Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

Canadian Science Advisory Secretariat (CSAS)

Research Document 2013/079

Maritimes Region

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

P.B. Hubley, A. Reeves, S.J. Smith, and L. Nasmith

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

May 2014

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Hubley, P.B., Reeves, A., Smith, S.J., and Nasmith, L. 2014. Georges Bank ‘a’ and Browns Bank ‘North’ Scallop (*Placopecten magellanicus*) Stock Assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/079. vi + 58 p.

TABLE OF CONTENTS

ABSTRACT iv
RÉSUMÉ v
INTRODUCTION 1
Fishery 1
Survey 2
ASSESSMENT METHODS 2
Growth and Condition 2
Non-harvest Mortality 4
Observation Error 5
Other Changes 6
GEORGES BANK “a” 6
Fishery 6
By-catch 7
Survey 7
Design 7
Distribution 7
Growth and Condition 7
Population Model 9
BROWNS BANK NORTH 10
Fishery 10
Survey 10
Design 10
Distribution 11
Growth and Condition 11
Population Model 11
REFERENCES 12
TABLES 15
FIGURES 21

ABSTRACT

This research document describes the analytical assessment of scallops (*Placopecten magellanicus*) on Georges Bank 'a' and Browns Bank 'north', where the majority of the catches from the offshore scallop fishery occur. Total reported landings in 2012 were 4,001 t and 475 t for Georges Bank 'a' and Browns Bank 'north', respectively. The analytical methods for this assessment are based on the 2009 framework of Georges Bank scallops (Jonsen et al. 2009), along with a number of improvements in the areas of growth, mortality and observation error. Annual dredge surveys using stratified random design, where the strata are defined by the historical abundance indices, are conducted on Browns and Georges banks every May and August, respectively.

Both commercial catch rate and survey indices show increases in fully-recruited biomass for Georges Bank 'a' from 2011 to 2012, and are well above the long-term median. The survey abundance indices of pre-recruits and recruit size scallop are comparable to the long-term median. The distribution pattern indicates that pre-recruit and recruit size scallops are mainly found on the northern half of Georges Bank 'a', while fully-recruited scallops are found throughout the survey area. The overall condition factor for Georges Bank 'a' in August 2012 was 16.07 g/dm^3 (meaning that on average a scallop with a 100 mm shell would have an 16.07 g meat). This was an increase from 2011 and above the long-term mean of 15.36 g/dm^3. Spatial patterns in condition seemed consistent with bottom temperatures collected during the survey. New growth parameters derived from recent age data were used for calculating growth terms in the model and to redefine the recruit size class to include scallops between 85 and 95 mm shell height.

Fully recruited biomass for Georges Bank 'a', estimated to be 23,400 t in 2012, increased from the 2011 estimate (21,370 t) and was above the 26-year median biomass of 14,810 t. Recruit biomass, estimated to be 4,685 t in 2012, declined from the 2011 estimate (7,657 t), but was still above the 26-year median biomass of 2,995 t. The 2013 interim Total Allowable Catch (TAC) of 4,000 t is expected to result in an exploitation rate of 0.16, and incoming recruitment is expected to be above the median. Harvest scenarios ranging from 2,000 to 6,000 t are all predicted to yield increases in commercial biomass for 2013 with a probability of decline ranging from 0.36 to 0.48.

The commercial catch rate in 2012 was at the long-term median (1991-2009). In 2012, the survey index for pre-recruits was similar to what it was in the early 2000s and well below the 21-year (1991-2011) median. The 2005 year class is now mainly fully recruited to the fishery and survey indices of recruit and fully recruited scallops were near their respective 21-year (1991-2011) median levels. The overall condition factor for Browns Bank north in May 2012 was 11.83 g/dm^3. This was an increase from 11.03 g/dm^3 in 2011, but is still below the long-term mean of 12.62 g/dm^3. The spatial pattern in condition on Browns Bank was less consistent with temperature and depth than it was on Georges Bank. Recent age data yielded similar growth parameters to what was used in previous assessments.

Fully recruited biomass for Browns Bank 'north', estimated to be 5,950 t in 2012, increased slightly from the 2011 estimate (5,504 t) and is approximately equal to the 21-year median biomass of 5,807 t. The 2013 interim TAC of 750 t will result in an exploitation rate of 0.13. Biomass is expected to remain relatively stable, however, there is little indication of strong year classes in the near future. Harvest scenarios ranging from 200 t to 1000 t were examined and all had moderate (0.40-0.56) probability of decline in commercial biomass for 2013. Biomass change ranged from 9 to -5 % for the range of catches considered here.

Évaluation du stock de pétoncles (*Placopecten magellanicus*) de la zone « a » du banc de Georges et du secteur « nord » du banc de Brown

RÉSUMÉ

Le présent document de recherche décrit l'évaluation analytique des pétoncles (*Placopecten magellanicus*) de la zone « a » du banc de Georges et du secteur « nord » du banc de Brown d'où proviennent la majorité des captures de la pêche hauturière du pétoncle. Les débarquements totaux déclarés en 2012 s'élevaient à 4 001 tonnes et 475 tonnes pour la zone « a » du banc de Georges et le secteur « nord » du banc de Brown respectivement. Les méthodes d'analyse employées pour la présente évaluation sont fondées sur le cadre d'évaluation du stock de pétoncle du banc de Georges de 2009 (Jonsen *et al*. 2009), ainsi que sur un certain nombre d'améliorations dans les domaines de la croissance, de la mortalité et de l'erreur d'observation. Les relevés de dragage annuels sont effectués sur les bancs de Brown et de Georges chaque mois de mai et d'août, respectivement, selon un modèle aléatoire stratifié dans lequel les strates sont déterminées par les indices d'abondance historique.

Les taux de prises commerciales ainsi que les indices des relevés montrent une augmentation de la biomasse des pétoncles pleinement recrutés pour la zone « a » du banc de Georges de 2011 à 2012 qui est bien supérieure à la médiane à long terme. Les indices d'abondance du relevé concernant la taille des prérecrues et des recrues sont comparables à la médiane à long terme. Le schéma de répartition indique que les prérecrues et les recrues se trouvent principalement dans la moitié nord de la zone « a » du banc de Georges, tandis que les pétoncles pleinement recrutés se trouvent dans toute la zone de relevé. En août 2012, le coefficient de condition générale pour la zone « a » du banc de Georges était de 16,07 g/dm^3 (ce qui veut dire qu'en moyenne, un pétoncle avec une coquille de 100 mm aurait 16,07 g de chair). Cela signifiait qu'il y avait eu une augmentation depuis 2011 et que le coefficient de condition générale était supérieur à la médiane à long terme de 15,36 g/dm^3. Les tendances spatiales relatives à la condition ont semblé cohérentes avec les températures au fond recueillies durant le relevé. De nouveaux paramètres de croissance dérivés de données récentes sur l'âge ont été utilisés pour le calcul des termes de croissance dans le modèle et pour redéfinir la classe de taille des recrues afin d'inclure les pétoncles avec une hauteur de coquille comprise entre 85 et 95 mm.

La biomasse des pétoncles pleinement recrutés de la zone « a » du banc de Georges, estimée à 23 400 tonnes en 2012, a augmenté par rapport à l'estimation de 2011 (21 370 tonnes) et elle se situe au-dessus de sa valeur médiane sur 26 ans (14 810 tonnes). La biomasse des recrues, estimée à 4 685 tonnes en 2012, a diminué par rapport à l'estimation de 2011 (7 657 tonnes), mais elle se situe toujours au-dessus de sa valeur médiane sur 26 ans (2 995 tonnes). Le total autorisé des captures (TAC) provisoire de 2013 (4 000 tonnes) devrait se traduire par un taux d'exploitation de 0,16 et le recrutement futur devrait se situer au-dessus de la médiane. Selon les prévisions, des scénarios de captures allant de 2 000 tonnes à 6 000 tonnes devraient tous produire des hausses de la biomasse commerciale en 2013, avec une probabilité de déclin de 0,36 à 0,48.

Le taux de captures commerciales en 2012 se situait à sa valeur médiane à long terme (1991-2009). En 2012, l'indice du relevé pour les prérecrues était similaire à celui du début des années 2000 et bien en deçà de la médiane sur 21 ans (1991-2011). La classe d'âge de 2005 est maintenant pleinement recrutée à la pêche, et les indices du relevé pour les recrues et les pétoncles pleinement recrutés étaient près de leur médiane sur 21 ans respective (1991-2011). En mai 2012, le coefficient de condition générale pour le secteur nord du banc de Brown était de 11,83 g/dm^3. Ce coefficient a augmenté par rapport à 2011 (11,03 g/dm^3), mais il est

toujours inférieur à la moyenne à long terme (12,62 g/dm^3). La tendance spatiale de la condition sur le banc de Brown était moins cohérente avec la température et la profondeur qu'elle ne l'était sur le banc de Georges. Des données sur l'âge récentes ont fourni des paramètres de croissance similaires à ceux qui avaient été utilisés dans des évaluations précédentes.

La biomasse des pétoncles pleinement recrutés au secteur « nord » du banc de Brown, estimée à 5 950 tonnes en 2012, a légèrement augmenté par rapport à l'estimation de 2011 (5 504 tonnes) et est à peu près égale à la biomasse médiane sur 21 ans, qui est de 5 807 tonnes. Le TAC provisoire pour 2013, à savoir 750 tonnes, entraînera un taux d'exploitation de 0,13. La biomasse devrait demeurer relativement stable, mais il y a très peu d'indications que des classes d'âge seront fortes dans un proche avenir. Des scénarios de captures allant de 200 tonnes à 1 000 tonnes ont été examinés, et tous avaient une probabilité modérée (0,40 à 0,56) de produire un declin de la biomasse commerciale pour 2013. Pour la fourchette de captures examinée dans le présent document, les changements dans la biomasse variaient de 9 % à -5 %.

INTRODUCTION

An assessment framework was developed for Georges Bank 'a' scallop (*Placopecten magellanicus*) at a framework meeting in February 2009 (Jonsen et al. 2009). This framework was later applied to Browns Bank north scallop in 2011, the first formal assessment of that fishery since 1998. The offshore scallop fishery also occurs on other banks in the Maritimes Region such as Georges Bank 'b', German Bank, Browns Bank south, Sable/Western Bank, Middle Bank and Banquereau (Figure 1). However, the majority of the landings come from Georges Bank 'a' and Browns Bank north, and these two areas are the fisheries on which an analytical assessment has been conducted. This document will describe that assessment, based on the 2009 framework, along with a number of recent improvements.

The 2009 framework for Georges Bank (Jonsen et al. 2009) used a simplified version of the delay-difference model (Quinn and Deriso 1999) for modelling the population dynamics,

$$B_{t+1} = \left(\exp(-m_t) \left(\rho + \frac{\alpha}{\overline{w}_t} \right) (B_t - C_t) + R_t \right) \mu_t \tag{1}$$

where B_t, $\overline{w}_t$, and m_t are the population biomass, average weight of the portion of the population recruited to the fishery, and instantaneous natural mortality, respectively, in year t. The term R_t denotes the biomass of the recruiting size classes in year t. C_t is the catch in year t. The μ_t represents the process error term associated with the model dynamics. When fitting the model biomass was rescaled by a constant K,($P_t = B_t/K$) to improve convergence. There have been modifications to this model in the areas of growth, mortality and observation error terms. The general aim of these modifications was to improve the assessment by incorporating more of the available data. These data inputs and the methods for their inclusion in the assessments are described in the Assessment Methods section. Results of the assessment are presented separately for each area.

FISHERY

Increased demands following the Second World War initiated the development of the offshore scallop fishery in Nova Scotia, primarily focused on Georges Bank (Naidu and Robert 2006), which continues to be the most important area. The success of the offshore scallop fishery can be attributed to important management decisions and industry support. The most important of which include the implementation of: limited entry, the ICJ (International Court of Justice) line awarding Canada the northeast portion of Georges Bank, enterprise allocation, the separation of the inshore and offshore fisheries, and the meat count (number of meats per 500 g) regulations. Table 1 provides a timeline of many of the important changes to this fishery since its inception (Jonsen et al. 2009; Stevens et al. 2008).

The current year-round offshore fishery consists of six Enterprise Allocation licenses composed of five freezer trawlers which land frozen product, and eight wet fish vessels which land fresh product. These vessels utilize one to three (most commonly two) 4.3 m to 5.2 m (most commonly 4.6 m) New Bedford style rakes (also known as drags or dredges). The rakes are made up of a rectangular metal frame attached to a mesh bag composed of 7.2 to 10.2 cm steel rings. Mandatory fishing logbooks provide information on catch, effort (number and size of rakes, number of tows and tow duration), and position are provided at the resolution of once every six hours.

Georges Bank and Browns Bank are both divided into management areas of good and marginal habitats, creating the areas of Georges Bank ‘a’ and ‘b’ and Browns Bank ‘north’ and ‘south’.

The current meat count regulations (numbers per 500 g) are 33 for Georges Bank ‘a’, 50 for Georges Bank ‘b’, 40 for Browns Bank ‘north’ and 60 for Browns Bank ‘south’.

The commercial catch rate index was calculated using a Jackknife estimator (Smith 1980) on corrected and verified data from the commercial logbooks. These data include prorated catch (kg), effort (hours metre, hm) and position (longitude, latitude) by day or by six hour watch since 2008. The Jackknife estimator is a robust method for estimating catch rate and also provides the means for calculating standard errors, which are used to inform observation errors in the model.

SURVEY

The primary data output from the annual dredge 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. Survey gear was a 2.44 m wide New Bedford style offshore dredge (75 mm ring size) lined with 38 mm mesh polypropylene netting. Each survey tow lasted 10 minutes and was tracked using a global positioning system (GPS). The tow tracks are then used to calculate the actual distance of each tow. Catches are standardized to a common distance of 800 m.

In 2010, the biological sampling protocols on the survey were modified. The sampling frequency increased from one sample for every 10 minute square of survey area to every other station. In order to mitigate the increased workload, the collection of gonads and viscera was discontinued so that only the abductor muscle and shell were collected for weight, height and age data. The collection of gonad and viscera weights were part of a historical sampling program and were no longer being used in the assessment. Increased sampling of shell height-meat weight data is particularly useful as the relationship between shell height and meat weight is highly variable in space and time.

ASSESSMENT METHODS

GROWTH AND CONDITION

The growth term ($\rho + \alpha/\overline{w}_t$) from the population model (equation 1) decreases (increases) as the average size increases (decreases) representing an older slower growing (younger, faster growing) population. The parameters α and ρ are obtained from a regression of the weights-at-age a on the weights-at-age $a-1$. This linear relationship is a consequence of using a von Bertalanffy (VB) growth curve for weight as a function of age (Quinn and Deriso 1999). The growth increment term assumes that growth can be modelled using mean meat weight of the commercial size animals as a proxy of the mean shell height. However, the relationship between meat weight and shell height, hereafter referred to as condition, has shown a great deal of inter-annual and spatial variability that has complicated the fit of the model. Variability in growth rates and condition are well documented in sea scallops and are likely related to both temperature and food availability (Robert et al. 1990; Kenchington et al. 1997; Smith et al. 2001). Seasonal factors such as the timing of plankton blooms and spawning are also factors, but because the surveys generally occur at similar times each year this variation should be minimized. In this assessment, spatial patterns of growth and condition were examined and, in the case of condition, incorporated into the estimates of survey biomass. Temporal patterns in condition and stock composition were used to calculate more accurate overall growth parameters for input into the model.

To calculate condition the approach presented in Hubley et al. (2011) was applied where the meat weight/shell height model is simplified by assuming an isometric height weight relationship, i.e., the weight is divided by the cube of the shell height. This ratio is commonly referred to as the condition factor (CF).

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

Calculating condition factor is useful because it expresses the changing weight-height relationship as a single metric that can be compared across various potential factors such as year, depth, and location. 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 (1 dm) shell (roughly commercial size). A linear mixed effects model was fit to meat weight (w) and shell height (h) data collected for each scallop in a given sample and the random effects are estimated for the condition factor of each sample location (l).

$$w_{il} = (A - a_l)h_{il} + \varepsilon_{il}$$

The resulting fits of this model produce a fixed effect (A) or the overall condition factor and a random effect (a_l) or the sample specific deviation from the overall condition factor. Sample specific condition factors are used to evaluate the effect of year, depth and location so that these data may be used to predict condition factor for tows where no weight sample was taken.

