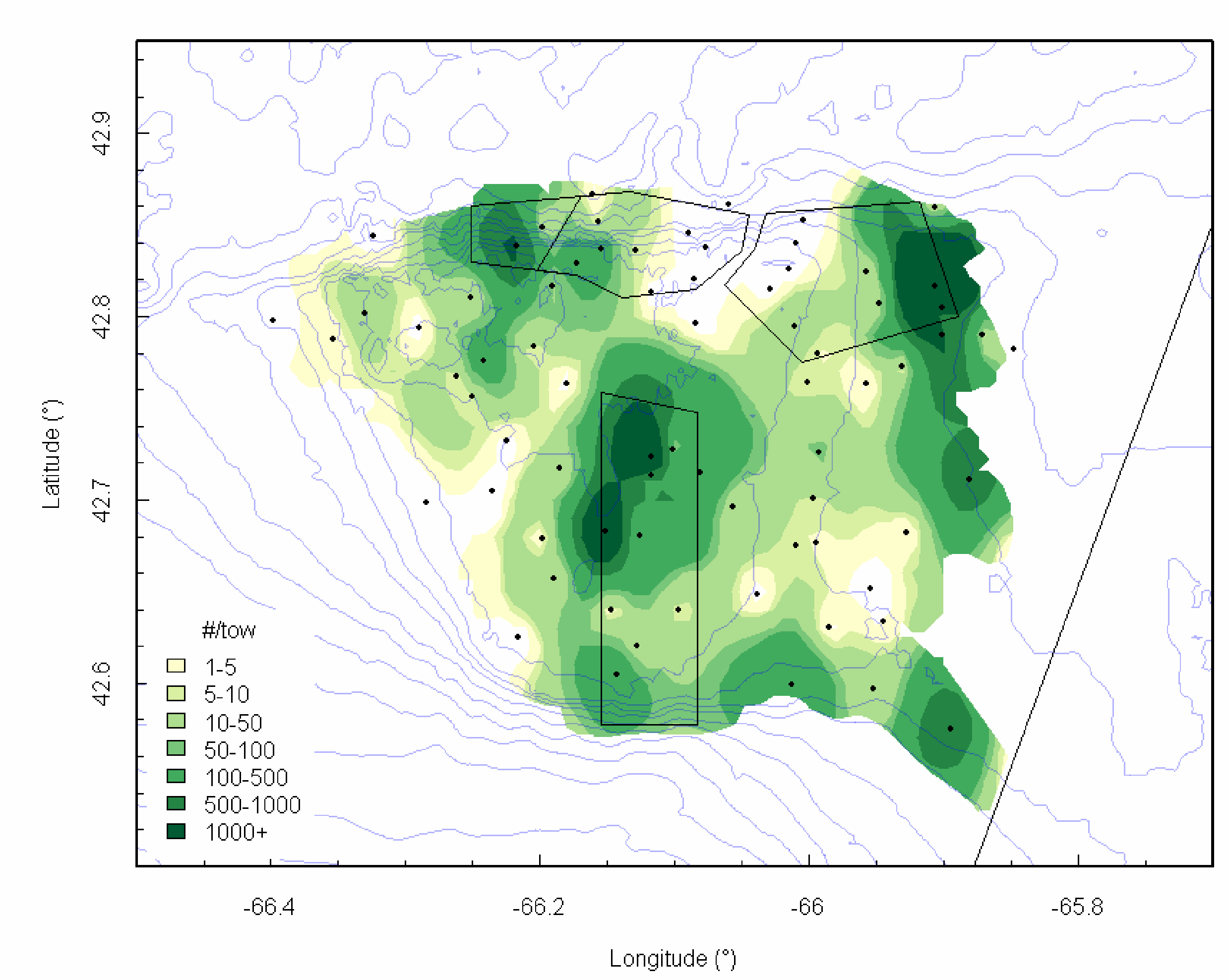

Figure 22. Distribution of pre-recruit (<50 mm shell height) scallops from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

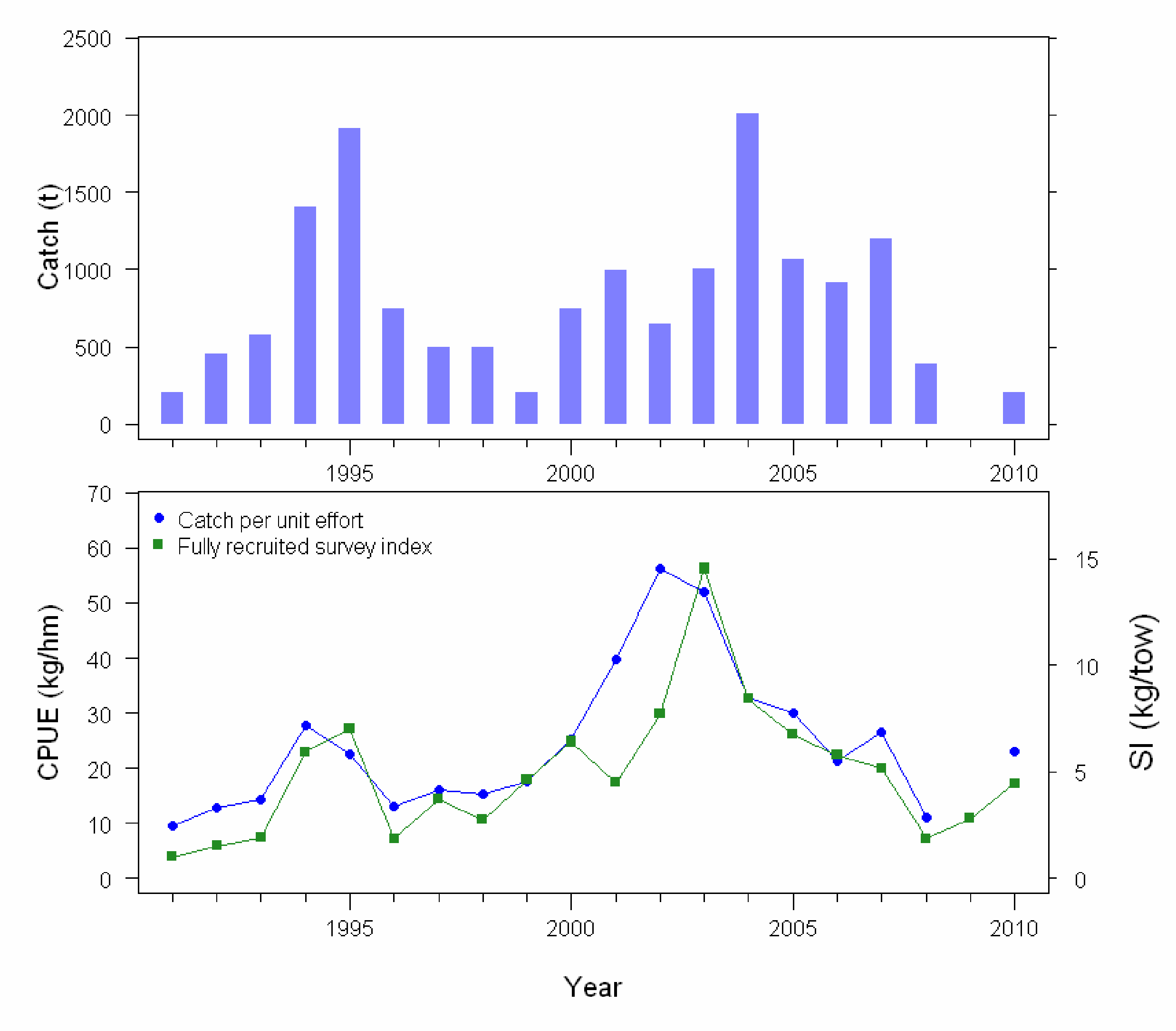

Figure 23. Summary of fishery inputs based on the calendar year (January – December). Upper panel shows landings in tons of meat (abductor muscle). Lower panel shows catch per unit effort (CPUE) against survey index of commercial size (fully recruited) scallops.

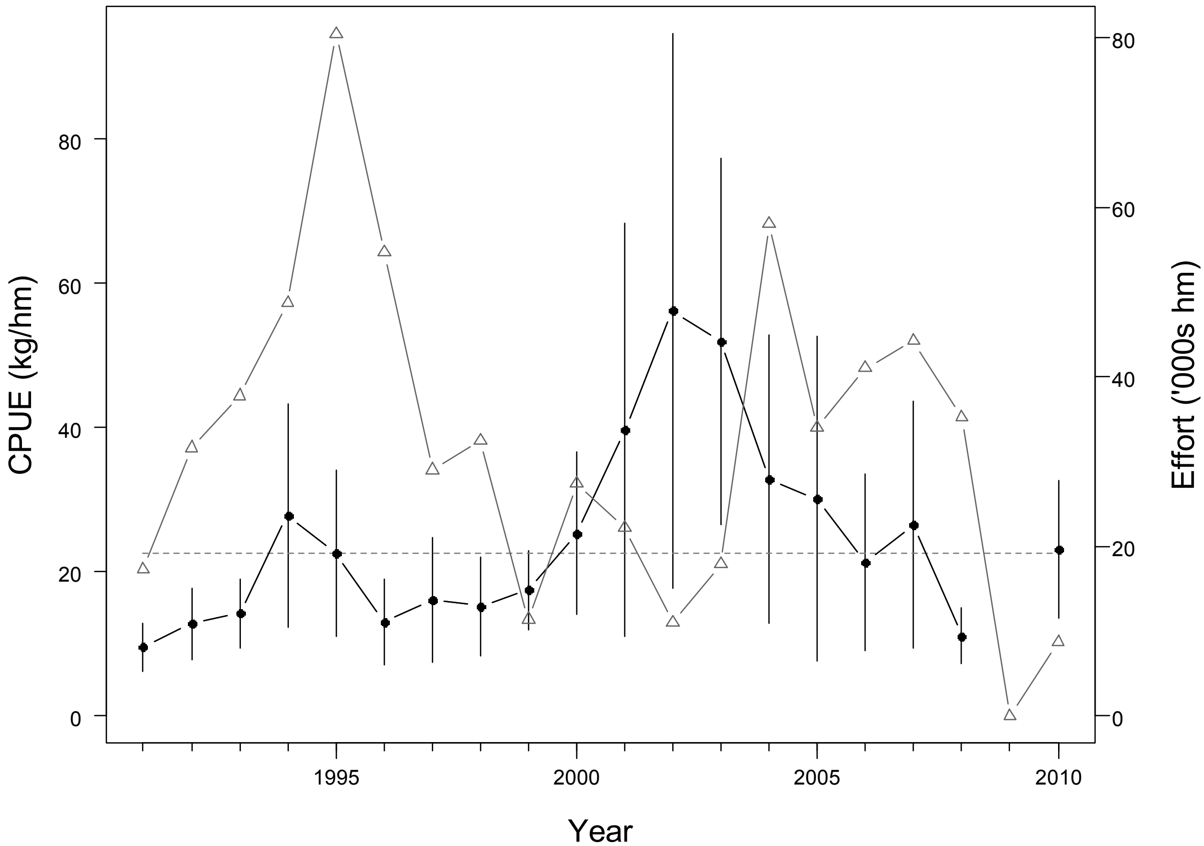

Figure 24. Catch per unit effort (●) and total effort (∆) for the scallop fishery on Browns Bank north during the calendar year (January – December). Vertical lines are ± one standard error from Jackknife estimates of CPUE.