As noted above, food availability and temperature are likely the factors which have the greatest effect on condition factor but detailed data for these variables are not available for each sample location in all years. Bottom temperature data have been recorded on recent surveys but are not available before 2010. Depth may serve as a proxy for the spatial variability in bottom temperatures. Generalized additive models (GAMs) were used in inshore areas to predict condition and this method proved to be effective even when the spatial pattern was not solely dependent on depth (Smith et al. 2012). GAMs use smoothing functions to fit data and are useful when explicit relationships are not clear. Location was used as a predictor in the GAM by fitting a two dimensional smooth to latitude and longitude of each sample location because depth alone was not sufficient to explain variability of condition for a given area in a given year.

$$CF_{ly} = f_1(D_l) + f_2(Lat_l, Lon_l) + a_y + b + \varepsilon_{ly}$$

where the condition factor for a given location (l) and year (y) is given by a smooth function (f_1) of the depth at the location (D_l), a two-dimensional smooth function (f_2) of the latitude (Lat_l) and longitude (Lon_l) at the location, an annual factor (a_y) that may represent variability in food availability and temperature, and intercept (b). More accurate estimates of biomass per tow were estimated by using this model to predict condition factors for each tow, instead of using the same parameters for every station. Annual condition factors that will be used in the models were calculated as the mean condition factor in each survey weighted by fully-recruited biomass.

Contemporary age data were not available for Georges Bank at the time of the framework and collecting more age data was identified as an area for improvement (Jonsen et al. 2009). Significant effort has been made to begin an ageing program for Georges Bank since the framework. Presently age data has been recorded for 6443 scallops, 3792 of which had the shell height at each annulus recorded. Recording the growth increments between annuli is useful for estimating height at the younger ages because only shells of scallops greater than 60 mm were collected for aging purposes.

A VB growth equation was fitted to available age data as a nonlinear mixed effects model with random effects assigned to each sample location (l).

$$L_t = \left(L_\infty - l_{\infty,l}\right)\left(1 - e^{(K-k_t)(t-t_0)}\right)$$

where L_∞, K, and t_0 are the fixed effects model parameters and $l_{\infty,l}$, and k_l are the random effects for each sample location (l). Since age data is not available for a wide range of years annual patterns in shell growth are difficult to discern. Fixed effects parameters from the growth models were used for the purposes of integrating variable annual growth rates into the stock assessment model, while random effects parameters were used to look at spatial variability in growth.

The annually varying growth rates for the model (g_t) are simply the ratios between the observed average meat weight of commercial or recruit size scallops and the observed average meat weight of the same scallops the following year. To calculate g, the average shell height of commercial or recruit size scallops is converted to a meat weight using the annual condition factor:

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

Then the average height of those scallops a year later ($\overline{h}_t$) is calculated using the VB parameters

$$\overline{h}_t = L_\infty\left(1 - e^{-K}\right) + e^{-K}\overline{h}_{t-1}$$

and then,

$$\overline{w}_t = CF_t\overline{h}_t^3$$

so that

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

The resulting annual observed growth potential tends to be more variable than the theoretical growth potential which varies only with respect to average weight. For the models used in this assessment, g_{t-1} has been substituted for the $\rho + \alpha / \overline{w}_t$ term in the assessment model so that the new formulation becomes

$$B_{t+1} = \exp(-m_{f(t)})(g_t)\left(B_t - C_t\right) + R_t \exp(-m_{r(t)})$$

A natural mortality term ($m_{r(t)}$) for recruits has also been added to the model.

NON-HARVEST MORTALITY

In past assessments natural mortality was assumed to be 0.1 (Jonsen et al. 2009; Robert et al. 1994, 2000). The model assumes all other mortality to be the result of the reported landings. Natural mortality is really a catch-all term for discard mortality resulting from undersized scallops being returned to the water, incidental mortality associated with gear contact yet not retained in the catch, as well as mortality from predators or other “natural” causes. For this reason, natural mortality will be referred to as non-harvest mortality. In the last assessment of Georges Bank scallops, levels of non-harvest mortality were identified as likely being higher than what was previously assumed (0.1) for scallops <95 mm (DFO 2011). This was perceived from a large decline in numbers of scallops between the 2009 and 2010 surveys that could not be accounted for in the catch. An increase in the number of clappers was also noted in the 2010 survey. Clappers are empty paired shells and are considered to represent scallops that have died of natural cause because the shells are separated when scallops are shucked at sea, therefore, they can be used as a proxy for natural mortality. These data can be incorporated into the assessment model using the equation shown here and described in detail in Smith and Lundy (2002).

$$m_t = \frac{2D_t}{S(SL_{t-1} + (2-S)L_t)}$$

Where *m, S, L and D* are natural mortality, dissolution rate in years and numbers of live and dead scallops observed from the annual surveys. The posterior for the dissolution rate (*S*) was not always well estimated so a prior was derived from the posteriors of *S* under a uniform prior from the model fit to an inshore area where the posterior distribution of *S* was well defined due to a large clapper events in previous years (Smith et al. 2012). Including estimates of *m* that are tied to real data is an effective way of introducing annual variability in non-harvest mortality without introducing excessive flexibility that could result in unrealistic estimates.

OBSERVATION ERROR

The observation model which relates the unobserved states to the observed indices was described in Jonsen et al. (2009) as follows:

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

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

These equations were modified in Hubley et al. (2011) to include the survey coefficient of variation (*CV*) as an additional component of the error (ε_t, τ_t). However, incorporating CV into model estimates of error has been further refined in Smith and Hubley (2013) where the impact of changes in survey *CV* on the results of the stock assessment were evaluated. Given that the survey estimates were assumed to follow a lognormal distribution in the observation equations of the population model, the following relationship between the CV of a lognormal random variable and the variance of the log transformed random variable, can be used (Johnson and Kotz 1970).

$$CV = \sqrt{\exp(\sigma^2) - 1}$$

Coefficients of variation for the commercial size and recruit survey indices were estimated for each year. Estimates of $\sigma^2_{\varepsilon,t}$ and $\sigma^2_{\tau,t}$ can be obtained directly from their respective survey *CV*s.

$$\hat{\sigma}^2 = \log(CV^2 + 1)$$

To account for the uncertainty in estimation, these variance estimates were used as expected values for informative priors on the variance terms in the model. That is, the prior for $\sigma^2_{\varepsilon,t}$ or $\sigma^2_{\tau,t}$ was modelled as an inverse gamma distribution, *IG(α; β)*,

$$p(\sigma^2 | \alpha, \beta) = \frac{\exp(-1/(\beta\sigma^2))}{\Gamma(\alpha)\beta^{\alpha}(\sigma^2)^{\alpha+1}}$$

with the mean μ_{σ^2} in year t and variance $\tau^2_{\sigma^2}$. The α and β parameters were calculated as (Carlin and Louis 1996),

$$\alpha = (\mu_{\sigma^2} / \tau_{\sigma^2})^2 + 2 \quad \text{and} \quad \beta = \frac{1}{\mu_{\sigma^2}\left((\mu_{\sigma^2} / \tau_{\sigma^2})^2 + 1\right)}$$

Carlin and Louis (1996) recommend setting $\tau_{\sigma^2} = \mu^2_{\sigma^2}$ to get a vague prior resulting in $\alpha = 3$ and $\beta = 1/(2\,\mu^2_{\sigma^2})$, with $\mu^2_{\sigma^2}$ set to the observed variance estimated from the survey CV (see also Clark and Bjørnstad 2004). This resulted in informative priors for observation errors that varied year to year with the CVs of the survey and catch rate indices.

OTHER CHANGES

The model was fit to the annual survey and commercial catch rate indices on Georges Bank 'a' from 1986 to 2012 as opposed to beginning in 1981 to avoid the complications associated with the unregulated fishery in the early 1980s. This had the added benefit of simplifying the model as the targeted size became more consistent over time and multiple estimates of catchability were not needed (DFO 2011).

Fishery data such as catch and catch rates were calculated for between surveys (September in year t to August in year $t + 1$ for Georges Bank). This was done to eliminate potential issue that may arise when the timing of the fishery varies from year to year as discussed in Hubley et al. (2011).

As described in Jonsen et al. (2009) a mildly informative prior was used for K with 10% and 90% quantiles approximately equal to 4,000 and 20,000, respectively.

$$K \sim LN(9.21034; 0.5409)$$

As more information has been incorporated into the model this informative prior was no longer needed to constrain biomass and a less informative vague prior was used

$$K \sim LN(7; 7)$$

Whereas the value of the mean (9.21034) of the previous prior had some influence on the resulting biomass estimates a sensitivity analysis determined that the value of the mean in the current prior did not.

The diagnostics presented at the framework meeting, were performed on this model to test performance. The performance of the model's prediction of biomass in the following year was also evaluated by comparing predictions from fits to the data up to year $t - 1$ (e.g., 2005) to year t (e.g., 2006) with the estimates of biomass from fitting the model to data up to year t. The prediction evaluation can be useful in assessing the effectiveness of the modifications in improving the capability of this model for providing advice.

GEORGES BANK "a"

FISHERY

The 2012 Total Allowable Catch (TAC) was 4,000 t for zone 'a' and 50 t for zone 'b' (Table 2). Total reported landings were 4,001 t for zone 'a' and 47 t for zone 'b'. Based upon preliminary analysis of the 2012 fishery data and the annual stock survey data, an interim TAC of 4,000 t was set for the 2013 Georges Bank zone 'a' fishery and 100 t for zone 'b'. Effort measured on Georges 'a' in hours fished multiplied by gear width in metres (hm) decreased from 260,937 hm in 2011 to 193,869 hm 2012. Catch rate has increased from 17.31 kg/hm in 2011 to 20.64 kg/hm in 2012 and is above the long-term median of 10.15 kg/hm. The commercial catch rate and landings that occurred between surveys (September through August) are presented in Figure 2.

The spatial pattern of the fishery in 2012 is expressed as tons of meats landed per one minute square in Figure 3. The greater proportion of the catch coming from the northern portion of the bank is evident along with the industry-managed closure areas that were in place during 2012. Variability in the spatial distribution of catch along with vessel differences and targeted fishing are factors that contribute to high degree of within year variability in catch rates that can be seen in the standard errors (Figure 2).

By-catch

By-catch of yellowtail flounder, cod and haddock were estimated using the method described in Gavaris et al. (2009). Estimated discards of yellowtail flounder have remained relatively stable from 51 t in 2011 versus 46 t in 2012 (Table 3). Estimated discards of cod increased from 29 t in 2011 to 41 t in 2012, and estimated discards of haddock increased from 15 t in 2011 to 28 t in 2012. Fishing effort increased by over 100% from 2007 to 2008 and was relatively constant from 2008 to 2010. Effort decreased from 34,617 hours (h) in 2010 to 19,031 h in 2012 (Table 3). The target for observer coverage is two trips per month. In 2012, this represented approximately 16% of the total hours fished.

SURVEY

Design

The annual dredge survey is conducted on Georges Bank every August and is augmented by monitoring stations each May. The August survey was redesigned for the 2009 framework to be a stratified random design where the strata are defined by the historical survey index from 1981 to 2008 (Hubley et al. 2009). The historical survey index was used to create four strata indicating low, medium, high and very high abundance, and the latter three strata were further divided into north and south of Latitude 41°50' so that in total there are seven strata (Figure 4; Hubley et al. 2009) These strata have remained unchanged with the exception of the low strata which was modified to represent areas where the historical survey index was between 50 and 115 scallops per tow as opposed to its original definition of 10 to 115 scallops per tow (Figure 4). This was done to reduce the amount of sampling that was done in areas where scallop density was too low to support a fishery. Prior to 2010, 150 sampling stations were allocated to each stratum proportionally to their areas and an additional 50 stations were part of a sampling grid covering part of the northern section of the bank. These grid stations were part of a historical sampling program but were no longer being used for assessment purposes. It was determined that redistributing these stations into the upper three strata for the northern part of the bank would be an effective way of incorporating them into the assessment and increasing the survey coverage.

Distribution

Scallop distribution patterns from the 2012 survey show that fully-recruited scallops (>95 mm shell height) are found throughout the survey area with moderately higher abundances in the northern portion of the bank (Figure 5). There are also a few small localized patches of very high abundance (>500 scallops per tow) in the industry-managed closure areas, northwest corner and near the Georges a/b line (Figure 5). The recruit scallop (85-95 mm shell height) distribution pattern shows a concentration in the northern portion with only a few patches of recruits in the south (Figure 6). Again the highest concentrations could be found in the industry-managed closure areas, in the northwest corner and near the a/b line (Figure 6). Similar to the recruits pre-recruits (<85 mm shell height) were found almost exclusively in the northern portion of the bank with very high concentrations located near the a/b line (Figure 7).

Growth and Condition

The spatial pattern of condition on Georges Bank reflects a strong depth correlation with the highest conditions found in the shallower areas of the northwest portion of the bank and lowest conditions found in the deeper areas of Georges 'b' (Figure 8). Bottom temperature data also shows a similar spatial pattern. There is further evidence to suggest that depth is a proxy for temperature. A comparison of the bottom temperature data collected for each tow during the August survey for 2011 and 2012 shows a similar spatial pattern but with overall colder temperatures in 2011 (Figure 9). This pattern is repeated in a comparison of condition for 2011 and 2012, which shows the same spatial pattern but with overall lower condition in 2011 (Figure 8). These preliminary results demonstrate how temperature can affect both spatial and annual variability in condition. The trend in the time series of annual changes in condition is relatively consistent from both May and August sampling (Figure 10). The trend shows a dramatic increase in condition for 2012 after a recent low period from 2009 to 2011 (Figure 10).

Previous assessments (Robert et al. 2000; Jonsen et al. 2009) have used VB growth parameters from Brown et al. (1972) (L_∞ =145.5, K =0.38, t_0=1.5). However, these parameter estimates are outdated, and were derived from limited samples from the US side of Georges and estimated without the use of modern nonlinear statistical methods. A non-linear mixed effects model fit to the new data resulted in a significantly different growth curve (Figure 11). The fixed effects parameters which represent the blue line in Figure 11 are: L_∞ =149, K =0.22, t_0 =0.22. Random effects were calculated for L_∞ in each sample in order to get a sense of the spatial variability (Figure 11). The pattern that emerged for spatial variability in L_∞ was not expected because it did not mirror the pattern of condition which closely matched the spatial patterns of temperature and depth (Figure 12). Unlike condition, shell growth appears to be somewhat slower in the north than in the south (Figure 12). This pattern was also verified using the mean growth increment between the second and third annuli for each sample. The new growth parameters were also independently verified with a length-frequency analysis that tracked the modes of the last few year classes over selected regions of Georges Bank before they reached commercial size. The resulting assumed age-shell height modes of each year class are shown as green points in Figure 11. These points correspond better to the new growth parameters than the old ones.

The new growth parameters will be used in calculating g_{t-1} for input into the model. The new parameters also have consequences for what shell height size range is considered recruit size because they differ so strongly with the old parameters for scallops less than commercial size. The recruit size range is generally defined as the scallops that will reach commercial size within one year. Using the old growth parameters, this was considered to be scallops with shell heights between 75-95 mm. However, under the new parameters, scallops with shell heights between 85-95 mm are expected to enter the fishery within one year. This distinction in how one views recruitment can be seen in the shell height frequency where the old definition of recruits is represented by the red dashed line (Figure 13). The new definition of recruitment also appears to make more sense with how the shell height frequency has changed over recent years. A smaller range for recruit size scallops means that there is an overall decrease in numbers of recruits in the time series as those scallops are now considered to be pre-recruits, while the numbers of commercial scallops does not change (Figure 14). In terms of biomass, the decrease is less noticeable for recruits and more noticeable for the pre-recruits, which were formerly the smaller recruits and are now the larger pre-recruits (Figure 15). In the last assessment, it was noted that the growth of the 2006 cohort year class was slower than expected and did not fully recruit into the fishery in 2010 (DFO 2011). This can partially be explained, as the biomass of recruits in 2009 was not nearly as high, because many of those scallops should have been considered pre-recruits (Figure 15).

The survey index for recruits (85-95 mm) and fully recruited (≥95 mm) scallops were above their respective 31-year median levels in 2012 (Figure 14), while the index for pre-recruits (<75 mm) were at the 31-year median level. The abundance of recruits and fully recruited scallops has decreased from 120 and 182 scallops per tow in 2011 to 58 and 158 scallops per tow in 2012, respectively (Figure 14).

POPULATION MODEL

The way in which error is now carried through from the survey into the model has led to the model fitting very closely to the survey and less so to the commercial catch rate due to its much larger standard errors (Figure 16). The types of factors that contribute to high variability in commercial catch rates are generally controlled for in the survey with the exception of spatial variability which is mitigated through the stratification scheme and as such survey standard errors are generally smaller.