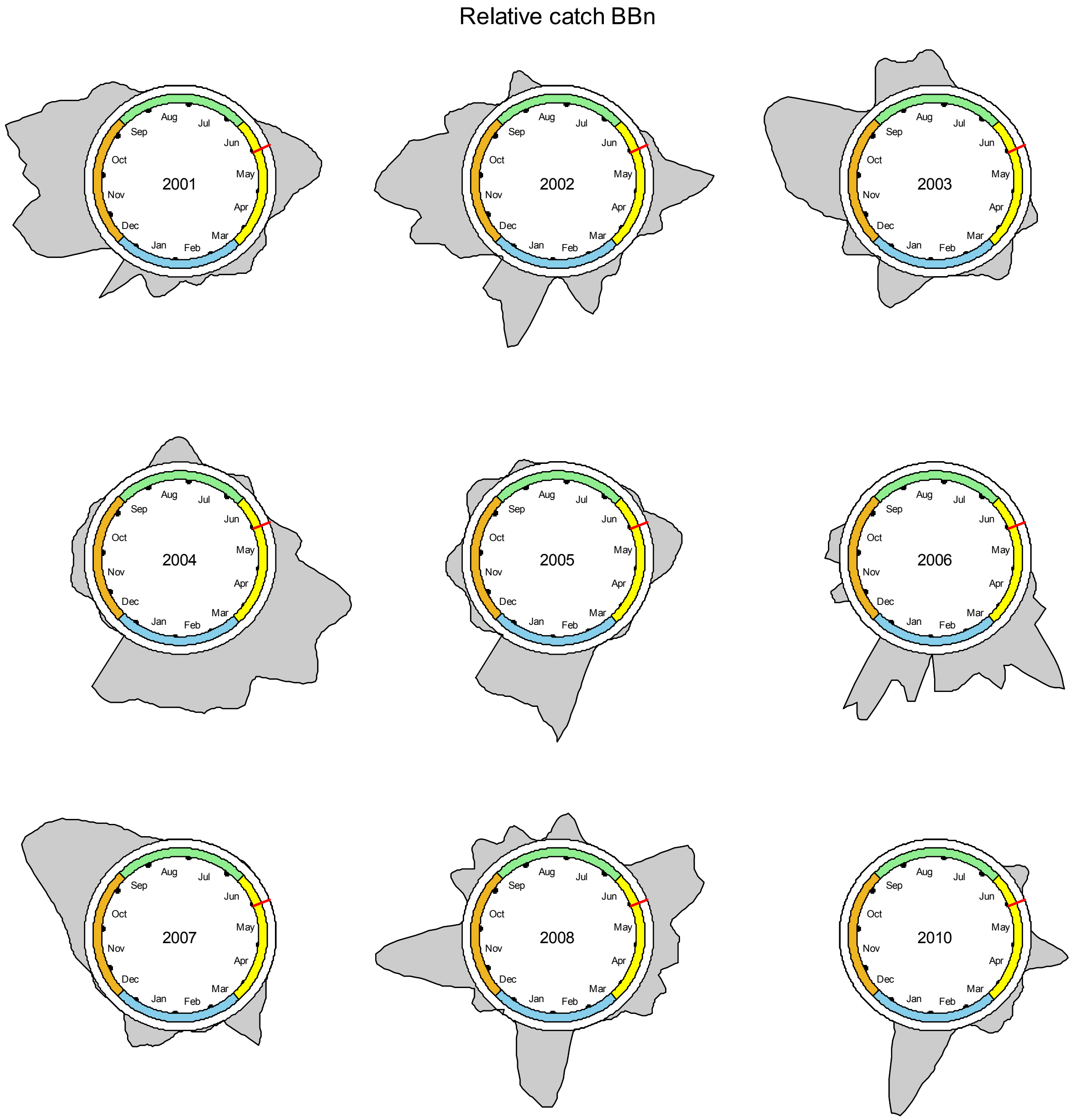

Figure 25. Seasonal variability in the scallop fishery on Browns Bank north. Grey densities represent the relative catch on a given day of the year. Colors represent the seasons: winter (blue), spring (yellow), summer (green) and fall (orange). The red line indicates the approximate timing of the survey.

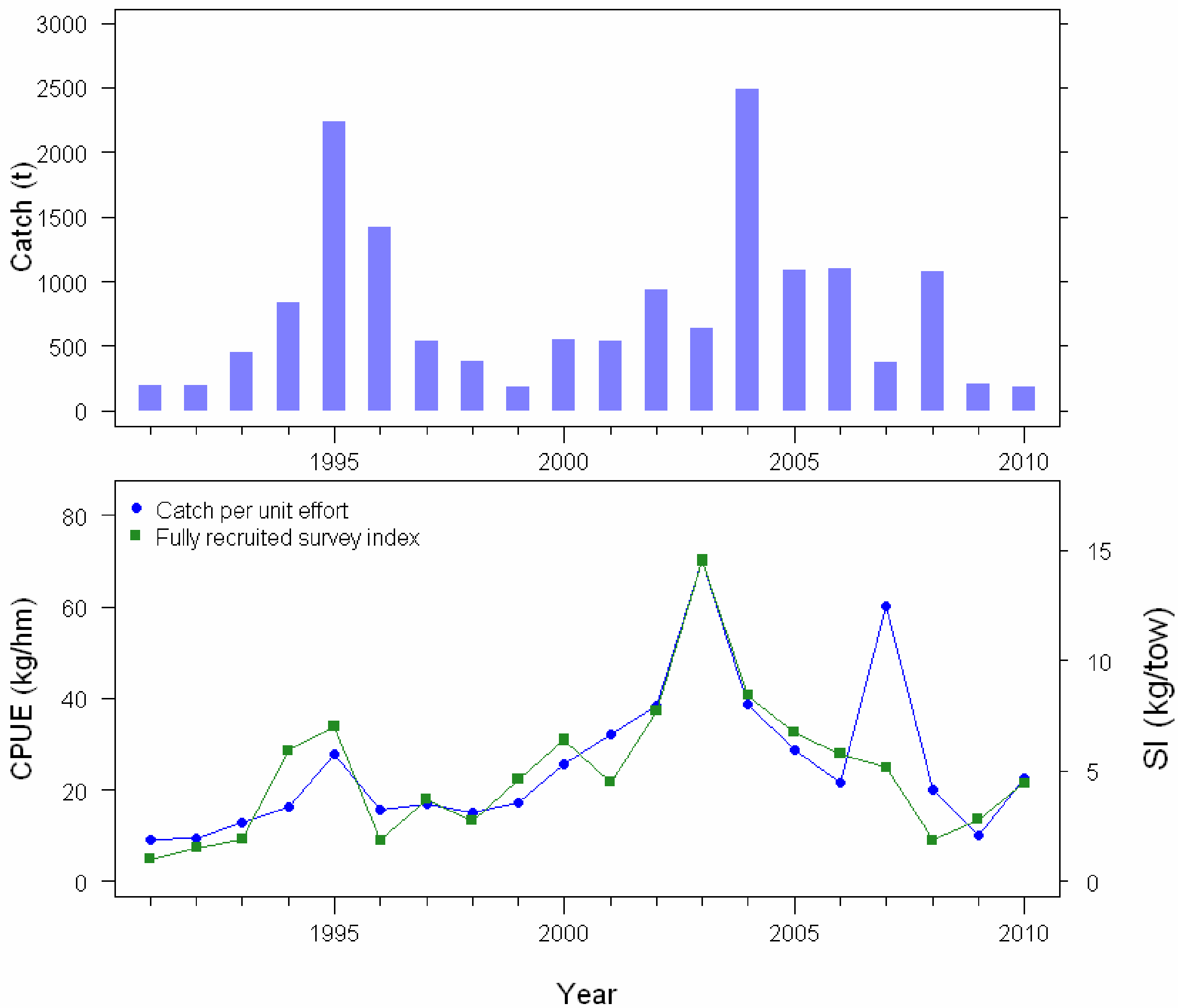

Figure 26. Summary of fishery inputs based on survey year (June – May). Upper panel shows landings in tons of meat (abductor muscle). Lower panel shows Catch per unit effort (CPUE) against survey index of commercial size (fully recruited) scallops.

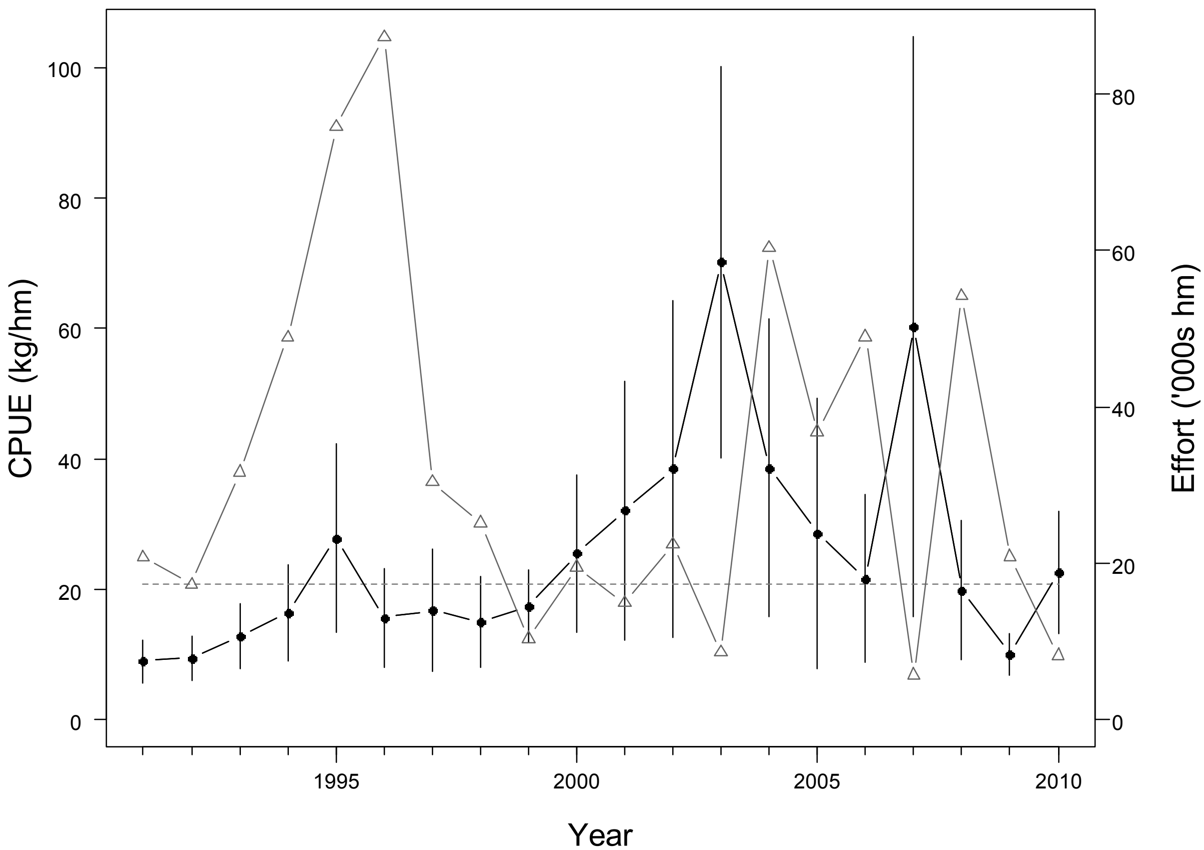

Figure 27. Catch per unit effort (●) and total effort (Δ) for the scallop fishery on Browns Bank North during the survey year (June to May). Vertical lines are ± one standard error from jackknife estimates of CPUE.

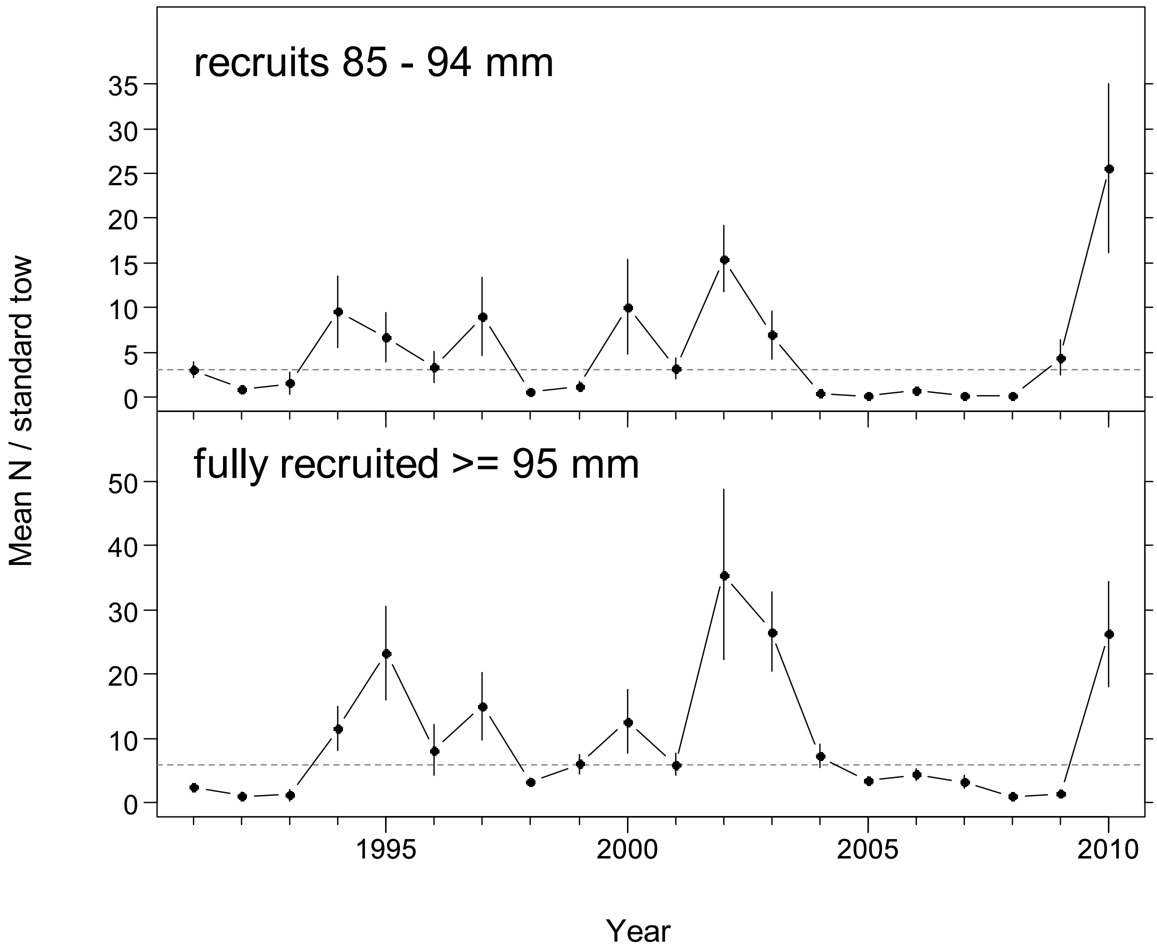

Figure 28. Stratified mean abundance per standard tow (800 m x 2.44 m drag) of dead (clappers) scallops from spring survey of Browns Bank north (1991-2010). Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error.

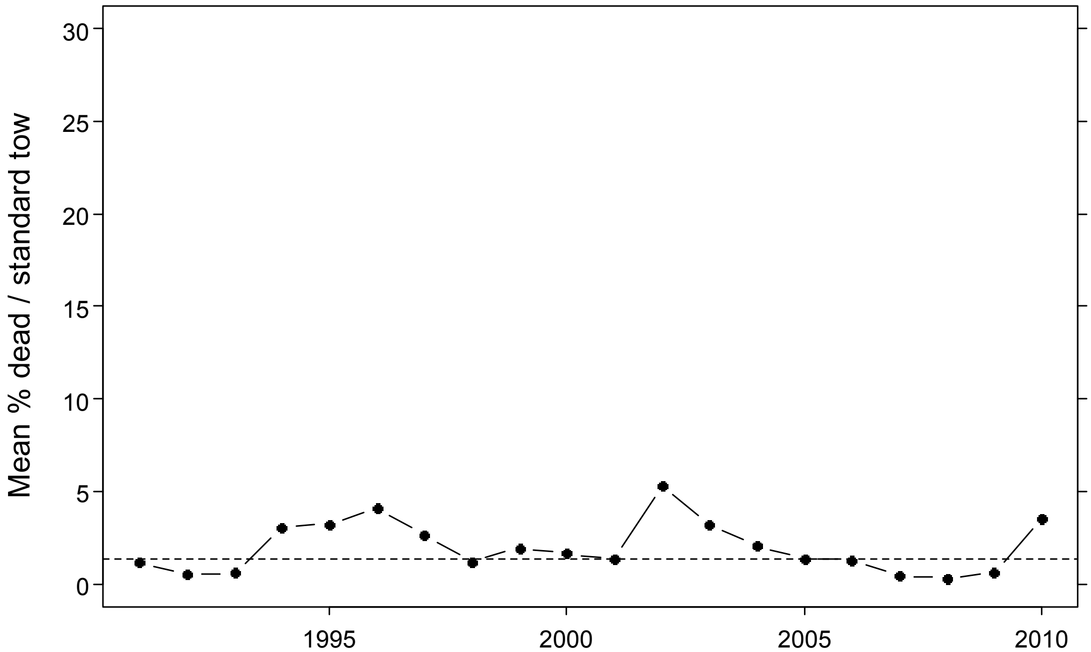

Figure 29. Mean percentage of dead scallops (clappers) per standard tow (800 m x 2.44 m drag) from spring survey of Browns Bank north (1991-2010).

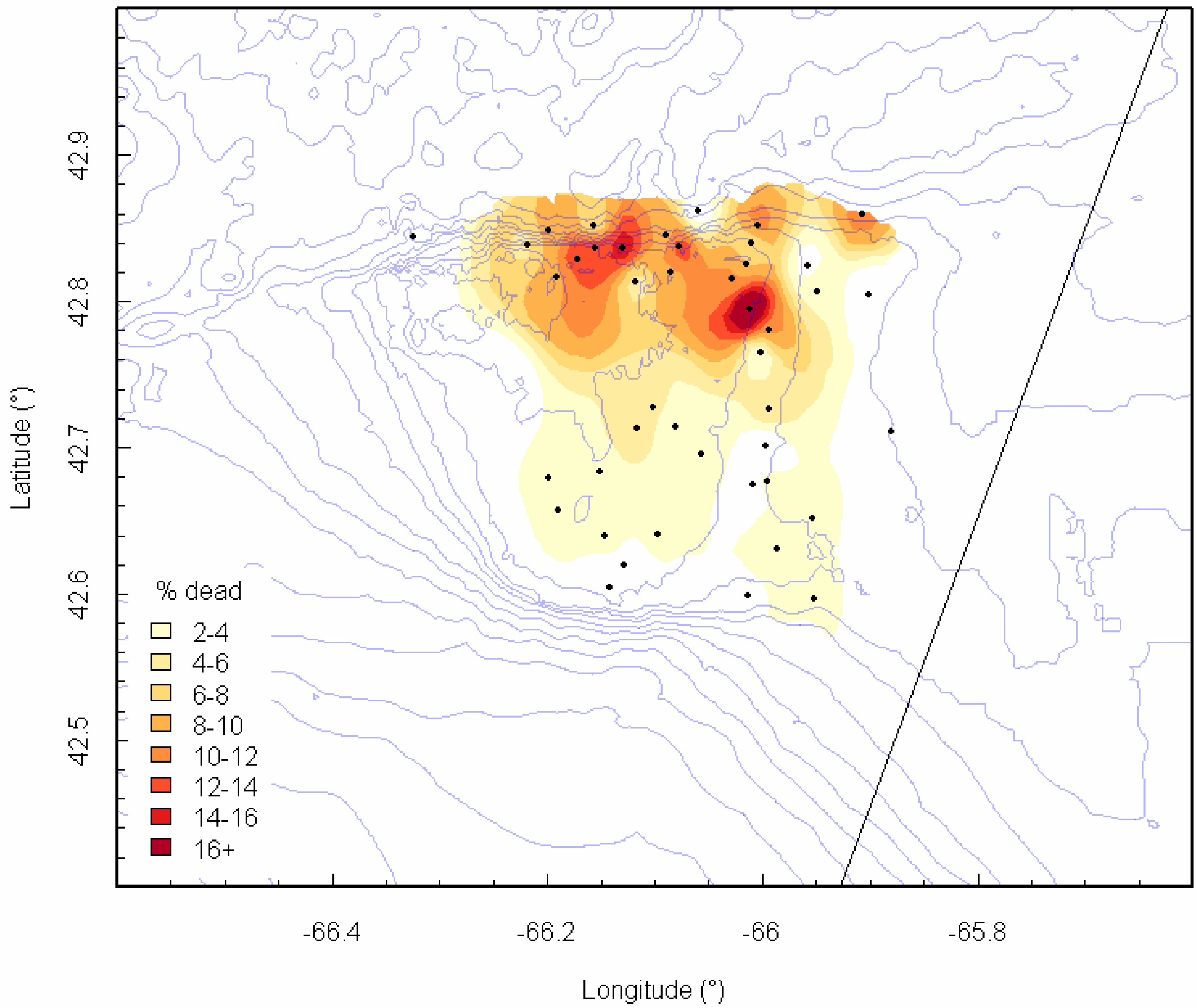

Figure 30. Distribution of dead scallops (clappers) from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used on the standardized number of clappers per tow divided by then total number of scallops (alive or dead) to produce a contoured color image. The key on the right shows the color associated with the percentage of dead scallops.

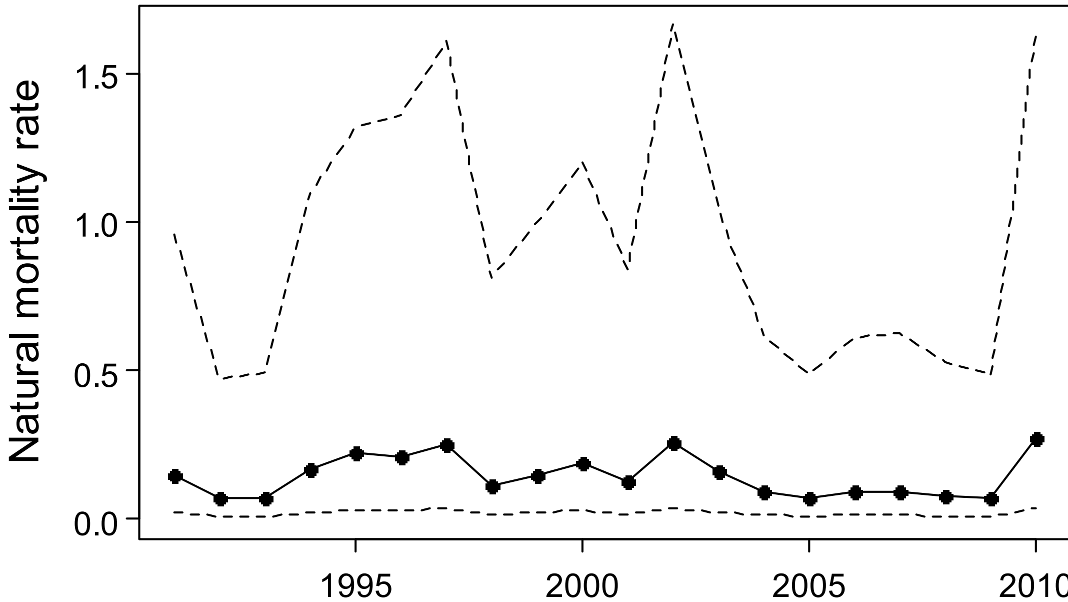

Figure 31. Natural mortality rate of fully-recruited scallops (≥95 mm shell height) estimated from the popcorn model with 95% credible limits (dashed lines).