The model was fit using both old and new growth parameters to examine their effect on the resulting advice. The difference in the recruit indices had a significant effect on one key parameter, survey catchability (q). The model uses q to scale the survey biomass estimates to true biomass, and the only information it has about the true biomass comes from magnitude of the catch. Since the catch did not change but the survey biomass decreased, the model estimated a new catchability that was lower than before (Figure 17).

As required for the first annual audit of their Marine Stewardship Council (MSC) certification, the offshore scallop fishing industry proposed a precautionary approach framework in February 2011 using proxies for biomass-based reference points for Georges Bank ’a’. Consistent with the Fisheries and Oceans Canada (DFO) policy, the industry set B_{MSY} equal to the mean biomass (1981 to 2009) from the stock assessment model (DFO 2010). The upper stock reference (USR) was set at 80% of B_{MSY} and 30% of B_{MSY} was used for the limit reference point (LRP). It was noted in Smith and Hubley (2012) that emphasis should be on the approach or method used over the actual values proposed because estimates of biomass may change from year to year as new information is added to the assessment. A lower estimate of q results in overall higher biomasses and a change in our understanding of the stock. If one were to continue with the approach of setting the USR to 80% of mean biomass, then under the new growth parameters it becomes 12,779 t significantly higher than 8,000 t (Figure 18). Under the old growth parameters upon which the reference points were originally based, an updated USR would be 9,249 t, much closer to 8,000 t (Figure 18). This illustrates how new information can change the understanding of the stock and its relation to its reference points. Under the current circumstances, regardless of which reference points are used, there is an extremely high probability (>0.99) that the stock is currently above the USR.

Fully recruited biomass, estimated to be 23,400 t in 2012, increased from the 2011 estimate (21,370 t) and is above the 26-year median biomass of 14,810 t (Figure 18). Recruit biomass, estimated to be 4,685 t in 2012 declined from the 2011 estimate (7,657 t), but is still above the 26-year median biomass of 2,995 t. The model’s forecast for 2013 biomass is 26,210 t, assuming a catch of 4,000 t (the interim TAC), no change in condition and natural mortality rates similar to 2012. This represents an estimated 11% increase in biomass from 2012. Harvest scenarios ranging from 2,000 t to 6,000 t are predicted to yield increases in commercial biomass with a probability of decline ranging from 0.36 to 0.48 (Table 4). A breakdown of size composition of the fishable biomass shows that meat count regulations are less likely to be an issue this year because the majority of the biomass of scallops >85 mm was expected to contain meats that would result in counts of less than 33 per 500 g (Figure 19). Exploitation declined in 2012 to 0.16 from 0.19 in 2011 (Figure 20). The estimates of non-harvest mortality decreased for both recruit and fully-recruited scallops to 0.06 and 0.04 in 2012, from 0.28 and 0.13 in 2010, respectively (Figure 20).

The estimated biomass for 2012 was only 10% lower than what would have been the median projection from 2011 (26,000 t). All of the model estimates fall within the 50% credible interval of the prediction from the previous year (Figure 21). The mean of the residual differences between predictions to biomass estimates was 14.24% (Table 5). There was a slight bias in the model to over predict for the years evaluated. On average the prediction was 1.08 times the estimate. The decision table outputs of expected exploitation and expected biomass change were also evaluated for previous years (Table 6).

BROWNS BANK NORTH

FISHERY

The 2012 TAC was 500 t for Browns Bank north and total reported landings were 475 t (Table 7). Based upon preliminary analysis of the 2013 fishery data and the annual stock survey data, an interim TAC of 750 t was set for the 2013 Browns Bank north fishery. Although no fishery has occurred on Browns Bank south since 2007 an interim TAC of 10 t has been set for 2013. Effort measured in hours fished multiplied by gear width in metres (hm) decreased from 38,532 hm in 2011 to 19,291 hm 2012. Catch rate has decreased slightly from 26.64 kg/hm in 2011 to 24.65 kg/hm in 2012 and is near the long-term median of 23.09 kg/hm. The commercial catch rate and landings that occurred between surveys (June through May) are presented in Figure 22. The spatial pattern of the fishery in 2012 is expressed as tons of meats landed per minute square in Figure 23 and shows fishing concentrated in specific areas of high abundance around the former industry-managed closure areas which are shown for context. High levels of variability in catch rates can be seen in the standard errors especially when low levels of effort resulted in high catch rates, i.e., 2003 and 2007 (Figure 22).

SURVEY

Design

The annual dredge survey conducted on Browns Bank 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 (Hubley et al. 2011). The survey design were initially stratified random designs with strata based on the commercial catch rates of the previous nine months (Robert and Butler 1998). The stratification scheme was changed to bottom types based on analysis of multibeam data in 2001 (Kostylev et al. 2001; Kostylev et al. 2003). Bottom type strata were fixed from year to year but did not always align with patterns of scallop abundance (Figure 24). Scallop grounds were assumed to be associated with the gravel bottom type identified from the multibeam data. However, geophysicists define the grain size for gravel as ranging from pebbles to large boulders, and as a result not all areas defined as gravel may be suitable as scallop habitat. Beginning this year, a combined science and industry survey working group recommended a change in design to fixed strata that were based on a more direct measure of scallop abundance. The historical commercial catch rate (HCR) from 2002 to 2012 was chosen as a stratifying variable (Figure 24) because of the limited survey coverage in the early years (Hubley et al. 2011). The stratification scheme was compared to the bottom type stratification using the same methods that were used to evaluate survey designs for the Georges Bank framework (Hubley et al. 2009). Realized relative efficiency was calculated by comparing the variance of the stratified population estimate to the variance of the population estimate under simple random sampling and potential relative efficiency is the relative efficiency if stations were allocated optimally to strata to reduce variance (Hubley et al. 2009). The comparison showed significantly greater gains in realized and potential efficiency for the HCR design over the bottom type design (Figure 25).

The change in stratification scheme resulted in some minor changes to the survey indices of abundance and biomass (figures 26 and 27). The survey index for pre-recruits (<85 mm shell height) in 2012 was 88 scallops per tow, similar to what it was in the early 2000s and well below the 21-year (1991-2009) median of 411 scallops per tow (Figure 26). The large cohort (2005 year class) observed in the 15 to 50 mm range in 2007 is now mainly fully recruited in the 85-115 mm range (Figure 28), and the abundance of recruit scallops has returned to near median levels (Figure 26). The abundance of fully recruited scallops has remained fairly stable since 2010, at 237 scallops per tow it is just above 21-year (1991-2009) median of 205 scallops per tow (Figure 26).

Distribution

Scallop distribution patterns from the 2012 survey show high abundances of fully-recruited scallops (>95 mm shell height) in areas noted for historically higher catch rates and recent fishing activity (figures 23, 24 and 29). Substantial abundances of recruits were found in the southern area, in the northwestern box known as “happy valley” and in one tow in the east, but no recruits were caught in the central part of the bank (Figure 30). The survey found a few isolated patches of pre-recruits on the southern edge, in the middle and in the box east of “happy valley” but there were no large concentrations (Figure 31).

Growth and Condition

The spatial pattern of condition on Browns Bank north does not reflect as strong a correlation with depth as it did on Georges Bank (Figure 32). While high condition scallops were found in the central part of the bank where it is relatively shallow, significantly higher conditions were found along the northern edge compared to areas of similar depths on the southern edge (Figure 32). Bottom temperature data collected on the survey did not show any pattern consistent with depth or condition (Figure 33). In fact, the warmest temperatures were found along the southern edge, waters that are relatively deep and where the lower condition factors of the survey area were found (Figure 33). These results suggest more complexity is involved in explaining condition for Browns Bank than for Georges Bank possibly the result of different current/circulation patterns. It is likely that the seasonal timing of the survey would affect the spatial pattern of bottom temperatures, however, the bottom temperatures collected on Georges Bank in May, although colder, were consistent with the pattern observed in August. Despite a lack of spatial correlation between condition and bottom temperature on Browns Bank north, there was some temporal correlation in that bottom temperatures were warmer and condition was higher in 2012 compared to 2011 (figures 32 and 33). The trend in the time series of annual changes in condition shows a small increase in condition for 2012 but remains below the long-term mean (Figure 34).

The growth parameters used previously were based on age data from 56 samples from 1997 to 2003 and were estimated using a non-linear mixed effects model: L_∞ =147, K =0.22, t_0=1.0 (Hubley et al. 2011). The new VB parameters (L_∞ =148, K =0.19, t_0=0.11) were based on four samples from 2012 and despite producing similar growth curves show a clear difference in the data (Figure 35). The recent samples indicate that there is likely a high degree of spatial variability on the bank while the older data exhibited lower spatial variability in height at age despite coming from many more samples. Fortunately both data sets produce similar growth curves so that the impact of switching to VB parameters estimated using the new data has negligible effects on the model and subsequent advice.

POPULATION MODEL

As with Georges Bank, the model fits very closely to the survey and less so to the commercial catch rate particularly in the 2008-09 survey year when very high catch rates occurred with very low effort (Figure 36). Fully recruited biomass, estimated to be 5,950 t in 2012, increased slightly from the 2011 estimate (5,504 t) and is approximately equal to the 21-year median biomass of 5,807 t (Figure 37). Recruit biomass, estimated to be 857 t in 2012 declined from the 2011 estimate (1,819 t), but is still above the 21-year median biomass of 583 t. The model's forecast for 2013 biomass is 5,912 t, assuming a catch of 750 t (the interim TAC), no change in condition and natural mortality rates similar to 2012. Harvest scenarios ranging from 200 t to 600 t are predicted to yield modest increases in commercial biomass with a probability of decline ranging from 0.40 to 0.48 and harvest scenarios ranging from 700 t to 1000 t are predicted to yield modest decreases in commercial biomass with a probability of decline ranging from 0.50 to 0.56 (Table 8). A breakdown of the size composition of fishable biomass shows that while the total fishable biomass has not changed from 2011, the meat count from scallops captured in 2012 was likely lower (Figure 38). Exploitation declined in 2012 to 0.08 from 0.14 in 2011 (Figure 39). The estimates non-harvest mortality increased for both recruit and fully-recruited scallops to 0.19 and 0.15 in 2012, from 0.15 and 0.09 in 2011, respectively (Figure 39).

The results of the projection evaluation for the Browns Bank north model were more variable than they were for Georges Bank. The estimated biomass for 2012 was 17% lower than what would have been the median projection from 2011 (7,128 t). The model estimates fall within the 50% credible interval of the prediction from the previous year nearly half of the time (Figure 40). The mean of the residual differences between predictions to biomass estimates was 26.38% (Table 9). There was a bias in the model to over predict for the years evaluated, on average the prediction was 1.22 times the estimate. Thus far, the methods used that have been effective for improving the performance of model predictions for Georges Bank have been less effective on Browns Bank north. The decision table outputs of expected exploitation and expected biomass change were also evaluated for previous years (Table 10).

REFERENCES

Brown, B.E., Parrack, M., and Flescher, D.D. 1972. Review of the current status of the scallop fishery in International Commission for the Northwest Atlantic Fisheries (ICNAF) Division 5Z. ICNAF Res. Doc. 72/113, Ser. No. 2829. 13 p.

Carlin, B.P., and Louis, T.A. 1996. Bayes and empirical Bayes methods for data analysis. Chapman and Hall, New York, NY. 399 p.

Clark, J.S., and Bjørnstad, O.N. 2004. Population time series: Process variability, observation errors, missing values, lags, and hidden states. Ecology 316 85: 3140-3150.

DFO. 2010. Assessment of Georges Bank scallops (*Placopecten magellanicus*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/036.

DFO. 2011. Assessment of Georges Bank scallops (*Placopecten magellanicus*). DFO Can.Sci. Advis. Sec. Sci. Advis. Rep. 2011/059.

Gavaris, S., Sameoto, J., Glass, A., and Jonsen, J. 2009. Discards of Atlantic cod, haddock, and yellowtail flounder from the 2008 Canadian Scallop Fishery on Georges Bank. TRAC Ref. Doc. 2009/06.

Hubley, B., Smith, S.J., Jonsen, I.D., and Sameoto, J. 2009. Georges Bank 'a' scallop (*Placopecten magellanicus*) annual stock assessment: Survey design. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/033.

Hubley, P.B., Glass, A., Reeves, A., Sameoto, J., and Smith, S.J. 2011. Browns Bank “north” scallop (*Placopecten magellanicus*) stock assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/042.

Jonsen, I.D., Glass, A., Hubley, B., and Sameoto, J. 2009. Georges Bank 'a' scallop (*Placopecten magellanicus*) framework assessment: Data inputs and population models. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/034.

Johnson, N.L., and Kotz, S. 1970. Continuous univariate distributions, part 1. Distributions in statistics. John Wiley and Sons, New York, NY. 300 p.

Kenchington, E., Lundy, M.J., and Smith, S.J. 1997. Bay of Fundy scallop stock assessment: Areas 2, 3, 4, 5, 7. DFO Can. Sci. Advis. Sec. Res. Doc. 1997/63.

Kostylev, V.E., Todd, B.J., Fader, G.B.J., Courtney, R.C., Cameron, G.D.M., and Pickrill, R.A. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Mar. Ecol. Prog. Ser. 219: 121-137.

Kostylev, V.E., Courtney, R.C., Robert, G., and Todd, B.J. 2003. Stock evaluation of giant scallop (*Placopectin magellanicus*) using high-resolution acoustics for seabed mapping. Fish. Res. 60: 479-492.

Quinn II, T.J., and Deriso, R.B. 1999. Quantitative fish dynamics. Oxford University Press, New York, NY.542 p.

Naidu, K. S., and Robert, G. 2006. Fisheries sea scallop, *Placopecten magellanicus. In* Scallops: Biology, ecology and aquaculture (2nd edition). Edited by S.E. Shumway and G.J. Parsons. Elsevier, New York, NY. 869-905 pp.

Robert, G., and Butler, M.A.E. 1998. Browns Bank north scallop stock assessment - 1997. DFO Can. Sci. Advis. Sec. Res. Doc.1998/070.

Robert, G., Butler, M.A.E., and Lundy, M.J. 1990. Bay of Fundy scallop stock assessment - 1989 . DFO Can. Sci. Advis. Sec. Res. Doc.1990/031.

Robert, G., Black, G.A.P., and Butler, M.A.E. 1994. Georges Bank scallop stock assessment - 1993. DFO Can. Sci. Advis. Sec. Res. Doc.94/97.

Robert, G., Black, G.A.P., and Smith, S.J. 2000. Georges Bank scallop stock assessment - 1999. DFO Can. Sci. Advis. Sec. Res. Doc.2000/016.

Smith, S. 1980. Comparison of two methods of estimating the variance of the estimate of catch per unit effort. Can. J. Fish. Aquat. Sci. 37(12): 2346-2351.

Smith, S.J., and Hubley, P.B. 2012. Reference points for scallop fisheries in the Maritime Region. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/018.

Smith, S.J., and Hubley, P.B. 2013. Impact of survey design changes on stock assessment advice: Sea scallops (*Placopecten magellanicus*). ICES J. Mar. Sci., doi:10.1093/icesjms/fst115 doi.

Smith, S.J., and Lundy, M.J. 2002. Scallop Production Area 4 in the Bay of Fundy: Stock status and forecast. DFO Can. Sci. Advis. Secret. Res. Doc. 2002/018.

Smith, S.J., Kenchington, E.L., Lundy, M.J., Robert, G., and Roddick, D. 2001. Spatially specific growth rates for sea scallops (*Placopecten magellanicus*) *In* Processes and management of marine populations. Edited by G.H. Kruse, N. Bez, A. Booth, M. Dorn, S. Hills, R. Lipcius, D. Pelletier, C. Roy, S.J. Smith, and D. Witherell. Spatial University of Alaska Sea Grant, AK-SG-01-02, Fairbanks. 211–231 pp.

Smith, S.J., Hubley, P.B., Nasmith, L., Sameoto, J., Bourdages, H., and Glass, A. 2012. Scallop production areas in the Bay of Fundy: Stock status for 2011 and forecast for 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/009.

Stevens, G., Robert, G., Burke, L., Poullioux, E., Roussel, D., and Wilson, J. R. 2008. The evolution of management in Canada's offshore scallop fishery. Case Studies in Fisheries Self-Governance: 111–123.

TABLES

Table 1. Timeline of offshore scallop fishery developments (1973 to present).