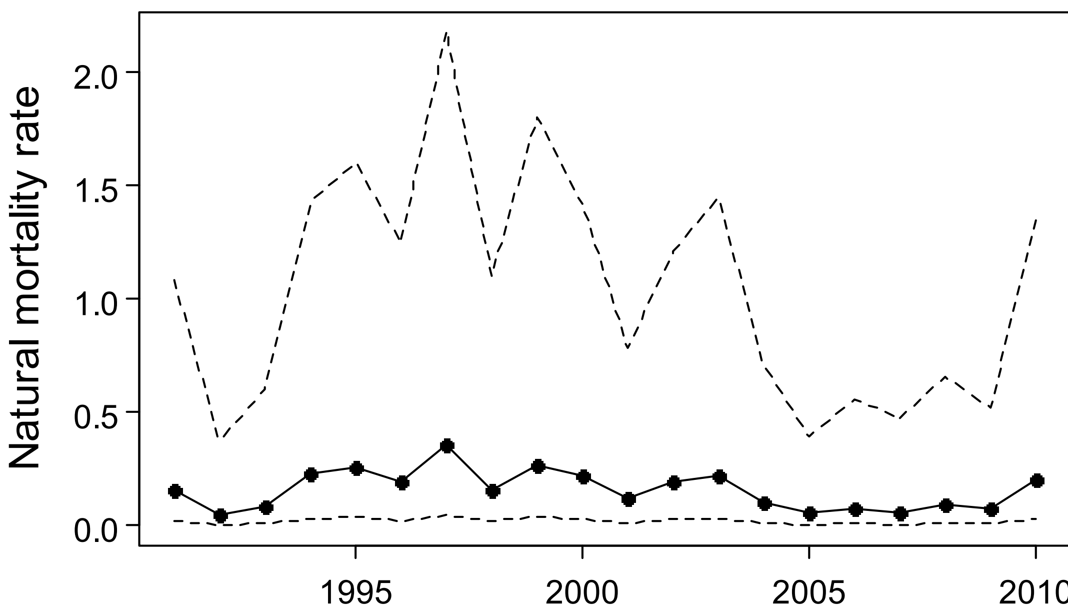

Figure 32. Natural mortality rate of recruit scallops (85 - 95 mm shell height) estimated from the popcorn model with 95% credible limits (dashed lines).

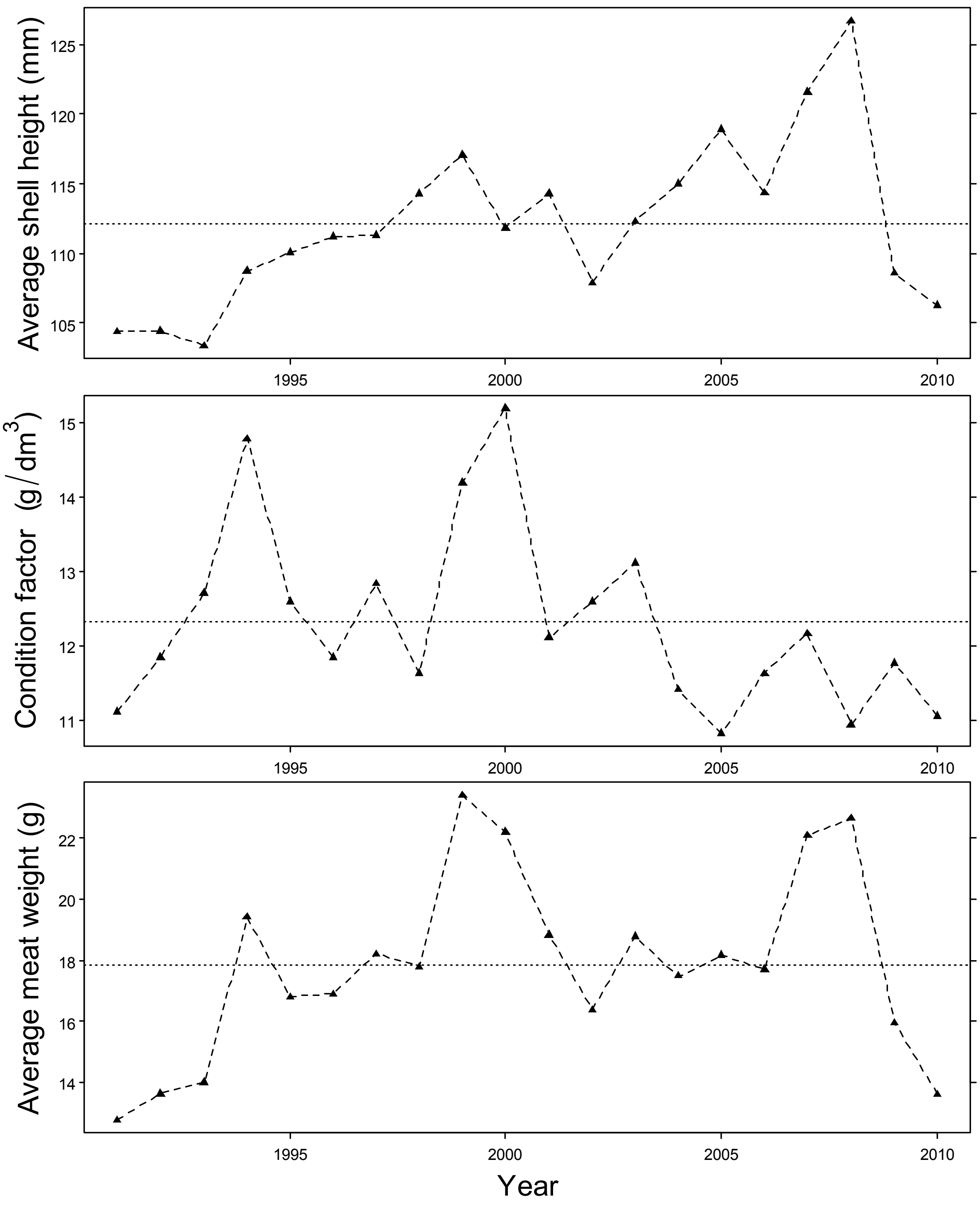

Figure 33. Annual variability in factors affecting scallop growth and yield. Average shell height (upper panel) represents the relative age of the stock and its growth potential. Condition (middle panel) is affected by environmental conditions and along with shell height determines the average meat weight (lower panel) which is directly related to the meat count. Horizontal dotted lines are the long-term medians

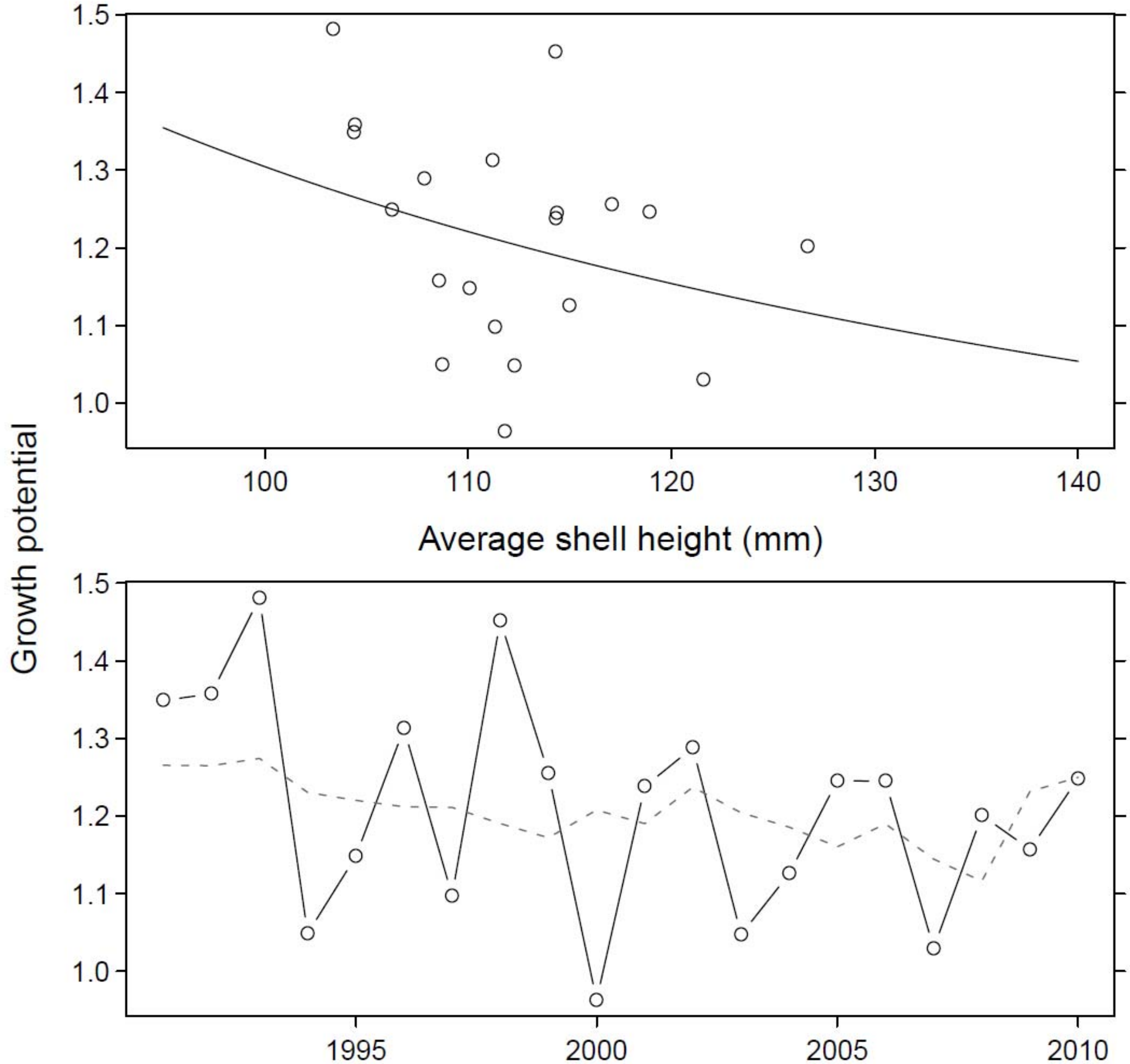

Figure 34. Top panel: Growth potential as a function of average scallop shell height comparing the theoretical relationship where variability in condition factor has not been included (—) to the observed relationship where condition factor has been accounted for (○). Bottom panel: Growth potential as a function over time comparing the theoretical relationship where variability in condition factor has not been included (- - -) to the observed relationship where condition factor has been accounted for (-○-).

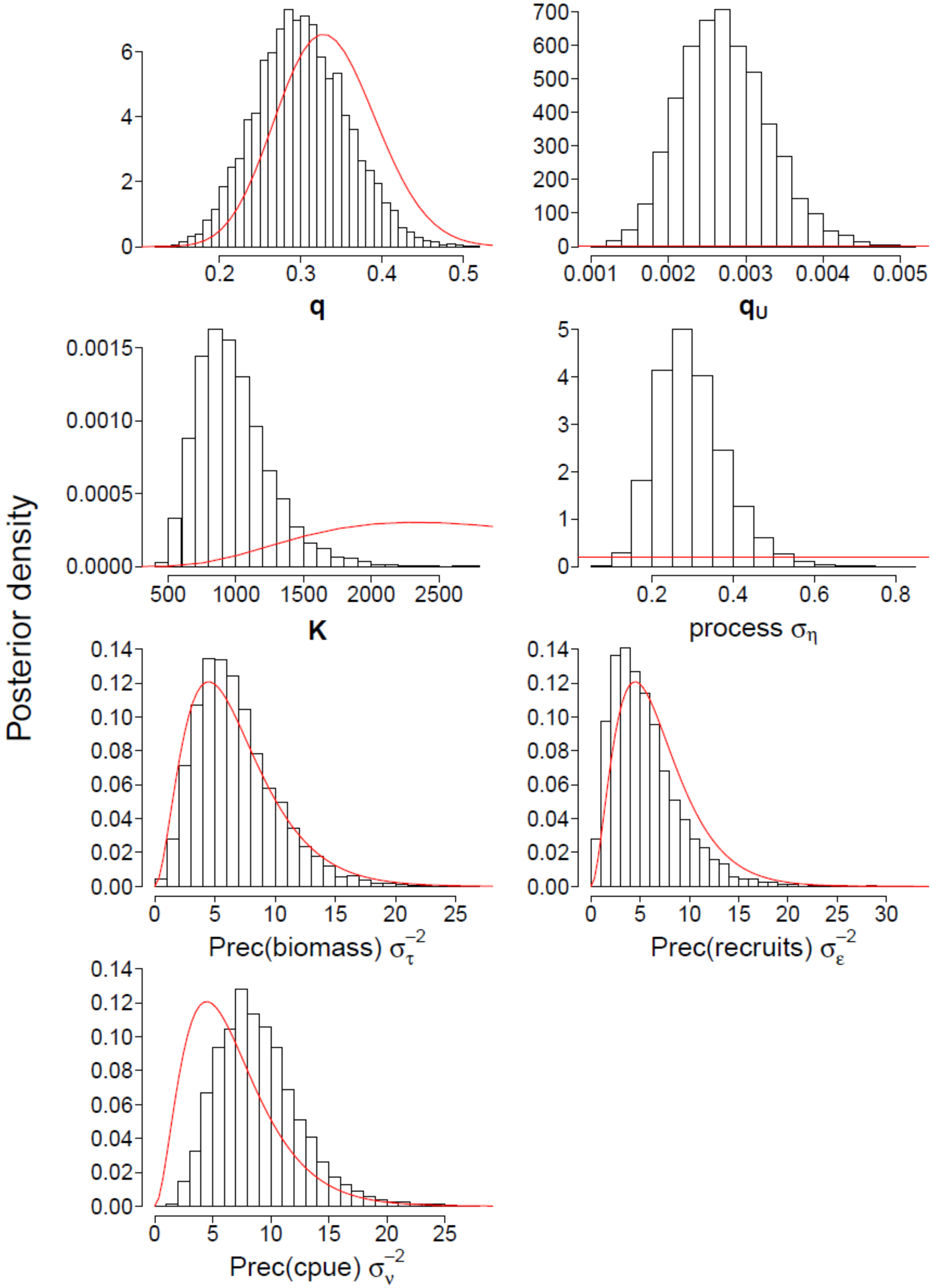

Figure 35. Posterior distributions for proportionality coefficients (q), K, and process and observation error terms in the delay-difference model. Solid red lines show the prior densities.

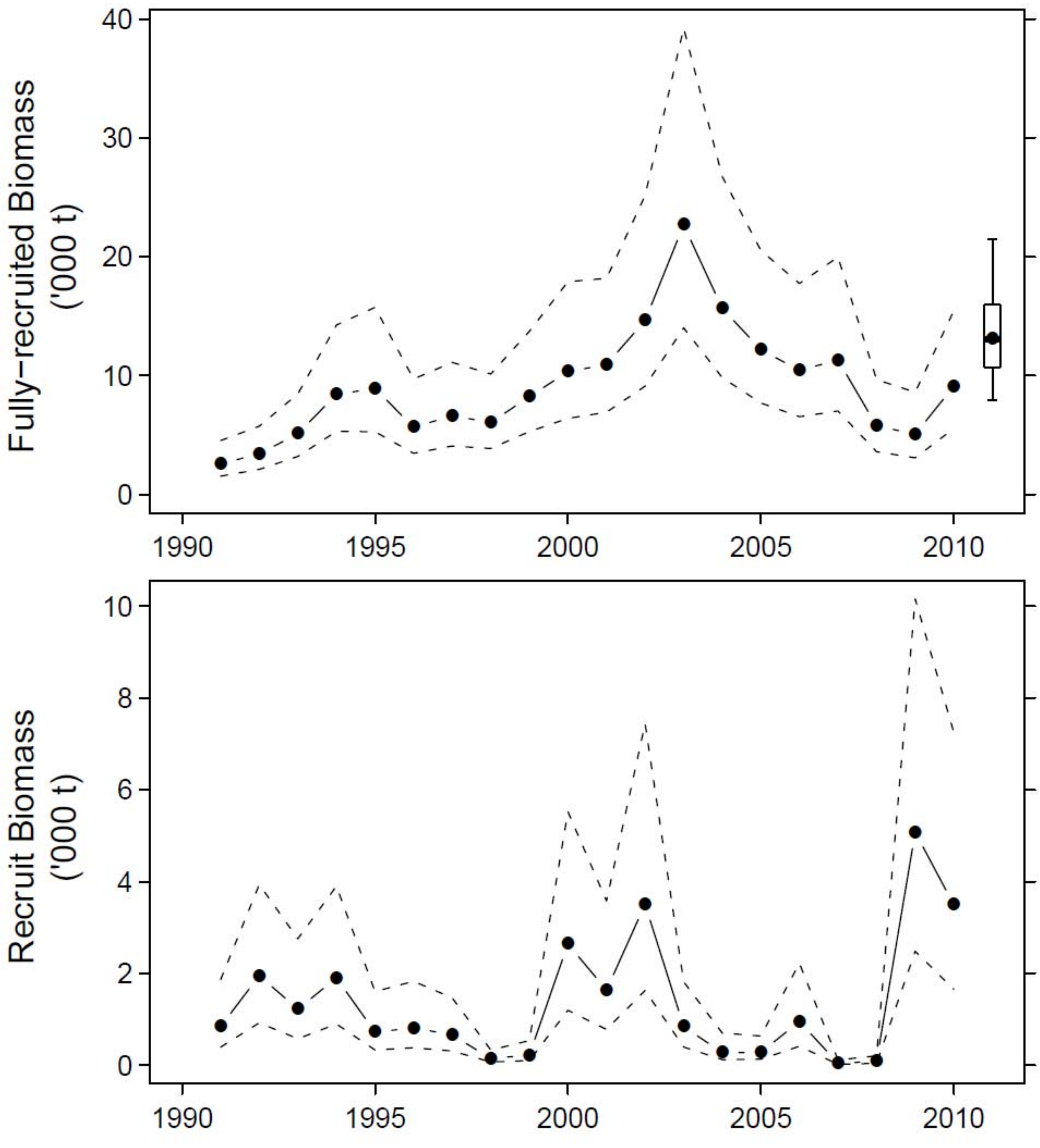

Figure 36. Biomass estimates for fully-recruited scallops and recruits from the delay-difference model. Dashed lines are the upper and lower 95% credible limits. The forecasted fully recruited biomass for 2011, assuming a catch of 500 t, is displayed as a box plot with median (●), 50% credible limits (box) and 80% credible limits (whiskers).

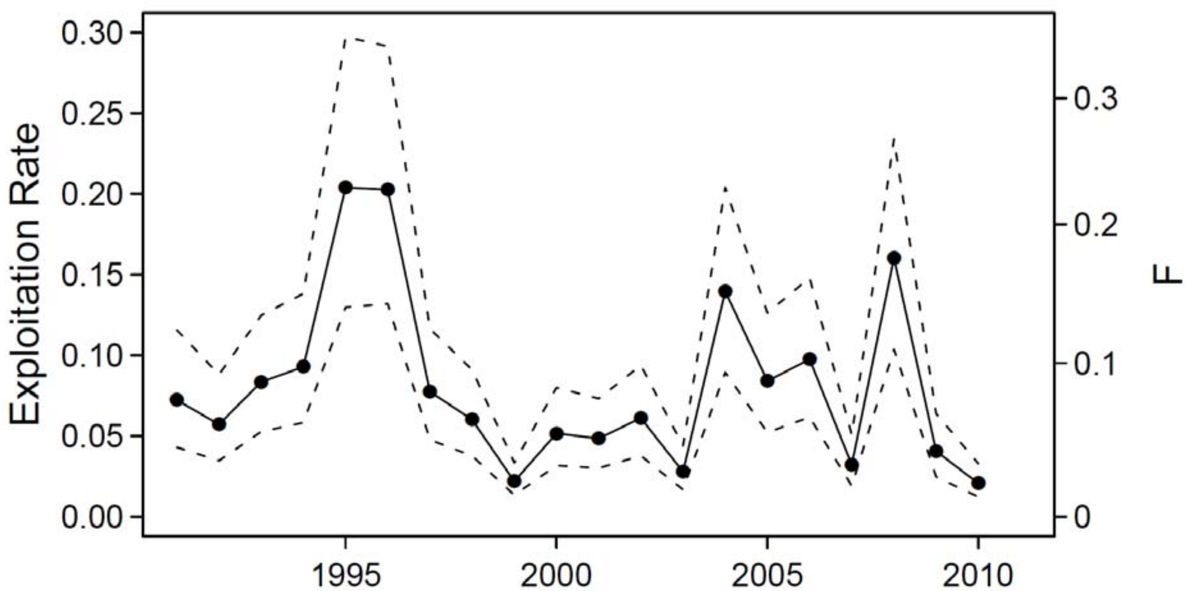

Figure 37. Estimated exploitation rates and instantaneous fishing mortality (F) from the delay-difference model. Dashed lines are the upper and lower 95% credible limits.

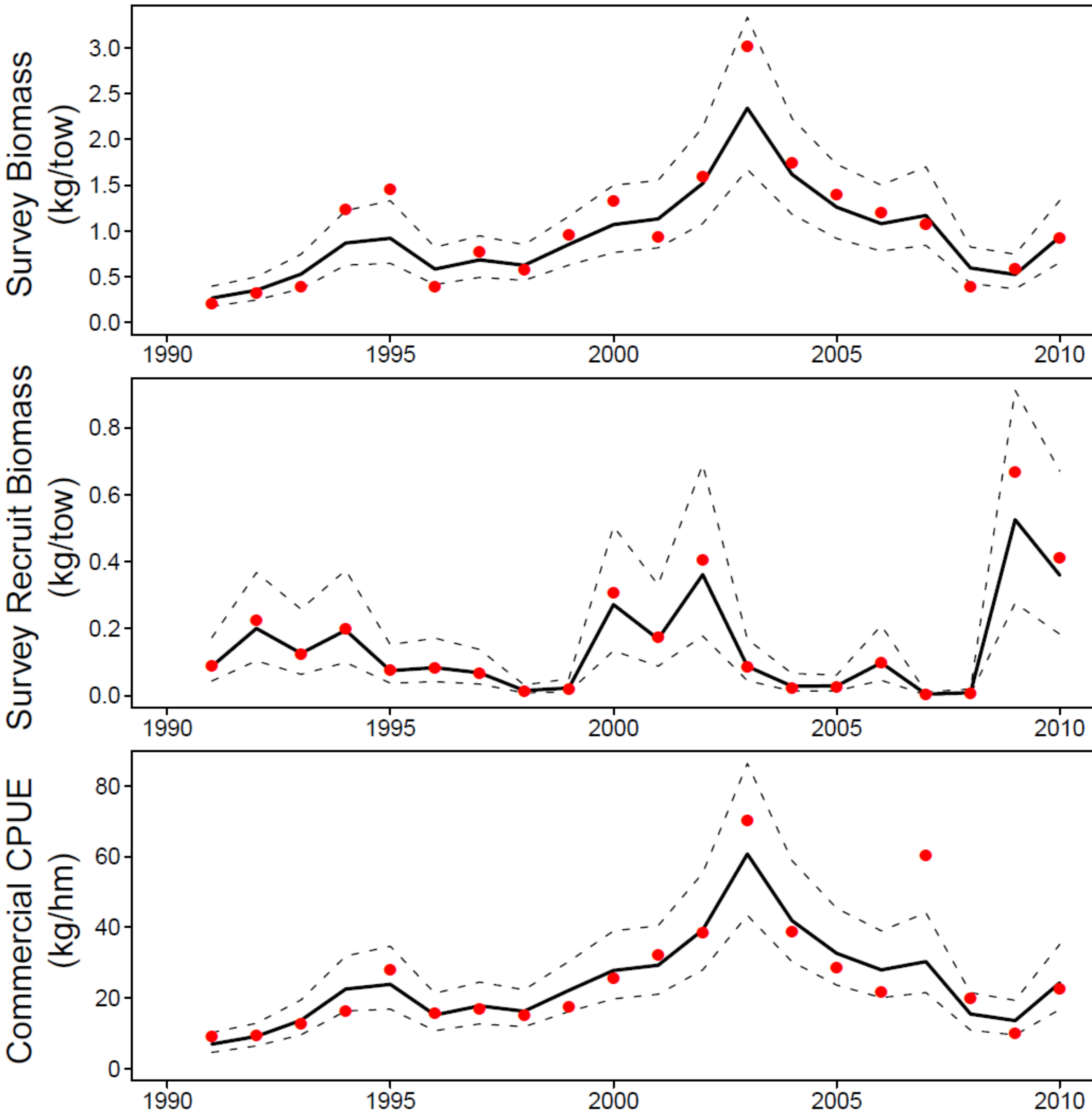

Figure 38. Fit of the delay-difference model estimates with 95% credible limits to observed biomass indices (●).