Year	Fishery Development
1973	Limited entry participation; 76 initial vessels
1977	200 mile limit boundary introduced
1984	ICJ line implemented awarding NE portion of Georges Bank to Canada
1984-85	TACs introduced; Minimum size limit (shell height) introduced
1986	Enterprise Allocation introduced; Scallop Fishing Areas (SFAs), blended meat counts and closed times introduced; partitioning of Inshore and Offshore (Inshore/Offshore boundary at 43°40’)
1989	Inshore allocation to offshore set to 0%; Offshore Management Plan developed
1995	100% dockside catch monitoring implemented
1998	Georges Bank subdivided into ‘a’ and ‘b’; Browns Bank subdivided into ‘north’ and ‘south’, Vessel Monitoring System (VMS) introduced; Industry initiated meat weight port sampling introduced with 100% coverage
2005 to present	Industry initiated and maintained closure areas to protect juvenile scallops began and continue

Table 2. Canadian landings of sea scallop meats from Georges Bank and total allowable catch (TAC), in metric tons (1981-2012). Since 1998, Georges Bank has been divided into zones 'a' and 'b'.

Year	Catch (t)	TAC (t)
1981	7612	--
1982	3918	--
1983	2418	--
1984	1945	--
1985	3812	--
1986	4900	4300
1987	6793	6850
1988	4336	5400
1989	4676	4700
1990	5218	5200
1991	5805	5800
1992	6151	6200
1993	6183	6200
1994	5003	5000
1995	1984	2000
1996	2996	3000
1997	4259	4250

	Catch (t)		TAC (t)	
Year	zone 'a'	zone 'b'	zone 'a'	zone 'b'
1998	3191	800	3200	800
1999	2503	1196	2500	1200
2000	6212	601	6200	600
2001	6480	395	6500	400
2002	6469	192	6500	200
2003	5985	199	6000	200
2004	3518	200	3500	200
2005	2484	201	2500	200
2006	3932	162	4000	200
2007	4000	401	4000	400
2008	5498	358	5500	400
2009	5524	261	5500	350
2010	5300	66	5500	200
2011	4517	0	4500	0
2012	4001	47	4000	50

Table 3. Estimated effort (h) and discards (t) of yellowtail flounder (ytf), cod, and haddock (had) caught as by-catch in the scallop fishery on Georges Bank 'a' and 'b' during the years 2007–2012.

Year	Observed Effort (h)	Total Effort (h)	Species	Total Estimated Discards (t)
2007	1565	14,394	ytf	**96**
			cod	**114**
			had	**56**
2008	3325	31,885	ytf	**117**
			cod	**37***
			had	**33**
2009	3431	32,556	ytf	**84**
			cod	**69**
			had	**54**
2010	3825	34,617	ytf	**200**
			cod	**44**
			had	**14**
2011	3569	25,782	ytf	**51**
			cod	**29**
			had	**15**
2012	2973	19,031	ytf	**46**
			cod	**41**
			had	**28**

* Discards from the Canadian scallop fishery on Georges Bank for 2007 and 2008 were adjusted for minor changes in input data from two 2007 trips and two 2008 trips. For 2007, this did not result in any change in the total estimated discards, however, for 2008, this update resulted in an increase of 1t for cod.

Table 4. Harvest scenarios for Georges Bank 'a' in 2013 in terms of exploitation and expected changes in biomass. Potential catches in 2013 are evaluated in terms of the probability of a decline in biomass and exceeding reference points. These probabilities account for uncertainty in the biomass forecasts.

Catch (t)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)	Probability biomass will exceed USR	Probability biomass will exceed LRP
2000	0.09	0.36	21.17	0.92	>0.99
2500	0.11	0.38	18.43	0.92	>0.99
3000	0.12	0.39	16.40	0.91	>0.99
3500	0.14	0.40	14.19	0.90	>0.99
4000	0.16	0.42	11.25	0.89	>0.99
4500	0.18	0.44	8.41	0.89	>0.99
5000	0.19	0.46	5.26	0.88	>0.99
5500	0.21	0.47	4.28	0.87	>0.99
6000	0.22	0.48	2.00	0.86	>0.99

Notes: USR = upper stock reference; LRP = limit reference point.

Table 5. Georges Bank 'a' prediction evaluation results showing the residual differences and proportions between predictions from fits to the data up to year t – 1 to year t and the estimates of biomass from fitting the model to data up to year t (from 2002-2012).

Year	Residual (Prediction – estimate)	Proportional (Prediction / estimate)
2002	-285	0.99
2003	1340	1.06
2004	6020	1.48
2005	-960	0.92
2006	-485	0.97
2007	-4775	0.77
2008	-2570	0.88
2009	7269	1.43
2010	3850	1.19
2011	2920	1.14
2012	1880	1.08

Table 6. Georges Bank 'a' prediction evaluation results comparing predicted and observed exploitation rates and changes in biomass for survey year catches (September-August; 2002-2012).

Year	Catch (t)	Predicted Exploitation Rate	Observed Exploitation Rate	Predicted Change in Biomass (%)	Observed Change in Biomass (%)
2012	3427	0.16	0.15	19.25	9.25
2011	2898	0.17	0.18	17.67	4.34
2010	4136	0.18	0.20	41.01	22.57
2009	6330	0.15	0.24	6.46	-25.36
2008	5928	0.20	0.16	-8.77	8.77
2007	6172	0.17	0.19	14.92	41.63
2006	5309	0.17	0.19	7.09	15.00
2005	1972	0.26	0.18	-8.11	-2.92
2004	4137	0.25	0.24	-20.01	-42.64
2003	3825	0.19	0.21	-19.05	-23.71
2002	2802	0.17	0.16	-1.70	-0.96

Table 7. Landings of sea scallop meats from Browns Bank and total allowable catch (TAC), in metric tons (1981-2012). 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

	Catch (t)		TAC (t)	
Year	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
2011	1027	0	1000	0
2012	475	0	500	0

Table 8. Harvest scenarios for Browns Bank north 2013 in terms of exploitation and expected changes in biomass. Potential catches in 2011 are evaluated in terms of the probability of a decline in biomass. These probabilities account for uncertainty in the biomass forecasts.

Catch (t)	Exploitation Rate	Probability of Biomass Decline	Expected Change in Biomass (%)
200	0.05	0.40	9.31
300	0.06	0.42	7.27
400	0.08	0.44	5.01
500	0.09	0.45	4.37
600	0.11	0.48	1.83
700	0.12	0.50	-0.04
750	0.13	0.51	-1.06
800	0.14	0.52	-1.42
900	0.15	0.55	-3.95
1000	0.17	0.56	-5.23

Table 9. Browns Bank north prediction evaluation results showing the residual differences and proportions between predictions from fits to the data up to year t – 1 to year t and the estimates of biomass from fitting the model to data up to year t (from 2002-2012).

Year	Residual (Prediction – estimate)	Proportional (Prediction / estimate)
2002	2055	0.88
2003	-2660	1.15
2004	5930	0.85
2005	-384	1.44
2006	5049	0.97
2007	1882	1.62
2008	3126	1.30
2009	-1490	1.97
2010	1107	0.61
2011	2569	1.17
2012	1178	1.44

Table 10. Browns Bank north prediction evaluation results comparing predicted and observed exploitation rates and changes in biomass for survey year catches (June-May; 2002-2012).

Year	Catch (t)	Predicted Exploitation Rate	Observed Exploitation Rate	Predicted Change in Biomass (%)	Observed Change in Biomass (%)
2012	896	0.11	0.08	20.97	7.42
2011	187	0.02	0.13	28.47	-7.36
2010	210	0.03	0.03	96.59	73.55
2009	1080	0.31	0.05	-28.46	13.82
2008	367	0.05	0.25	-0.37	-42.55
2007	1104	0.12	0.05	0.68	-14.85
2006	1093	0.08	0.12	2.04	-26.84
2005	2486	0.17	0.08	-8.95	-6.99
2004	634	0.03	0.15	9.44	-16.80
2003	930	0.06	0.03	9.12	29.87
2002	541	0.03	0.06	26.59	13.54

FIGURES

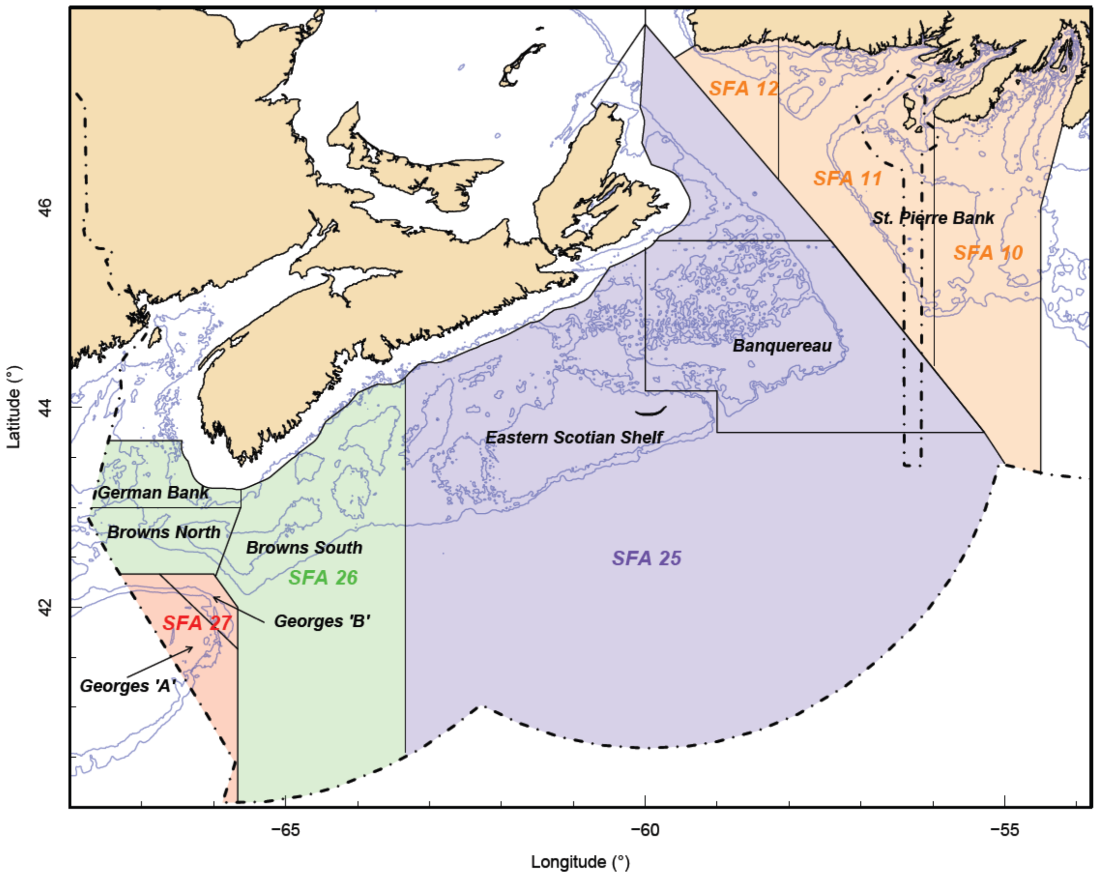


Figure 1. Map of offshore scallop fishing areas (SFA) used for management purposes in the Maritimes Region. Note the division of Browns Bank north as a subarea of SFA 26 and of Georges Bank 'a' as a subarea of SFA 27.

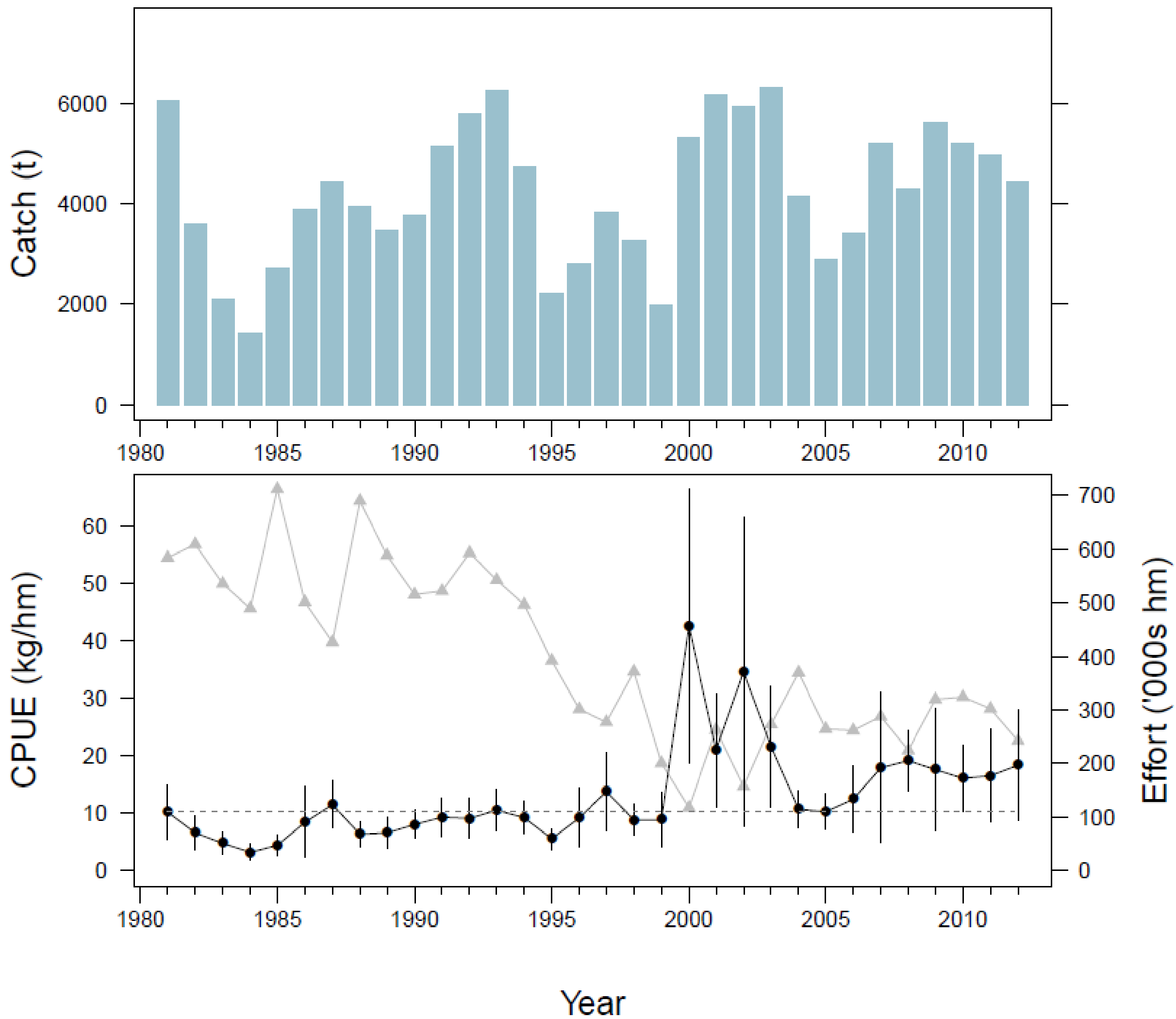


Figure 2. Summary of fishery inputs based on survey year (September to August; 1981-2012). Upper panel shows landings in tons of meat (abductor muscle). Lower panel shows catch per unit effort (CPUE; kg/hm) (●; black filled circle) and total effort (thousands hm) (▲; grey filled triangle) for the scallop fishery on Georges Bank 'a' during the survey year (September to August). Vertical lines are ± (plus or minus) one standard error from jackknife estimates of CPUE.