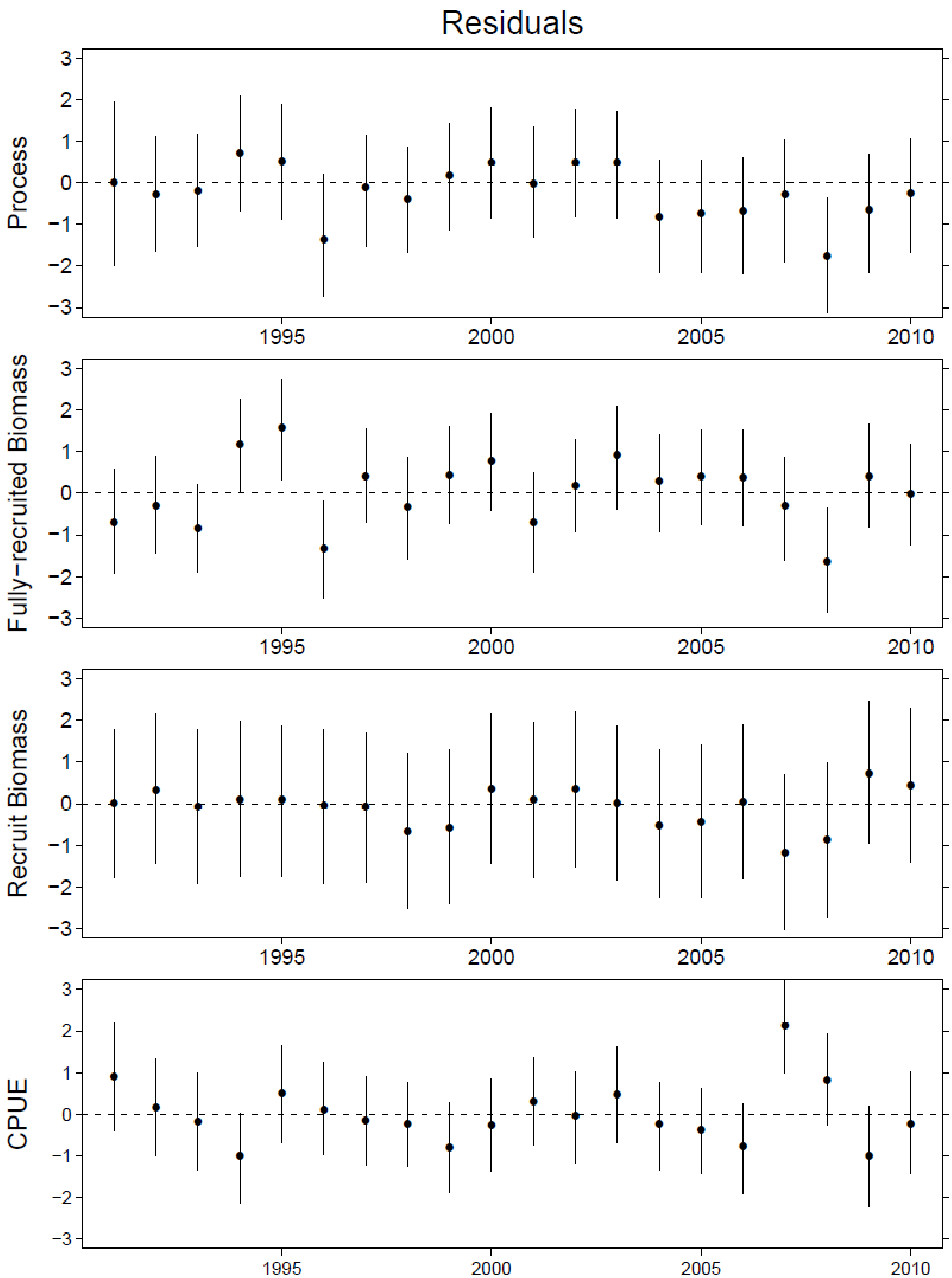

Figure 39. Standardized residuals with 95% credible limits (vertical lines) for process and observation errors.

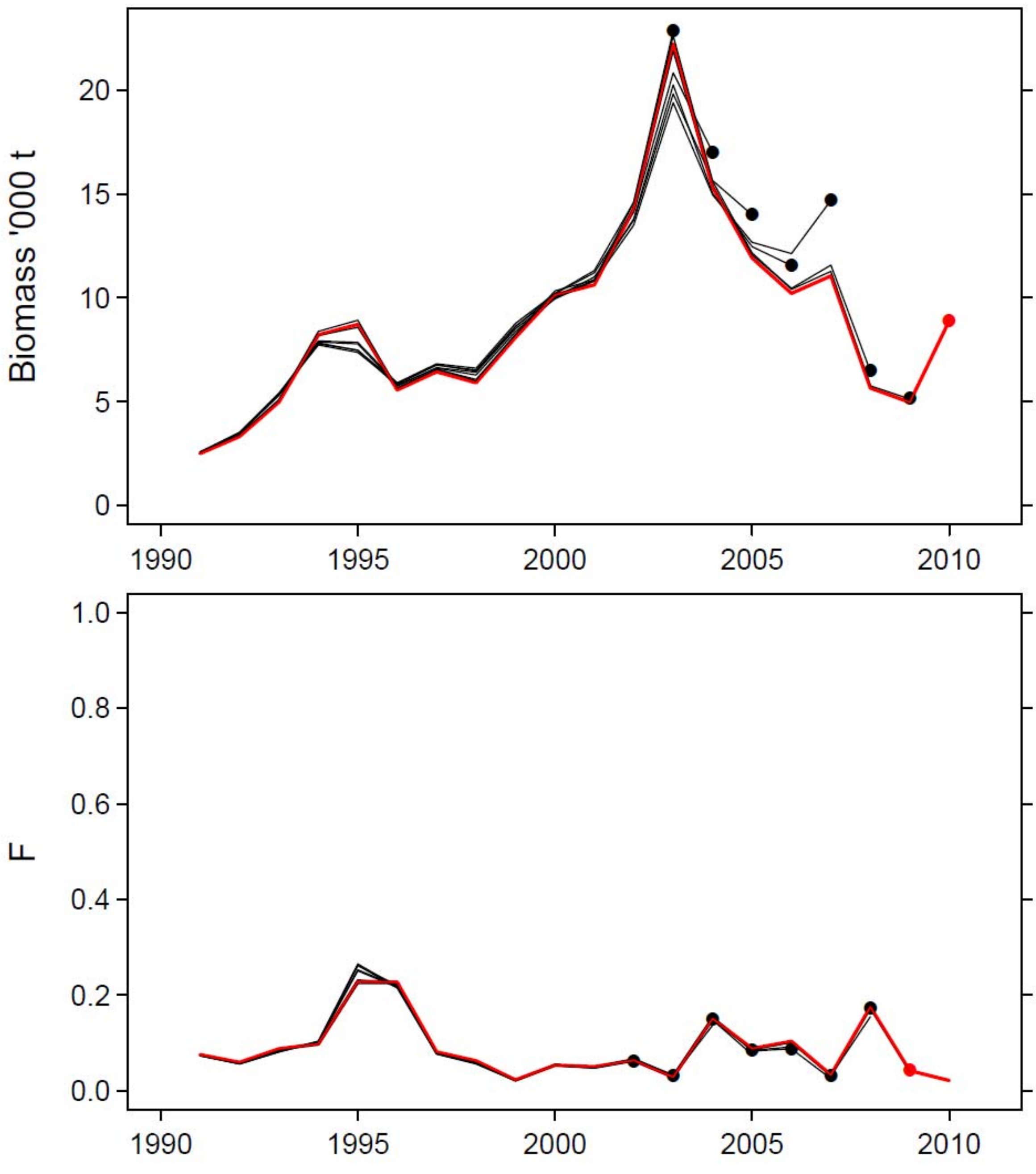

Figure 40. Retrospective plots for biomass estimates (upper panel) and fishing mortality (lower panel) from fits of the delay-difference model using time series up to 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009 or 2010. The red lines display the fit to the full time series.

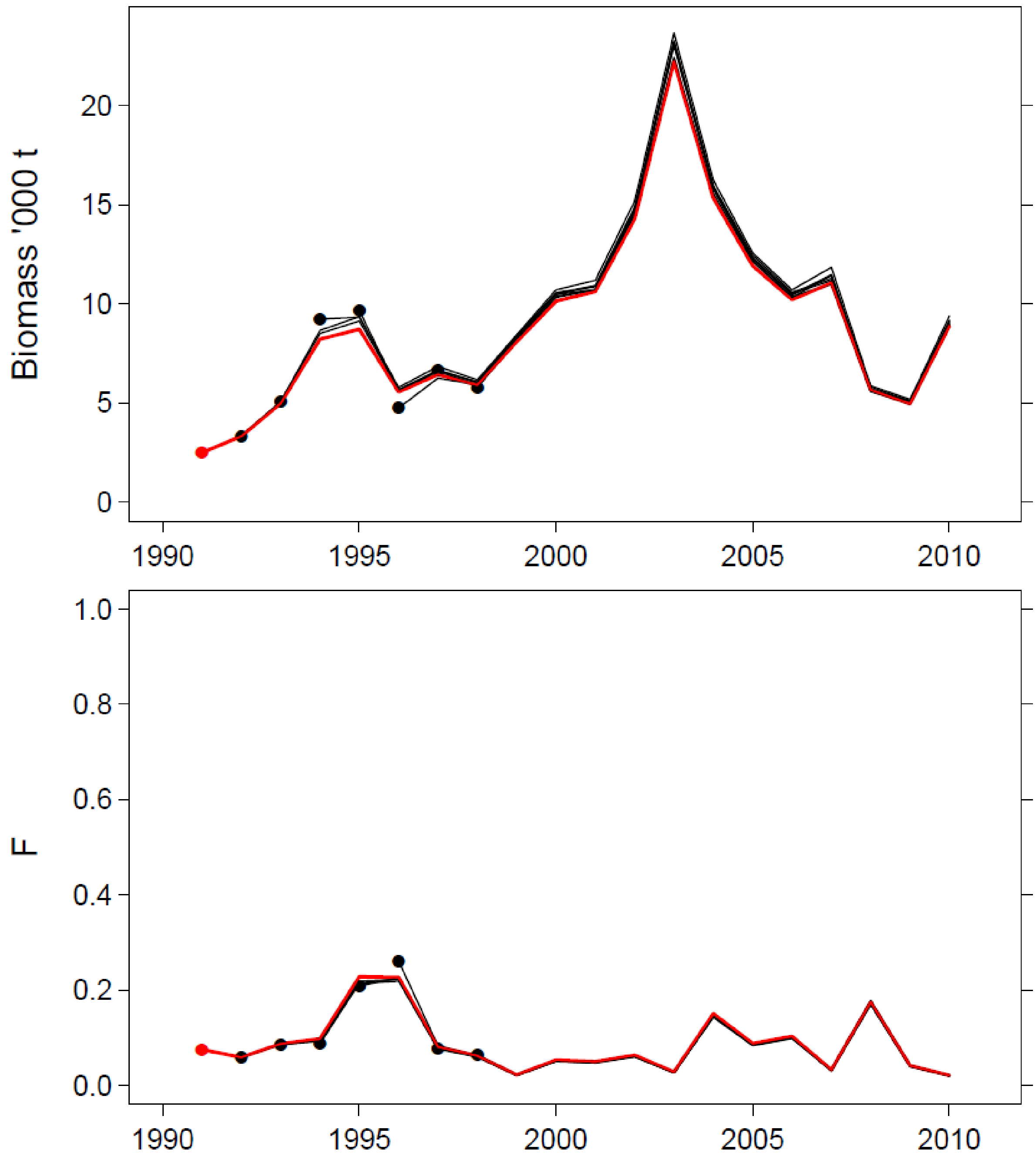

Figure 41. Prospective plots for biomass estimates (upper panel) and fishing mortality (lower panel) from fits of the delay-difference model using time series beginning in 1991, 1992, 1993, 1994, 1995, 1996, 1997 or 1998. The red lines display the fit to the full time series.