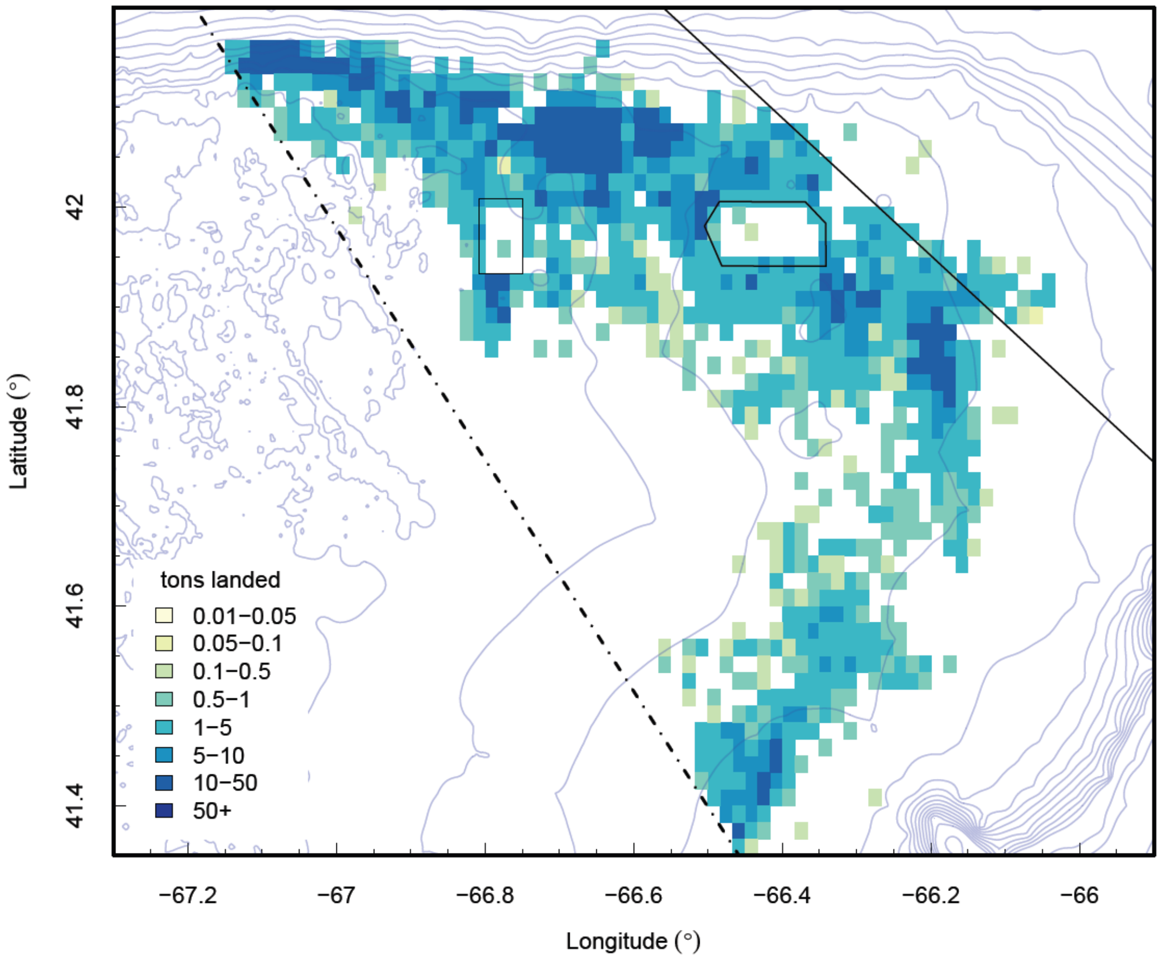


Figure 3. Spatial distribution of landings from Georges Bank in 2012. Landings reported in commercial fishing logs are summed for each one minute square. Industry-managed closure areas that were in place during 2012 are shown for context.

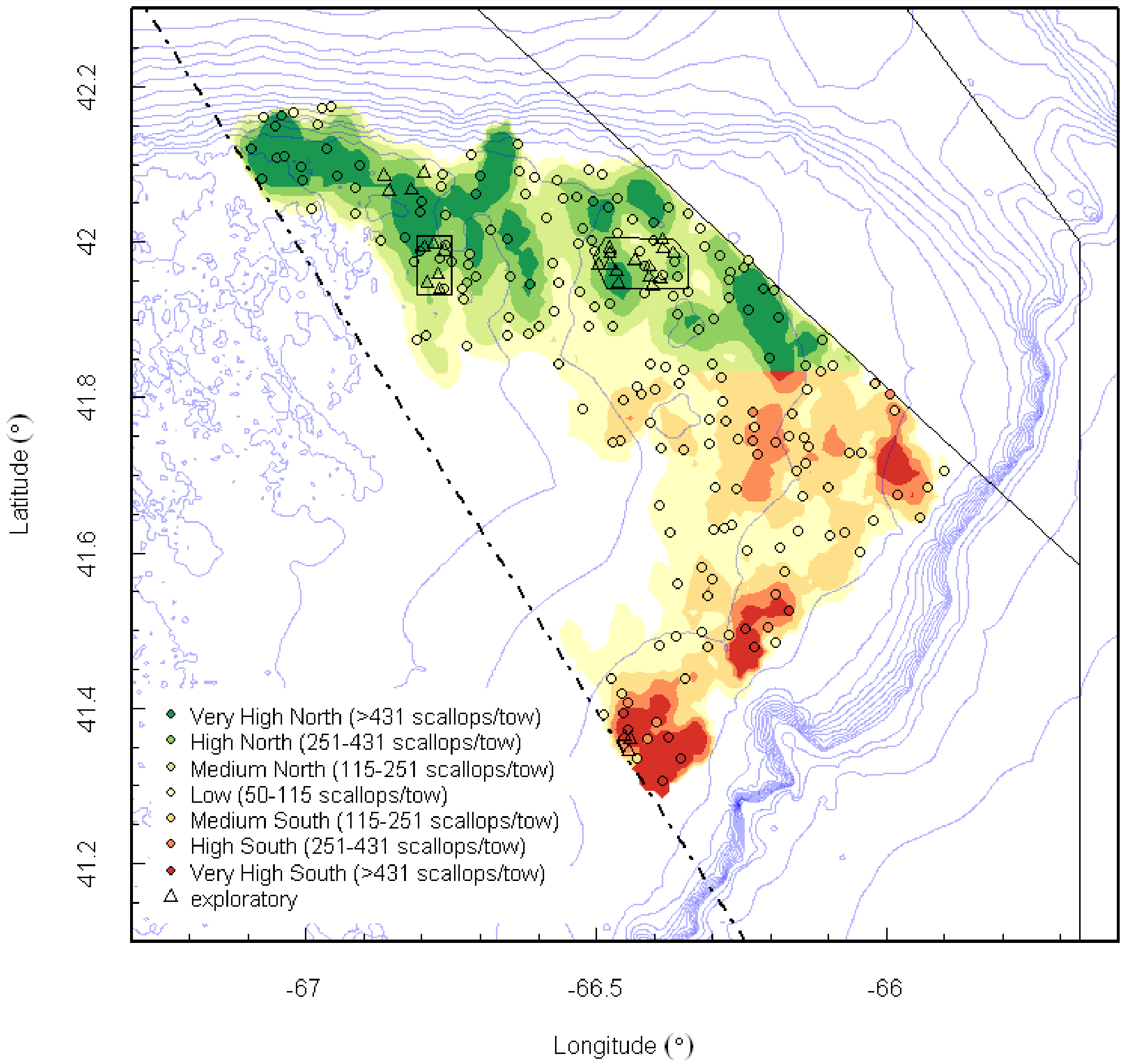


Figure 4. Georges Bank 'a' scallop survey in August 2012. Main survey stations (○; circle) were allocated using a random stratified design based on historical survey index (see legend). Exploratory survey stations (Δ; triangle) and industry-managed closure areas that were in place during 2012 are shown for context.

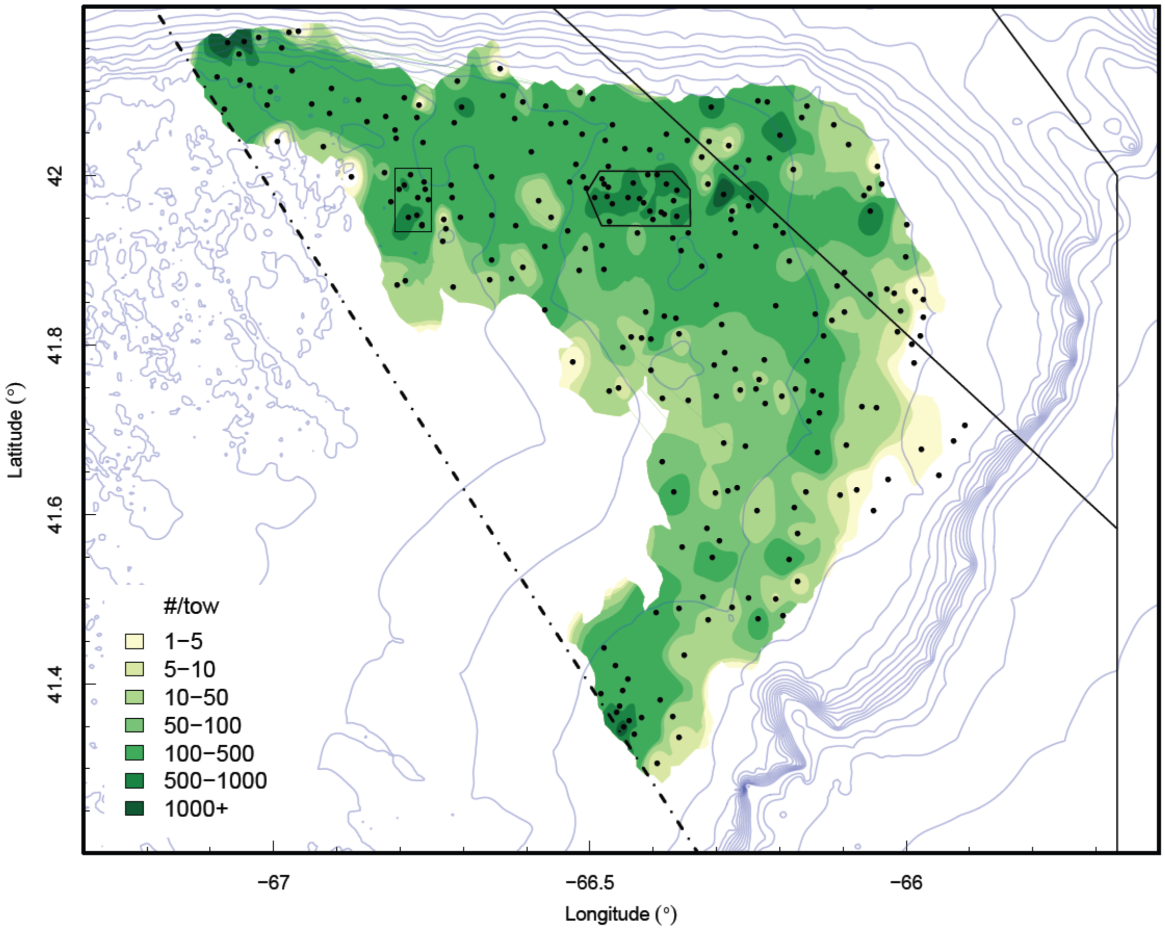


Figure 5. Distribution of fully recruited (≥95 mm shell height) scallops from the survey of Georges Bank August 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Industry-managed closure areas that were in place during 2012 are shown for context.

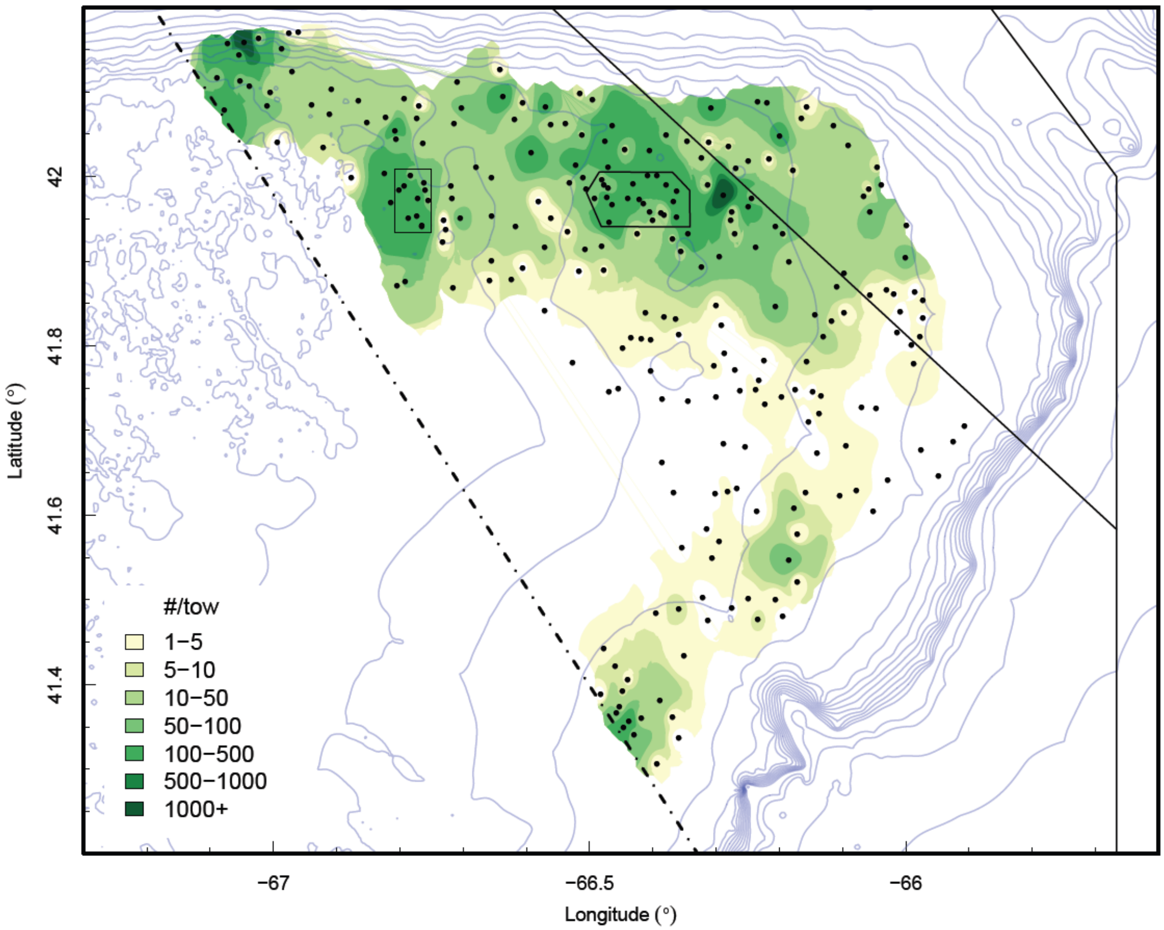


Figure 6. Distribution of recruit (85-95 mm shell height) scallops from the survey of Georges Bank in August 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Industry-managed closure areas that were in place during 2012 are shown for context.

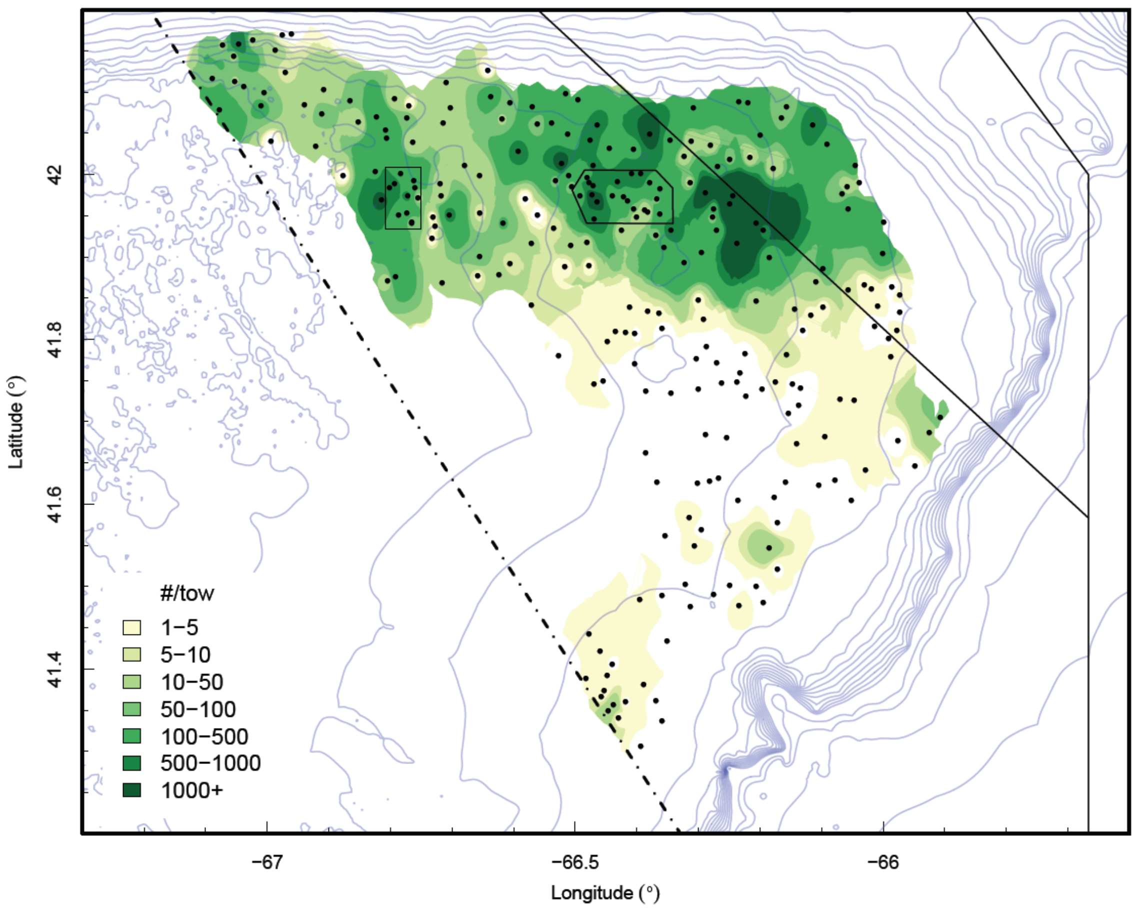
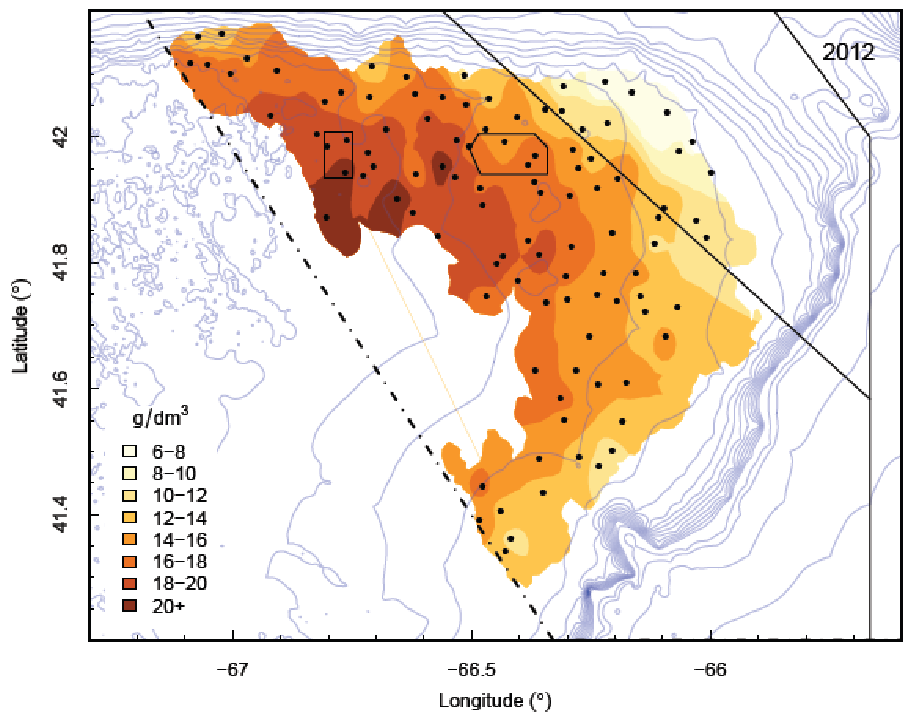


Figure 7. Distribution of pre-recruit (<85 mm shell height) scallops from the survey of Georges Bank in August 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Industry-managed closure areas that were in place during 2012 are shown for context.



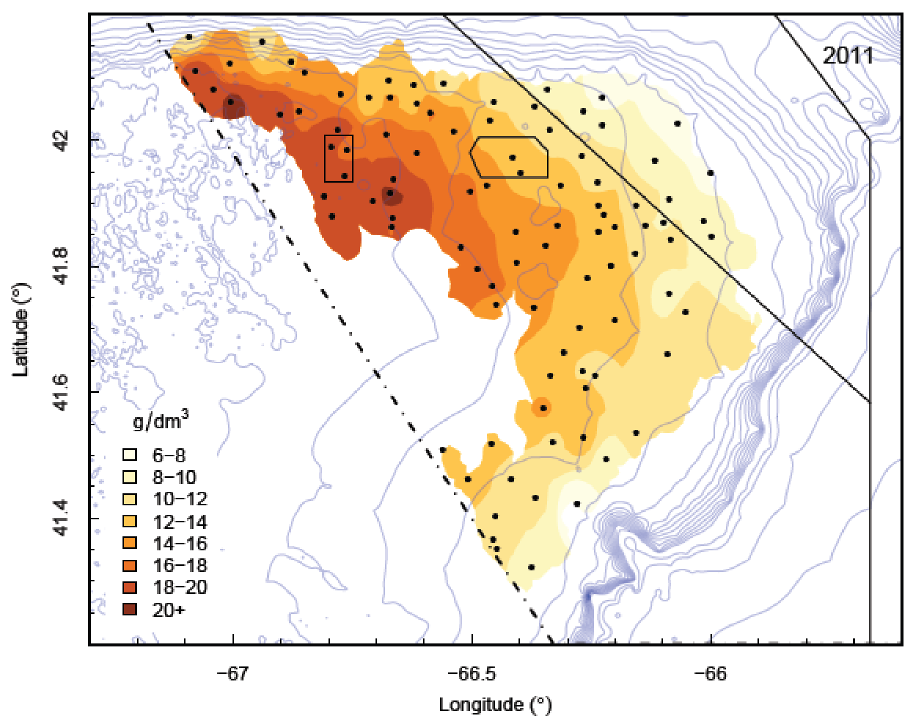


Figure 8. Spatial distribution of condition factor (g/dm^3) from the August survey on Georges Bank for 2012 (upper) and 2011 (lower).

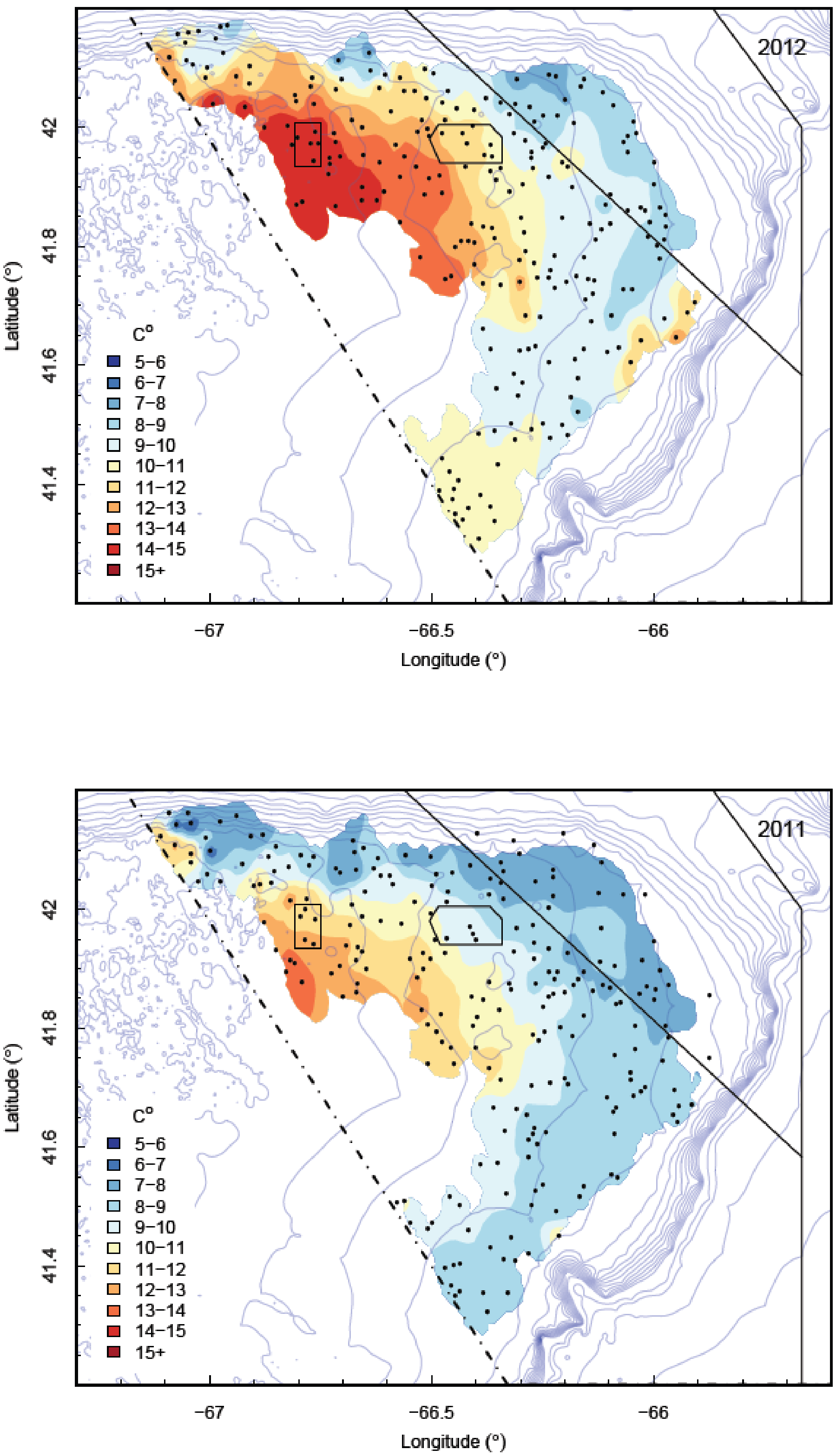


Figure 9. Spatial distribution of bottom temperature (C°) from the August survey on Georges Bank for 2012 (upper) and 2011 (lower).

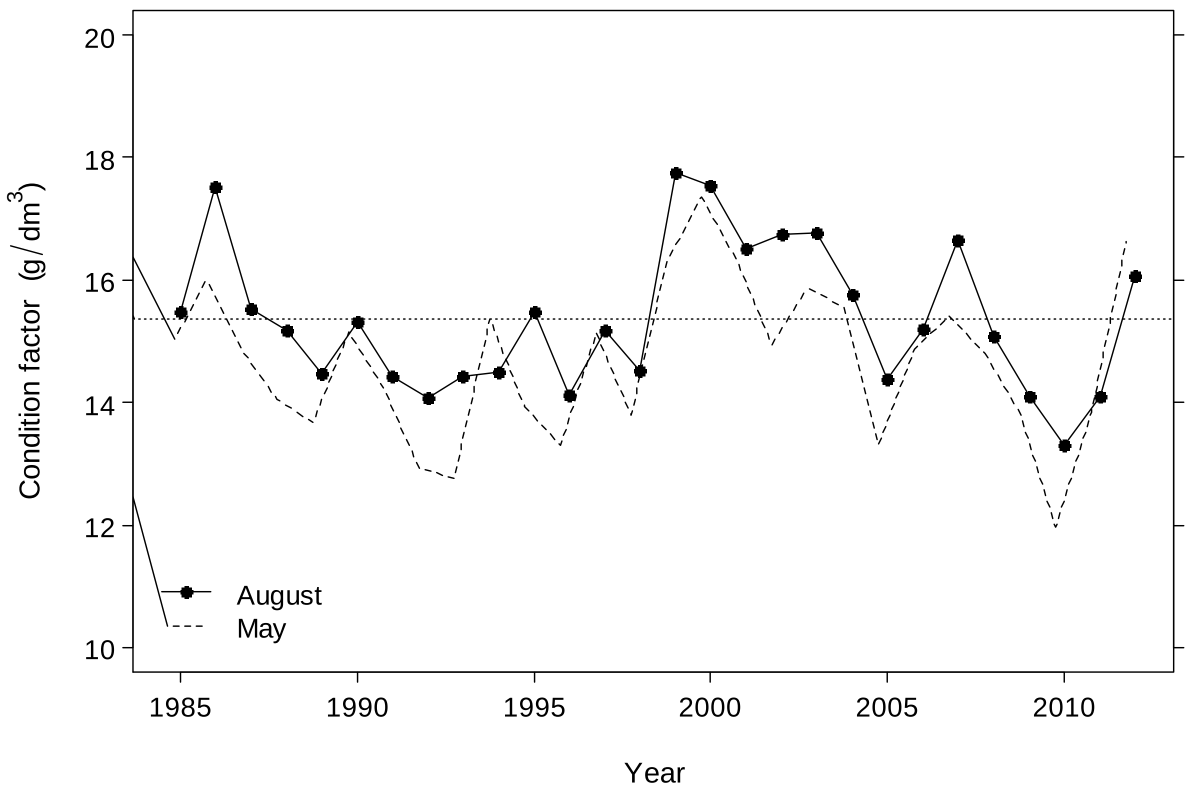


Figure 10. Georges Bank trend in condition factor (g/dm^3) from the annual August and May surveys, from 1985 to 2012.

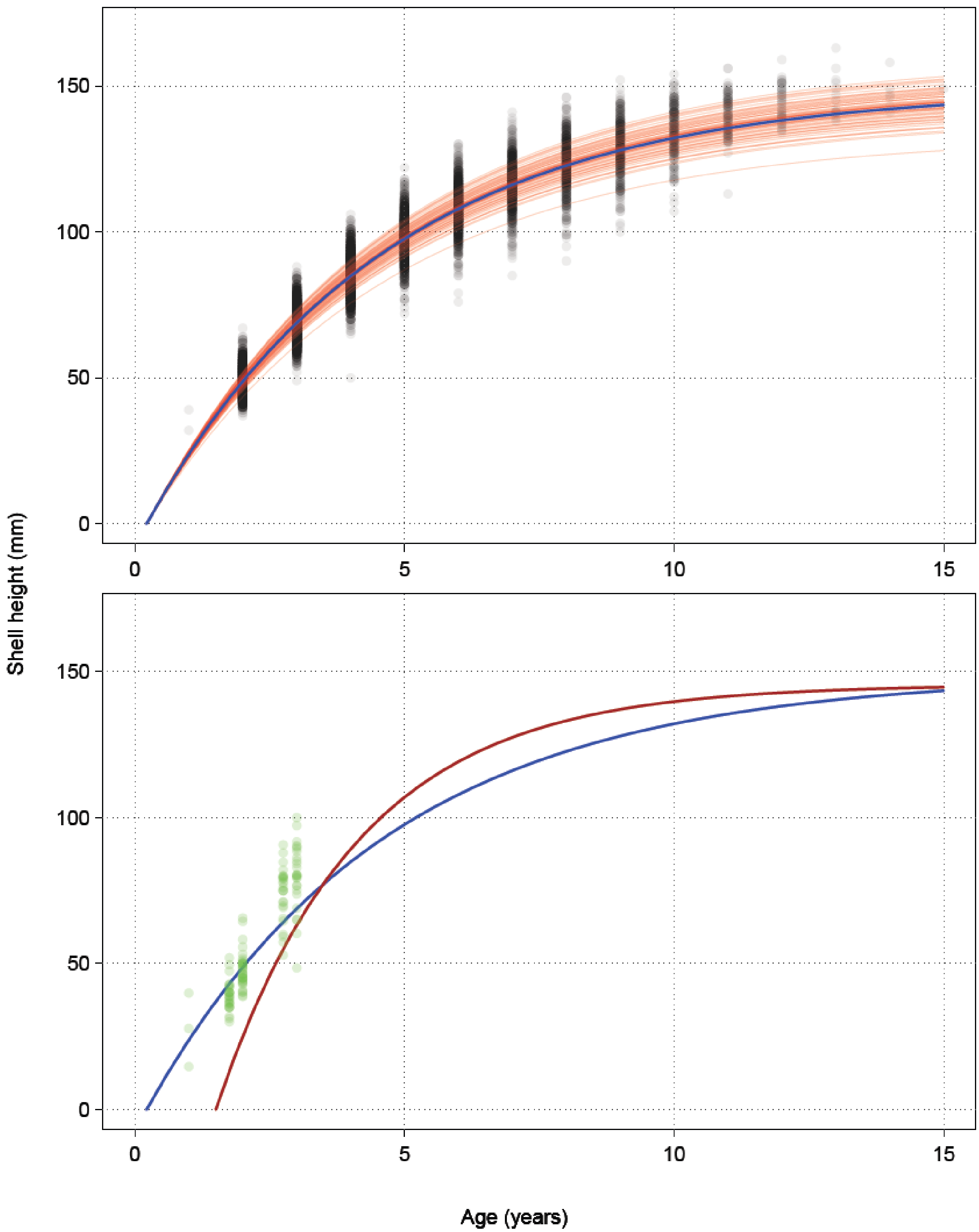


Figure 11. Von Bertlanffy model fit to age data (ages 1-15) collected on the August survey on Georges Bank for 2009-2012 (blue line) with station as a random effect (upper) compared to shell height frequency modes at age (green points) and a growth curve from Brown et al. (1972) (red line).