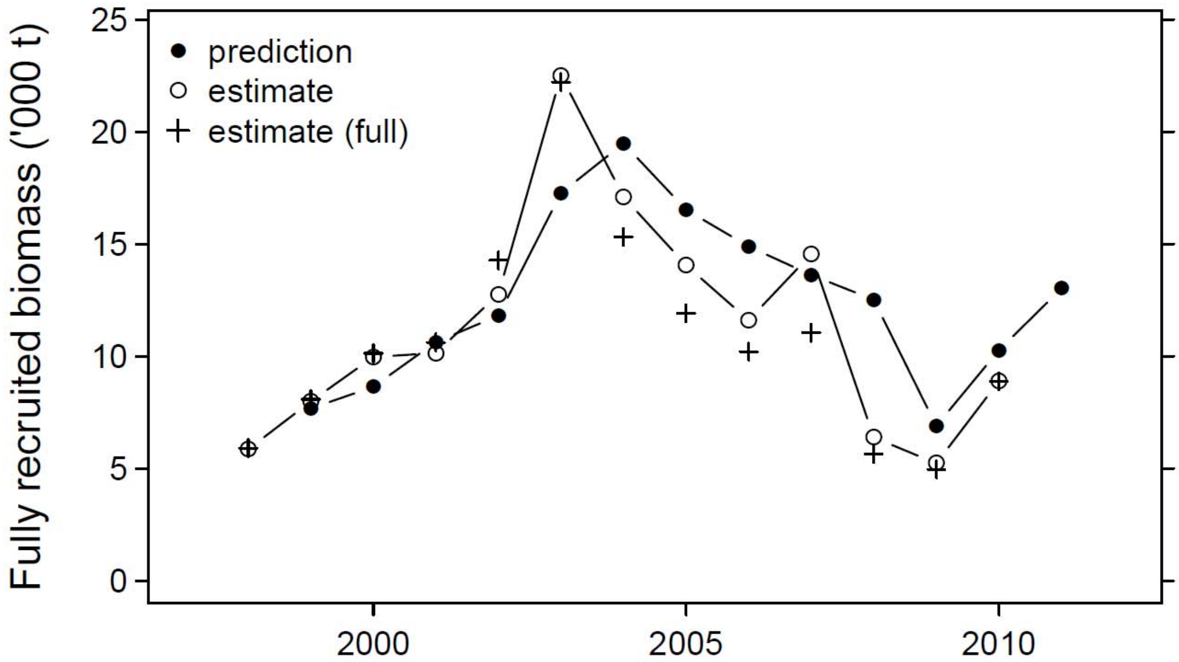

Figure 42. Comparison of predicted and estimated biomass from the delay-difference model. Biomass estimates using data only up to each year and the full time series (+) are presented.

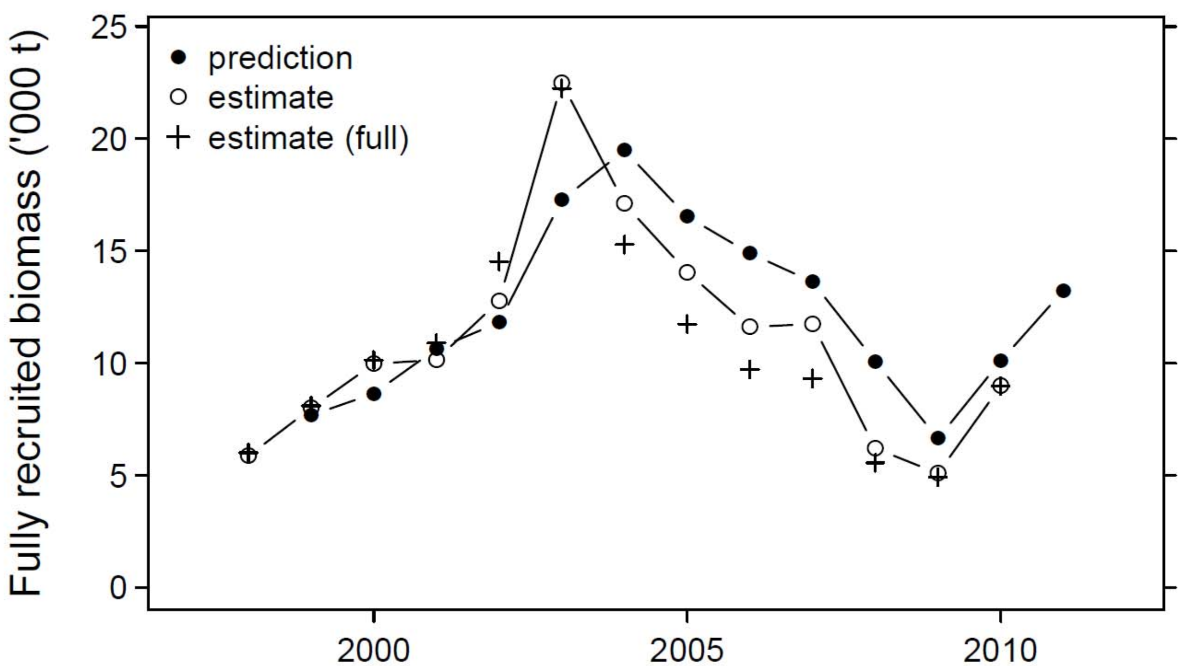

Figure 43. Comparison of predicted and estimated biomass from the delay-difference model. Biomass estimates using data only up to each year and the full time series (+) are presented.

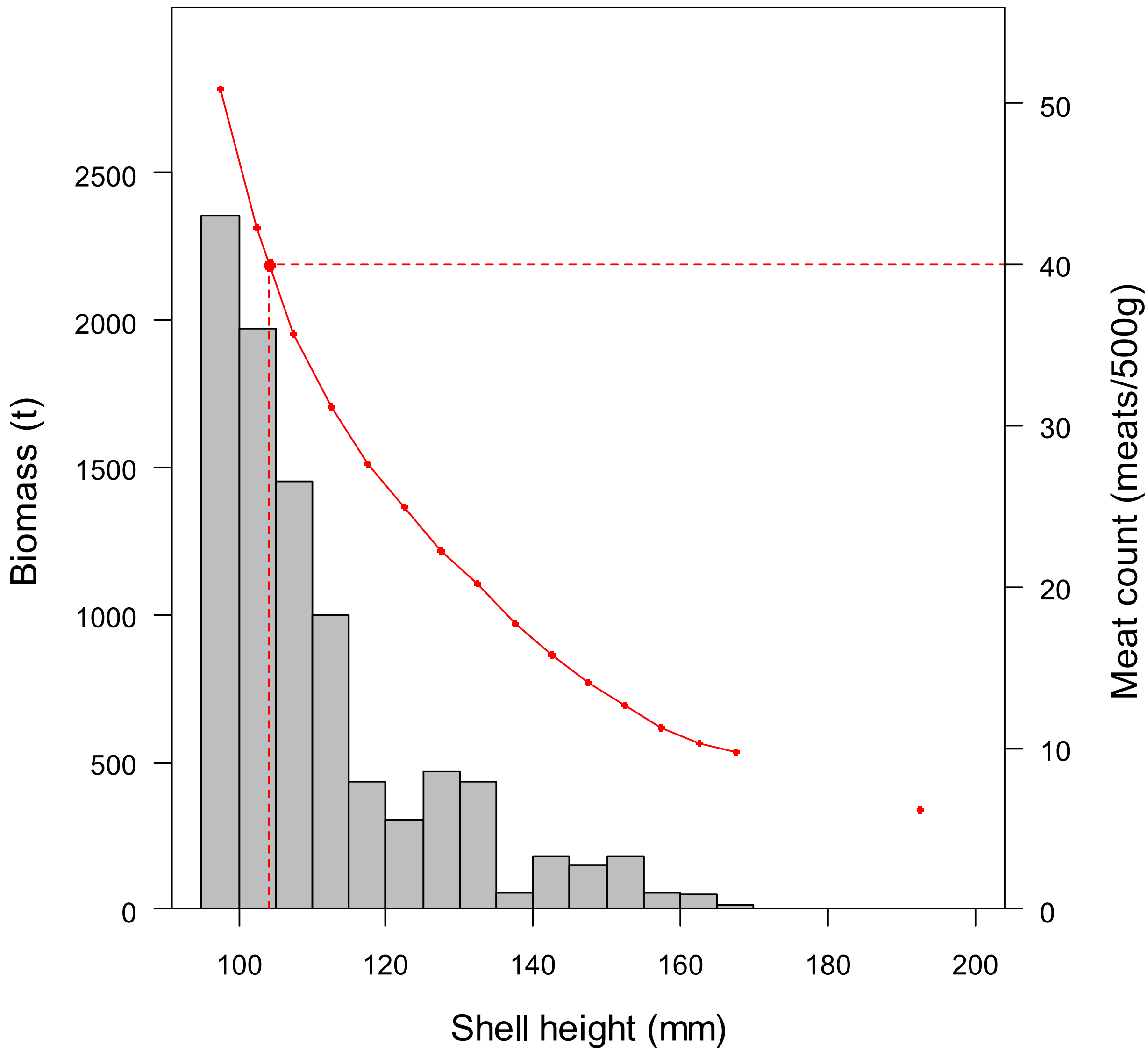

Figure 44. Breakdown of 2010 fully-recruited biomass by shell height. The solid red line is the observed meat count at shell height in the May survey. The dashed red line indicates what portion of the fully-recruited biomass is likely over the meat count.

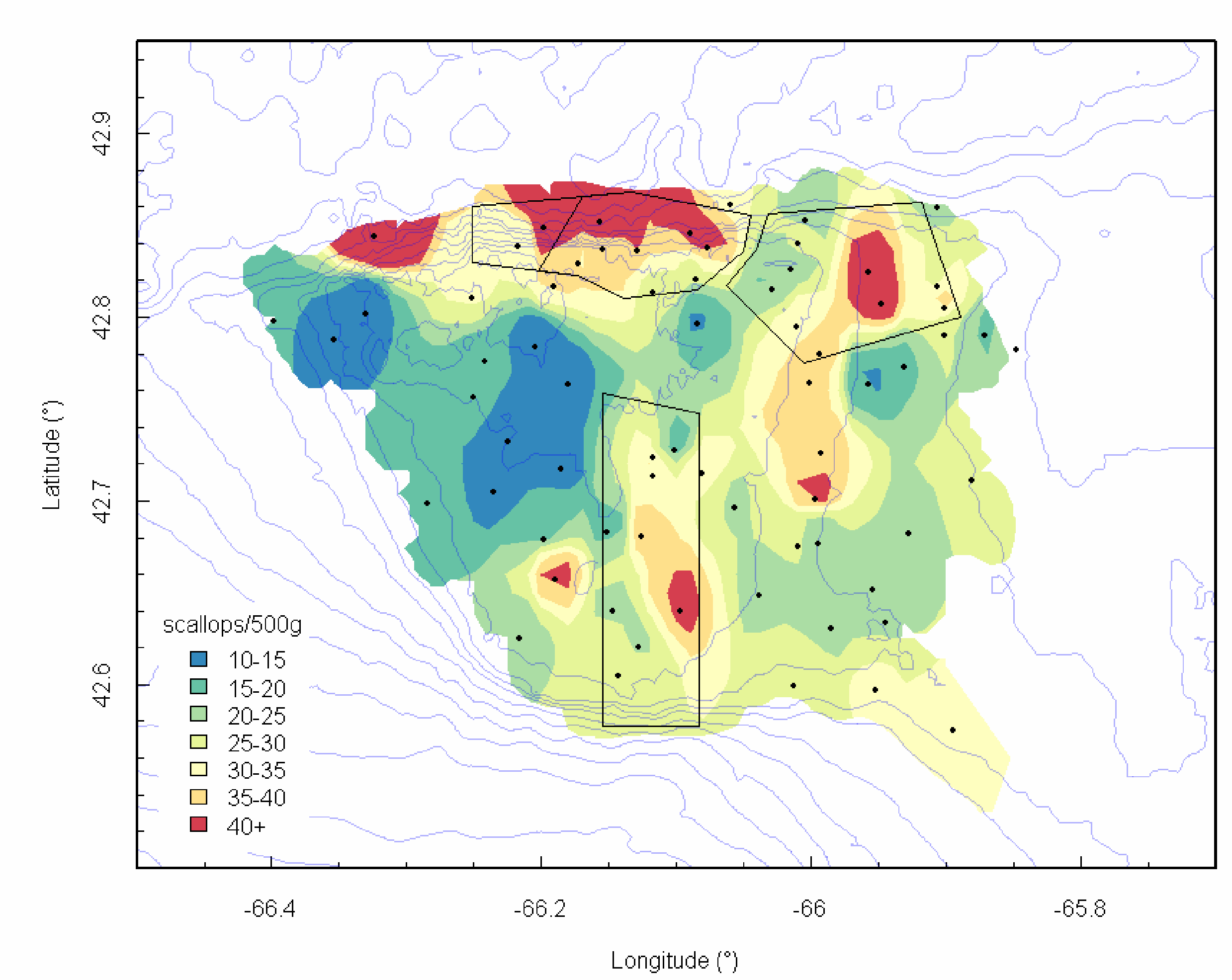

Figure 45. Estimated meat count of fully-recruited (>95 mm shell height) scallops from the survey of Browns Bank north May 2010. Inverse distance weighted interpolation was used with the average meat weight of fully-recruited scallops for each tow to produce a contoured color image. Recent industry managed closure areas are provided for spatial reference only.