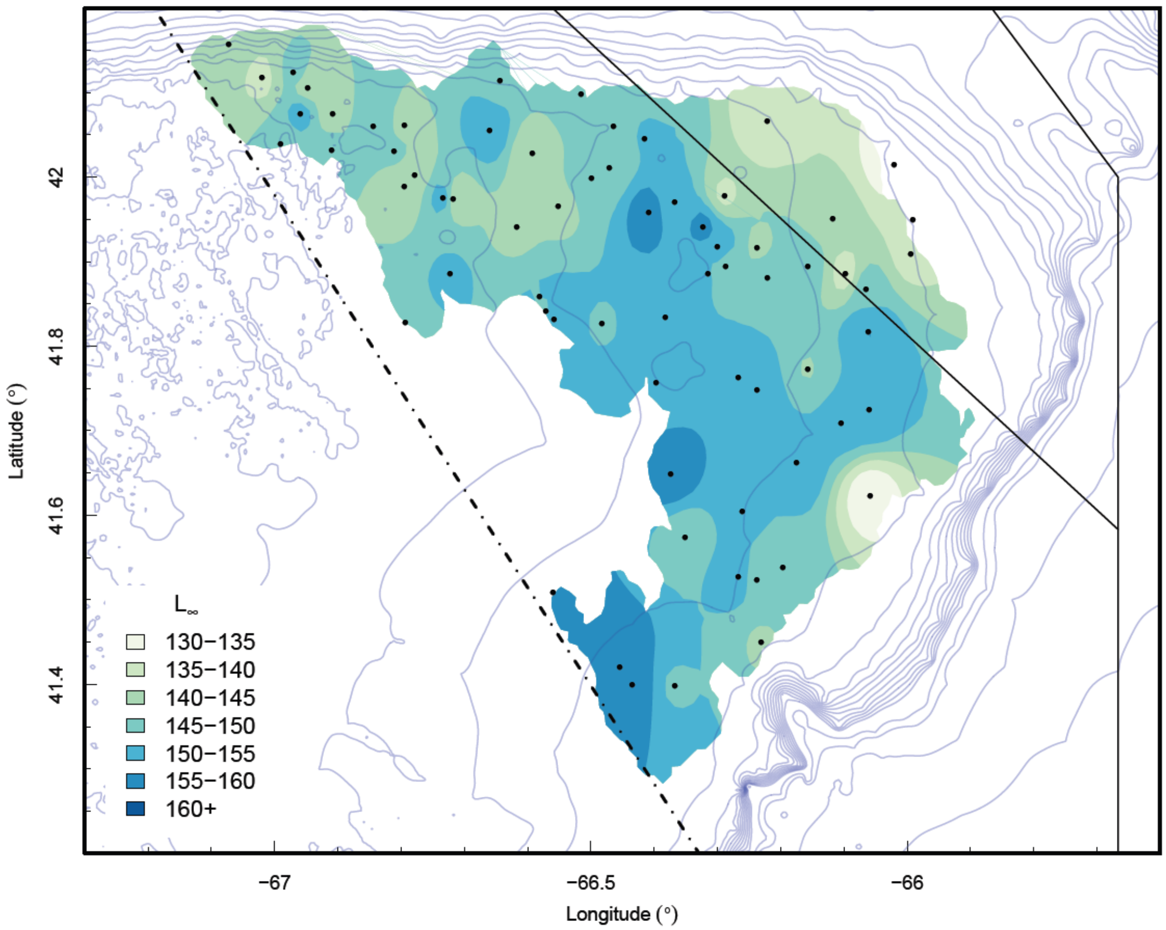


Figure 12. Spatial pattern of the asymptotic shell height parameter (L_∞) from age data collected on the August survey on Georges Bank for 2009-2012.

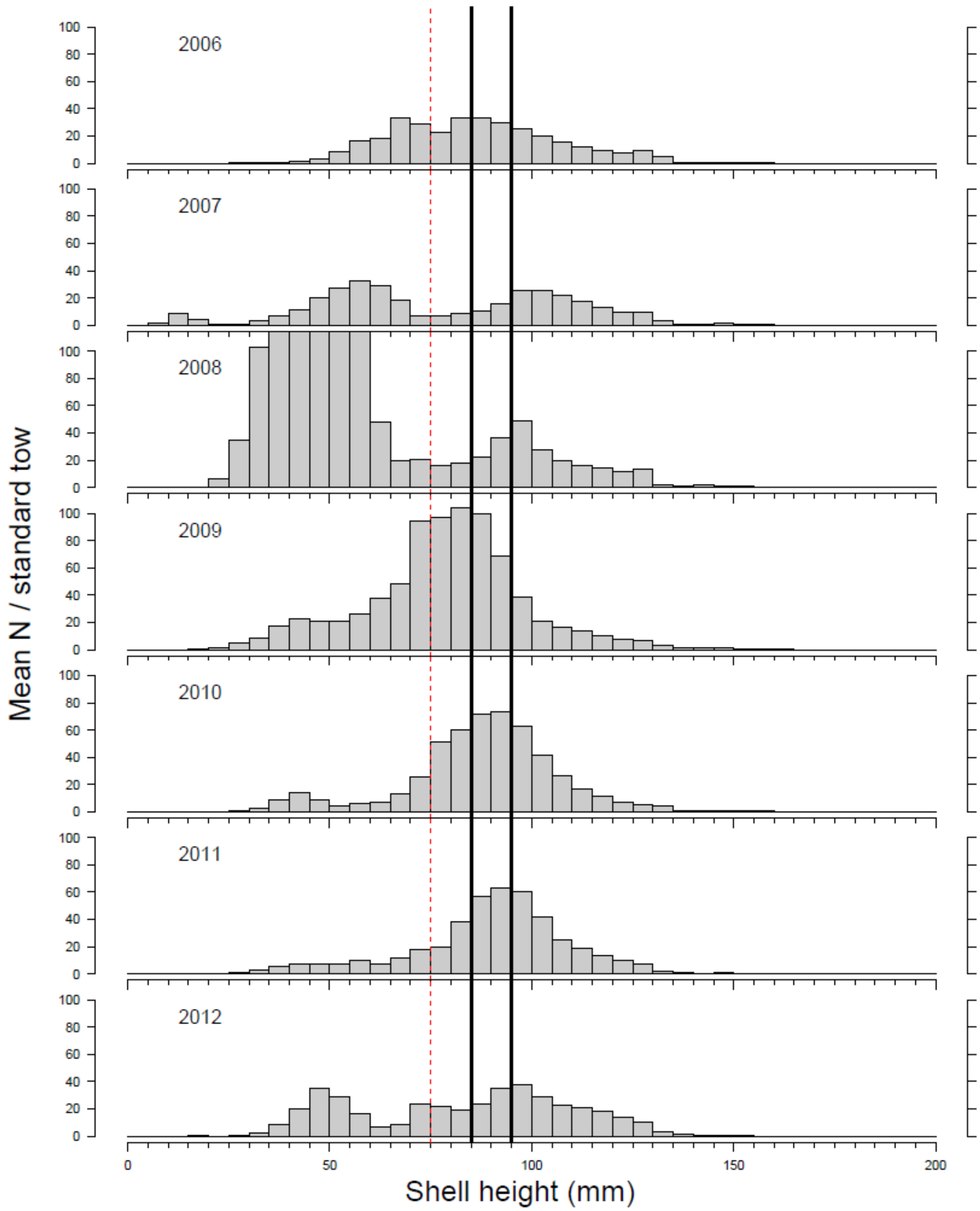


Figure 13. Shell height (mm) frequency plot showing the mean number (N) of scallops per standard tow (800 m x 2.44 m drag) from August survey of Georges Bank 'a' (2006-2012) for each 5 mm bin. Vertical lines divide the pre-recruit, recruit and fully-recruited size classes. Red dashed line is for the recruitment defined using the old growth parameters from Brown et al. (1972).

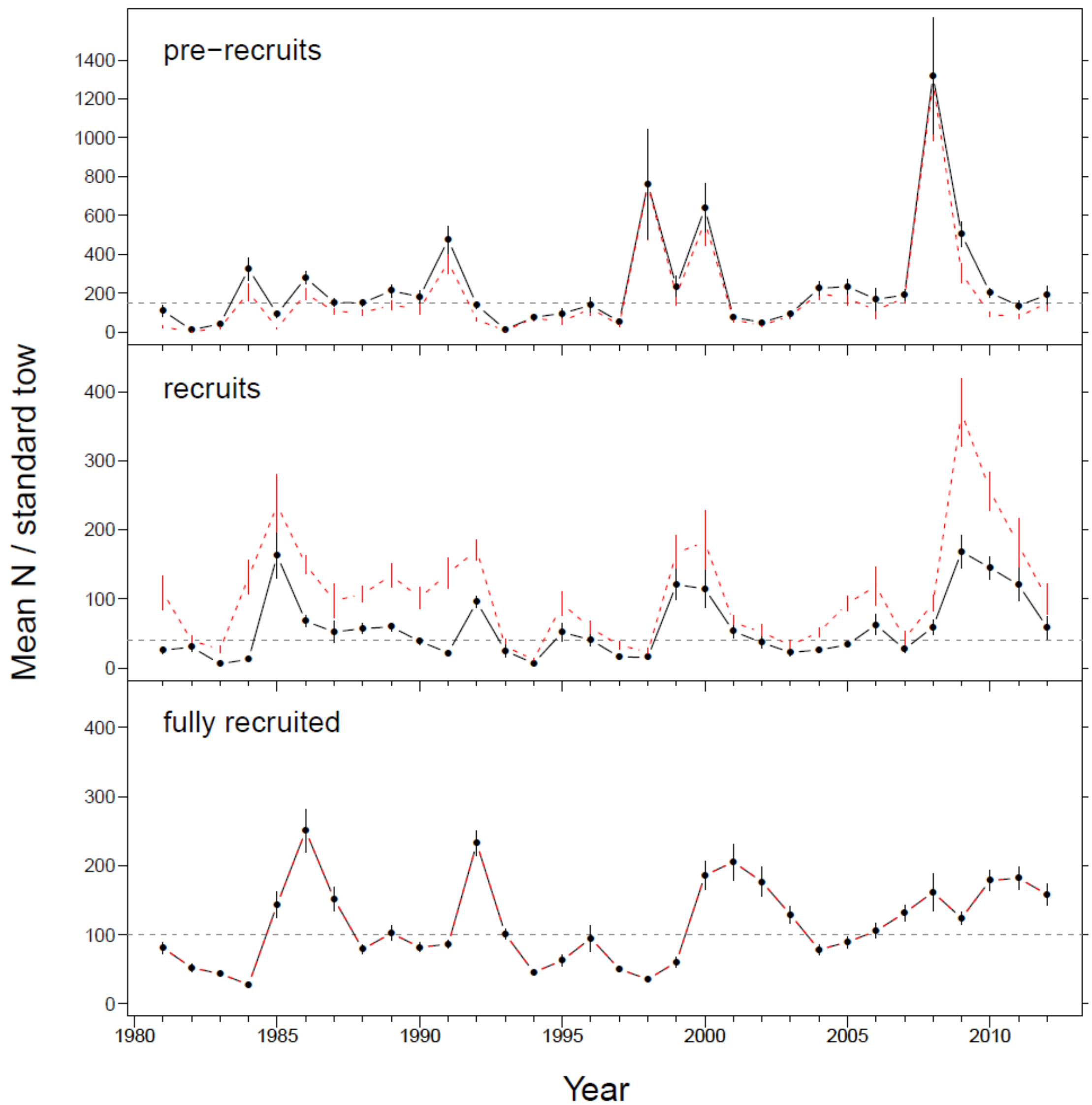


Figure 14. Stratified mean abundance per standard tow (800 m x 2.44 m drag) of scallops from August survey of Georges Bank 'a' (1981-2012). Upper panel shows pre-recruits, middle panel shows recruits and lower panel shows full-recruited. Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error. Red dashed line is for the recruitment defined using the old growth parameters from Brown et al. (1972).

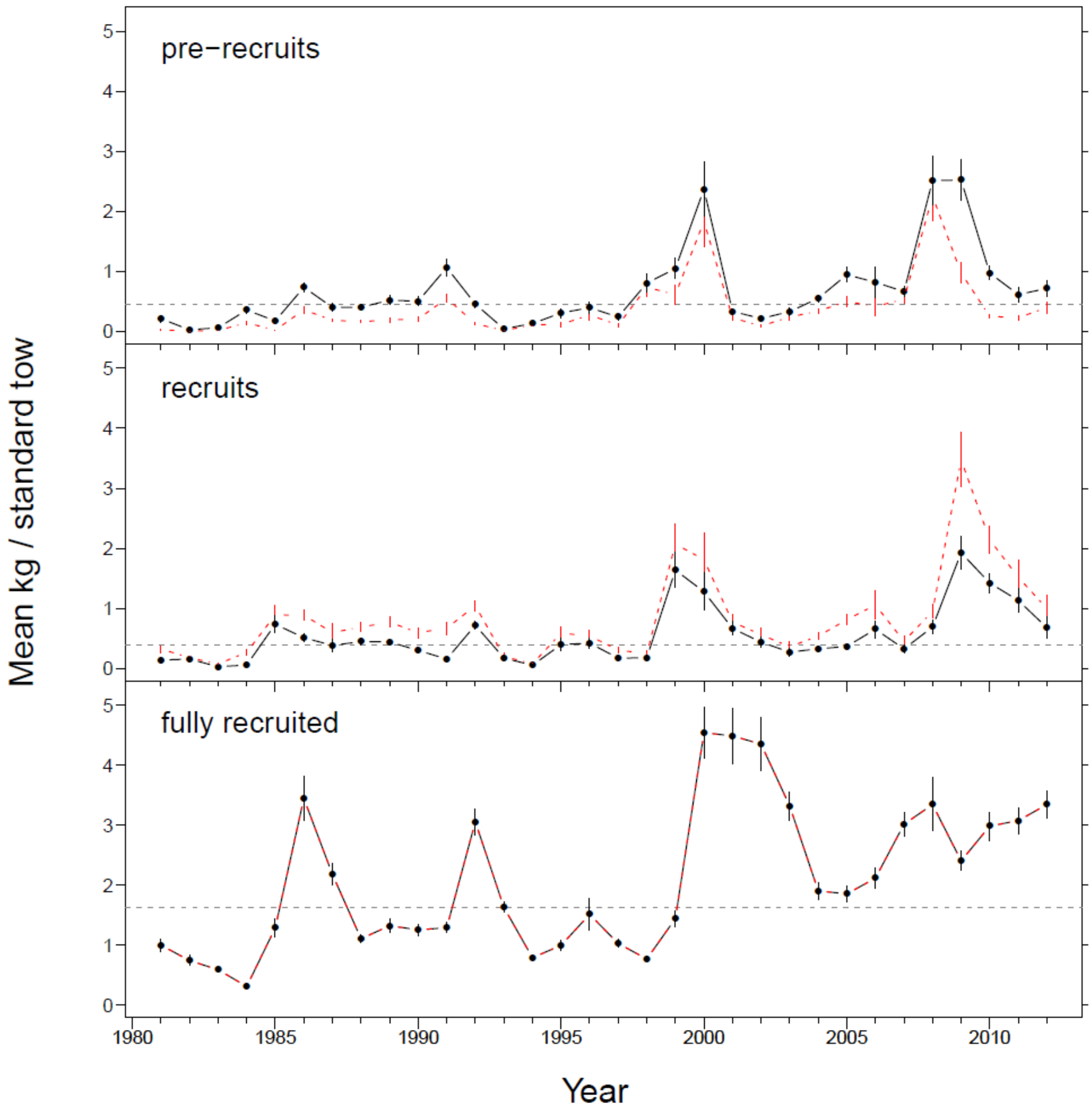


Figure 15. Stratified mean biomass per standard tow (800 m x 2.44 m drag) of scallop abductor muscles from August survey of Georges Bank 'a' (1981-2012). Upper panel shows pre-recruits, middle panel shows recruits and lower panel shows full-recruited. Horizontal dashed lines are the long-term medians and vertical lines are ± one standard error. Red dashed line is for the recruitment defined using the old growth parameters from Brown et al. (1972).