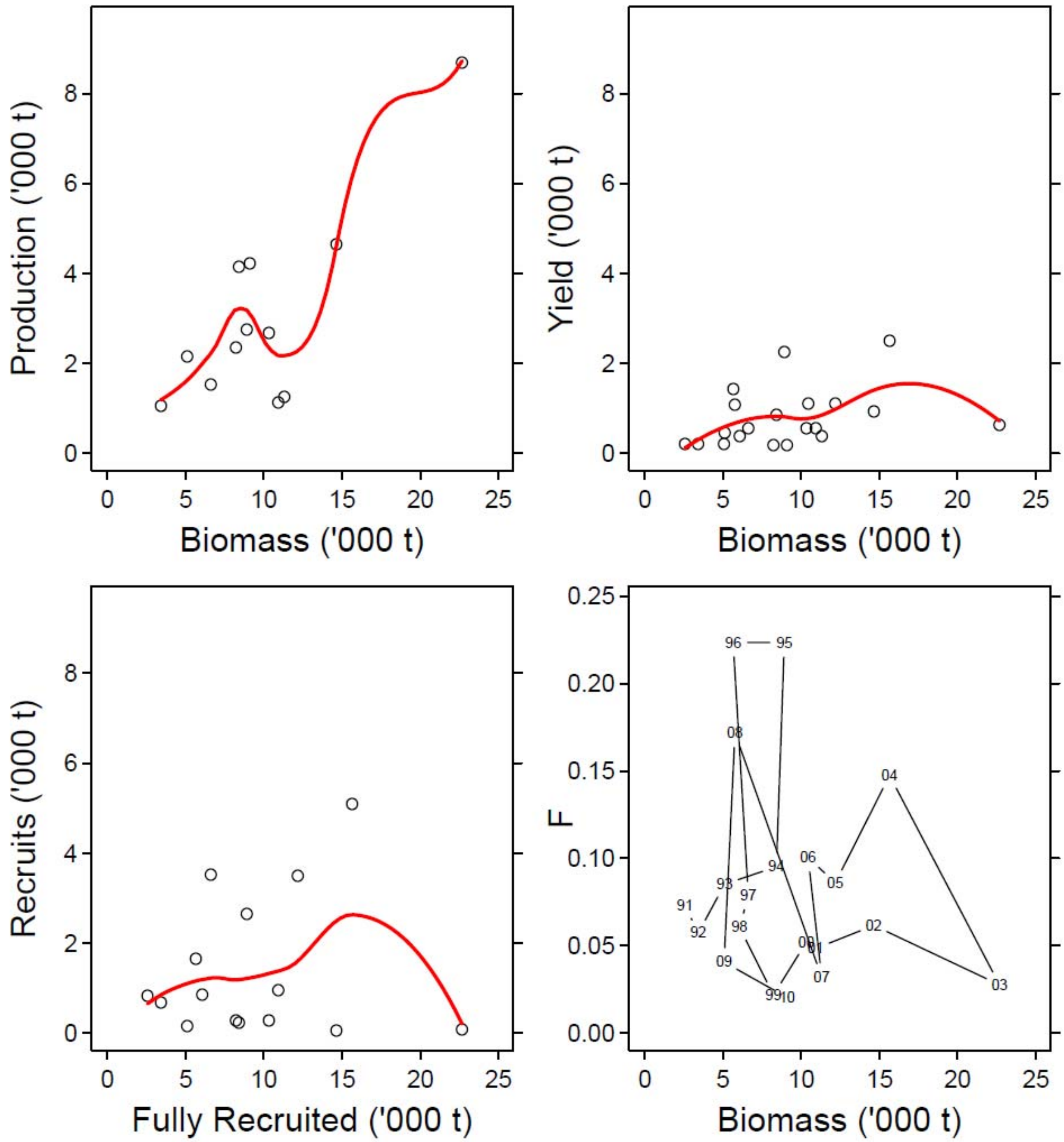

Figure 46. Production (topleft), Yield (topright), Spawner-Recruit (bottom left) and fishery phase (bottom right) plots. The red lines are nonparametric loess smoothes through the data with a span of 0.9.

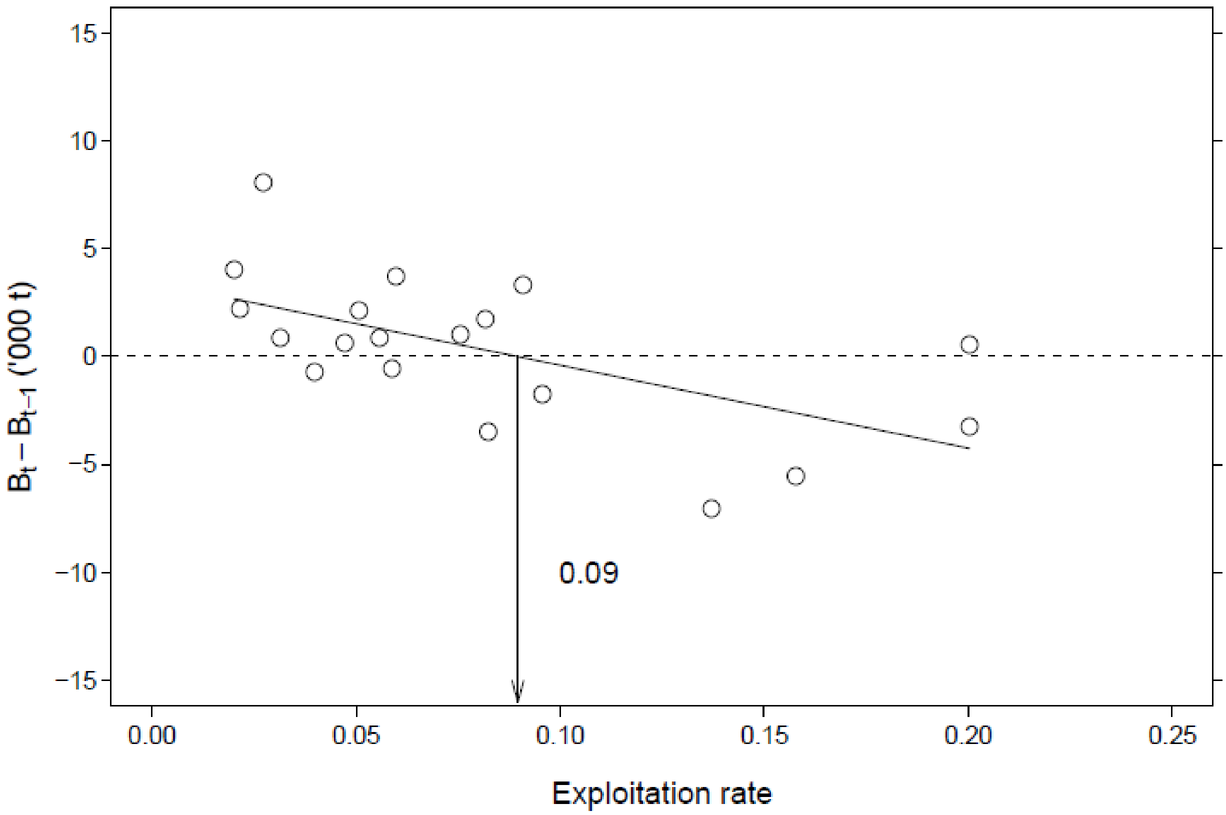

Figure 47. Change in estimated biomass (fully-recruited) versus exploitation rate. The removal reference point, i.e. the exploitation rate that results in no change in biomass, is indicated by the vertical arrow.

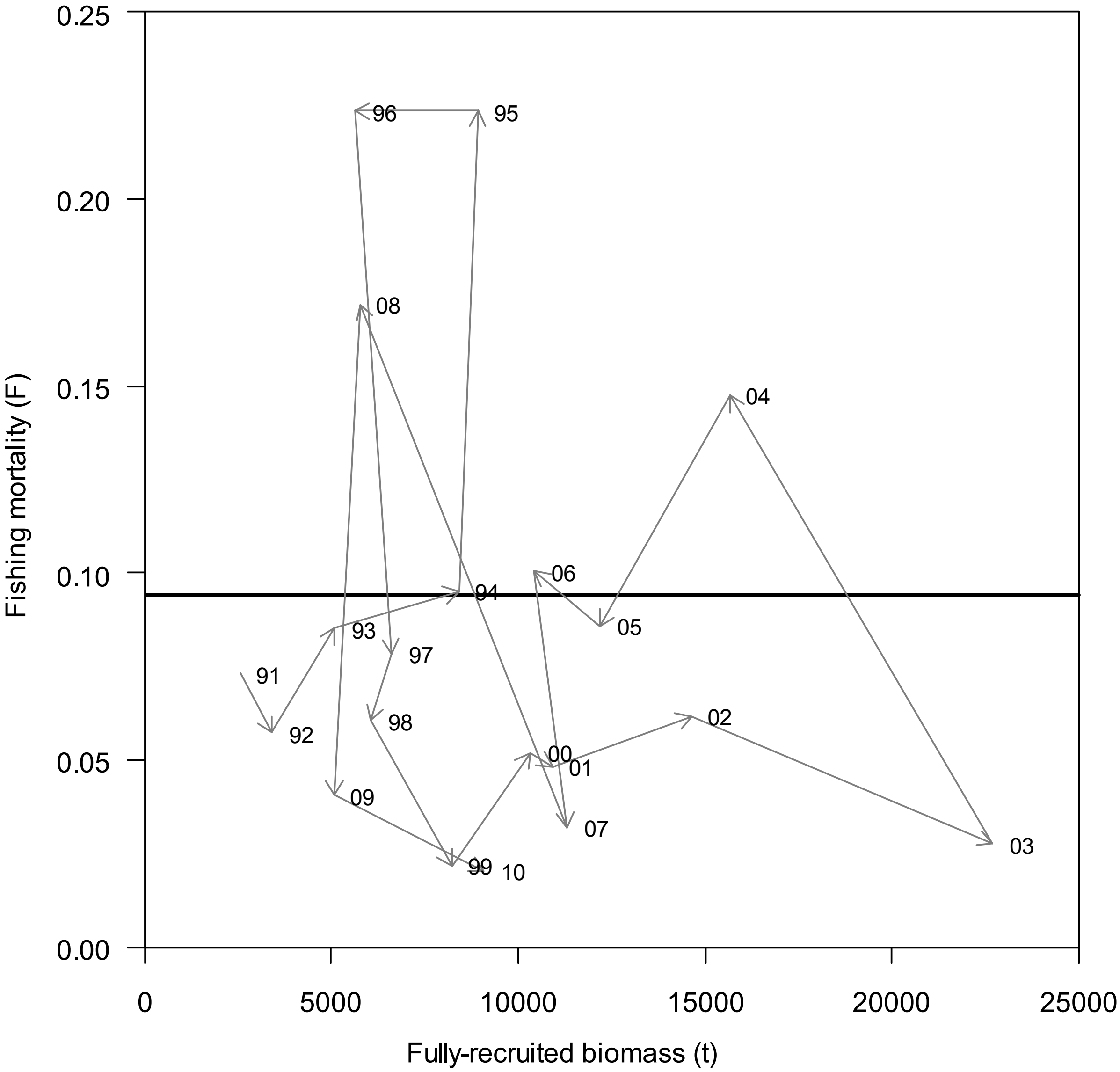

Figure 48. Phase plot of fishing mortality, F or –log(1-μ) and fully-recruited biomass with the suggested removal reference point from Figure 47 shown as the horizontal line.