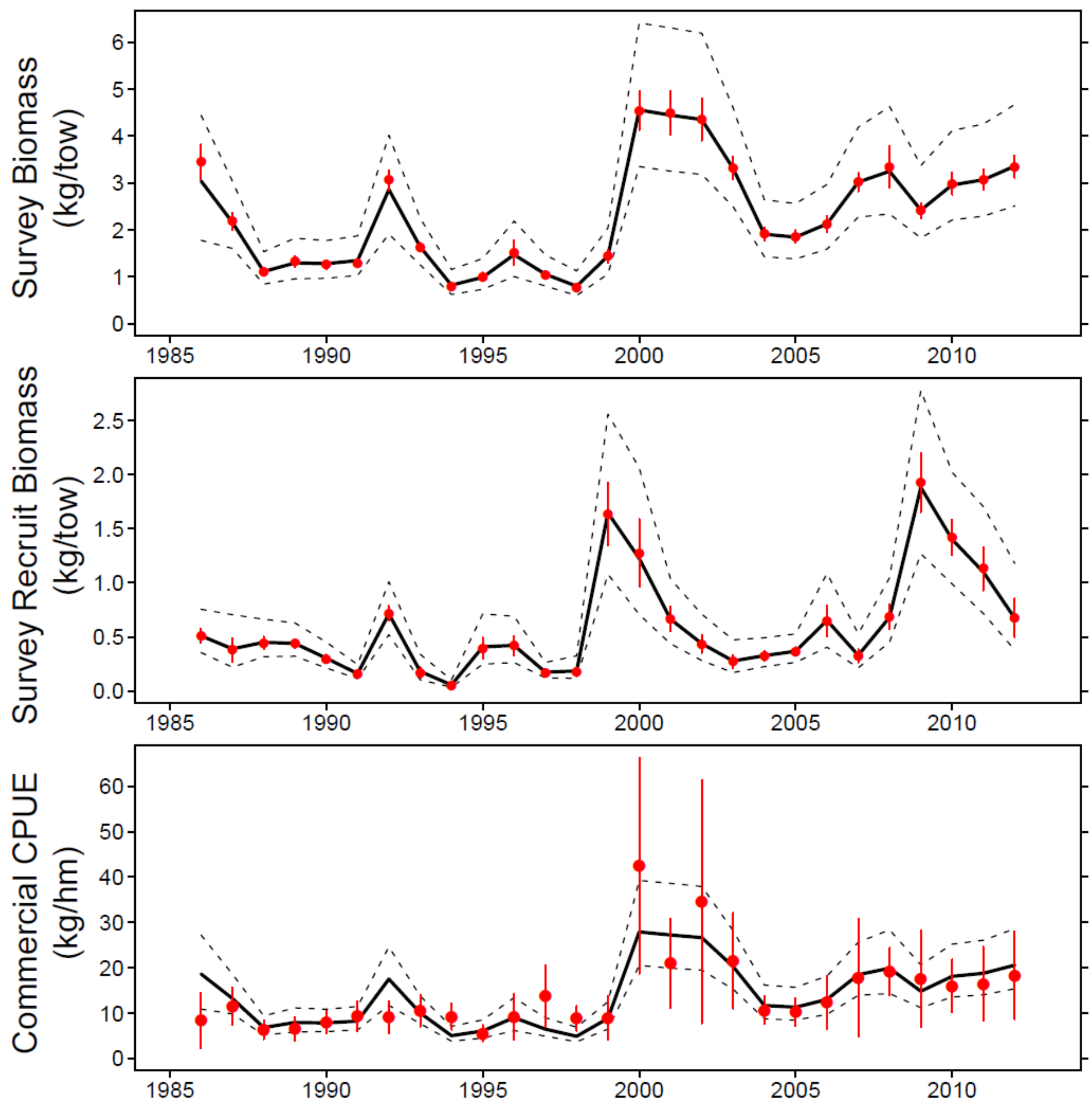


Figure 16. Fit of the stock assessment model to observed biomass indices(upper panel: survey biomass (kg/tow); middle panel: survey recruitment biomass (kg/tow); lower panel: commercial CPUE (kg/hm) (●; red filled circle) for Georges Bank 'a'. Dotted lines represent 95% credible limits and vertical error bars represent ± (plus or minus) one standard error.

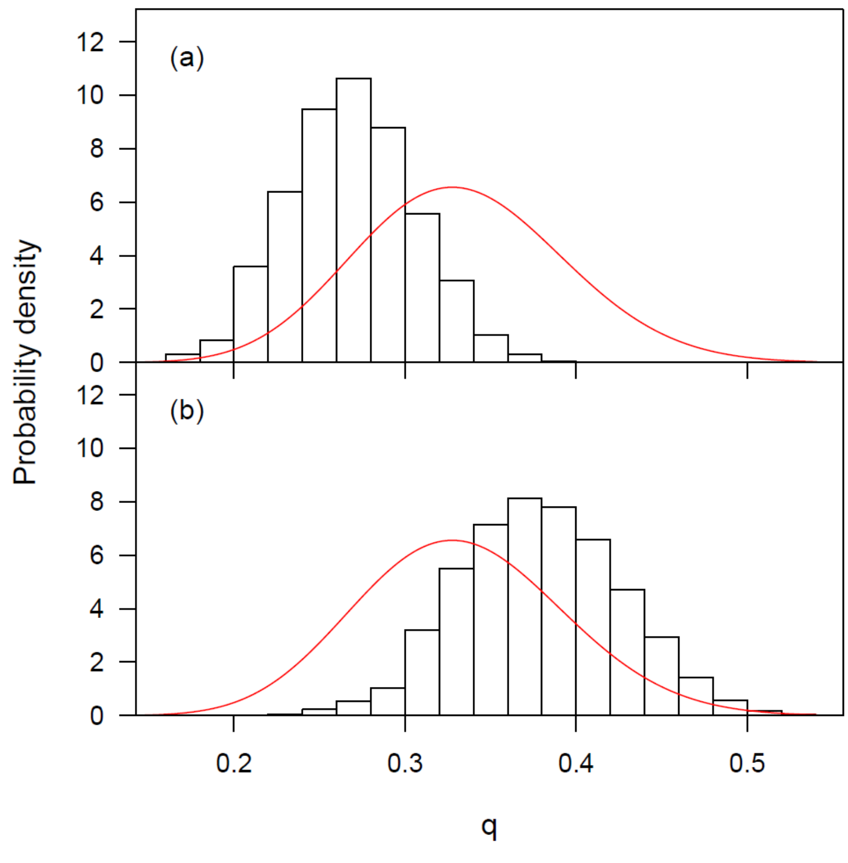


Figure 17. Posteriors and priors (red line) for the survey catchability parameter (q). Panel (a) shows a q posterior resulting from the model fit to the lower recruit index from the new growth parameters. Panel (b) shows a q posterior resulting from the model fit to the higher recruit index from the old growth parameters.

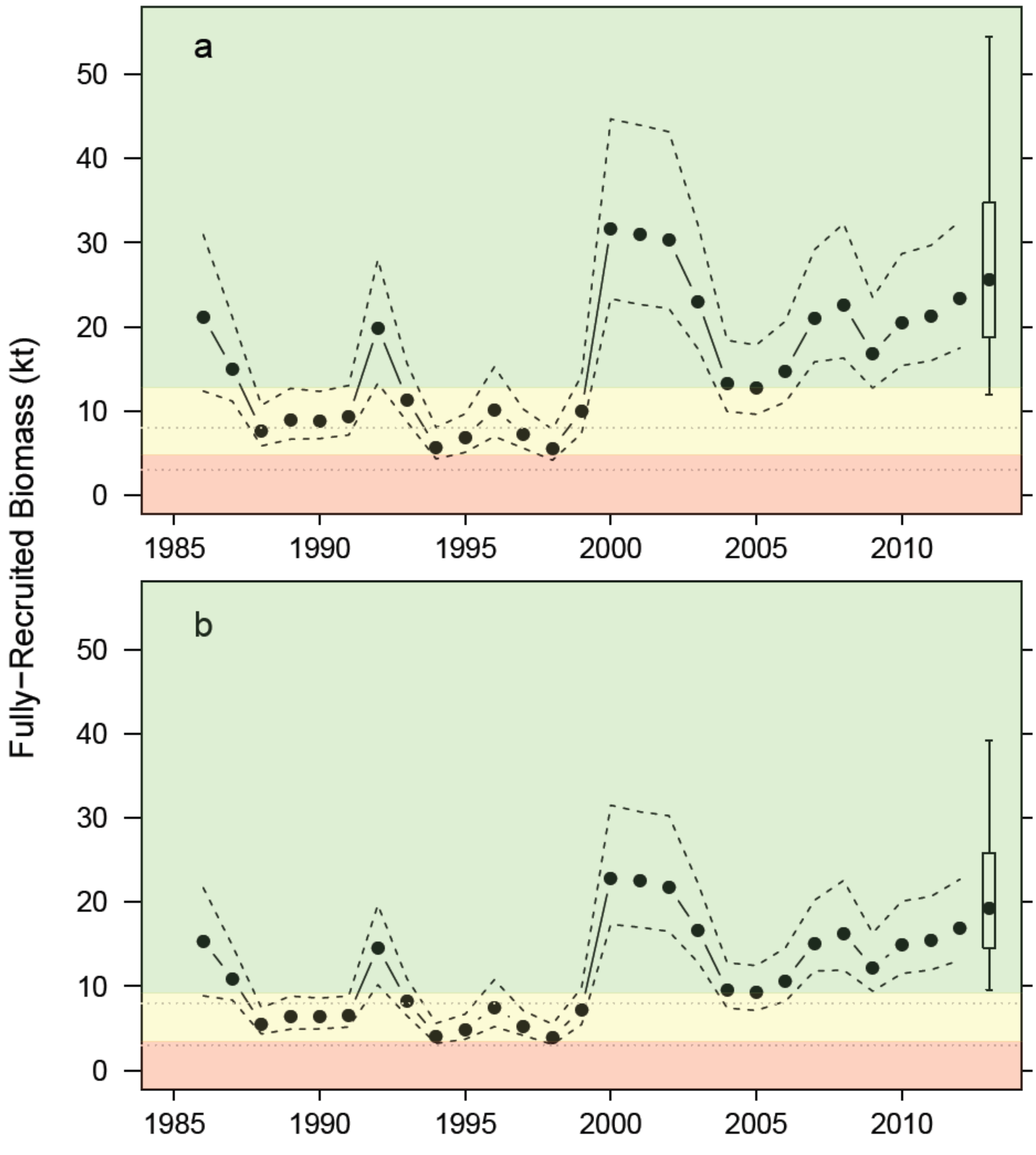


Figure 18. Biomass estimates (kt) for fully recruited scallops from the stock assessment model fit to the Georges Bank 'a' data using new (upper panel) and old (lower panel) growth parameters (1986-2012). Dashed lines are the upper and lower 95% credible limits on the estimates. The predicted fully recruited biomass for 2013, assuming the interim catch (4000 t), is displayed as a box plot with median, 50% credible limits (box) and 80% credible limits (whiskers). Coloured zones represent the healthy (green), cautious (yellow) and critical (red) when reference points are calculated as 80% and 30% of mean biomass. Dotted grey lines represent fixed reference points of 8,000 t and 3,000 t.

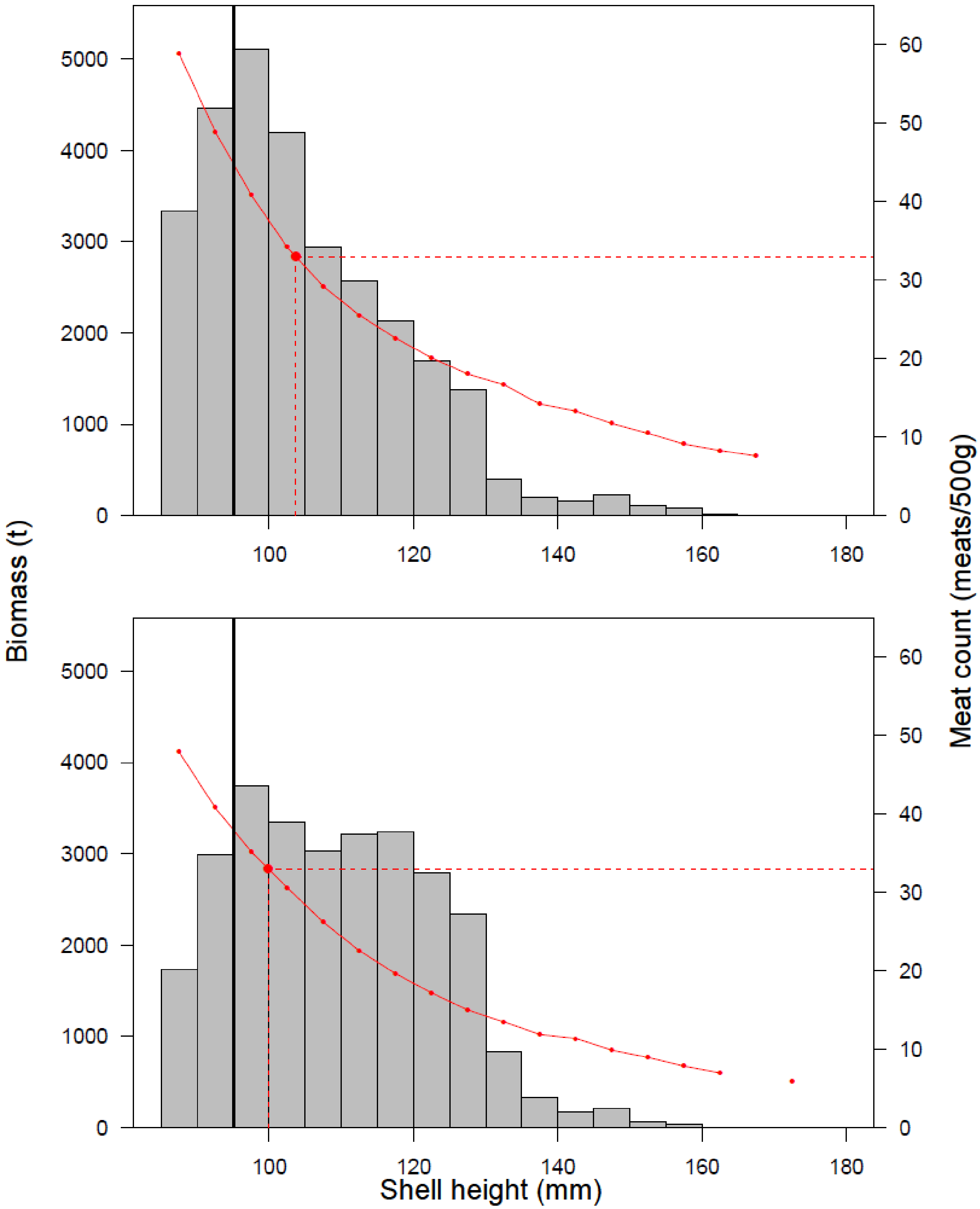


Figure 19. Breakdown of 2011(upper panel) and 2012 (lower panel) estimated recruit and fully recruited biomass (t) for Georges Bank 'a' by shell height (mm). The solid red line is the observed meat count (meats/500 g) at shell height in the August survey. The dashed red line indicates what shell height corresponds to the meat count regulation of 33 per 500 g.

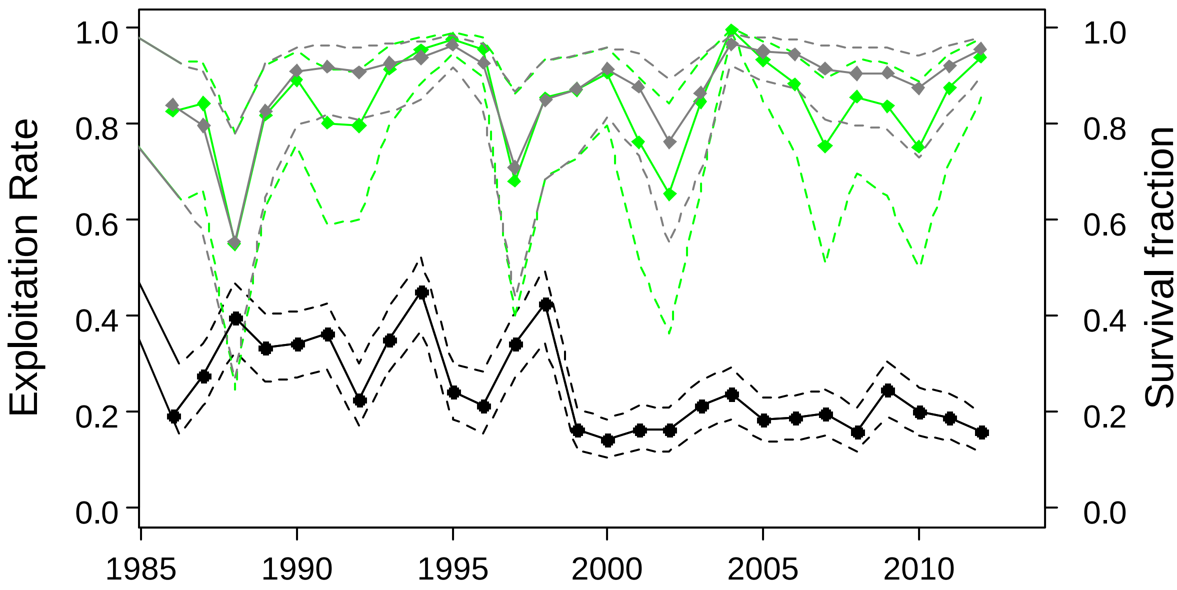


Figure 20. Annual trends in exploitation (black line, circles) and survival estimates (exp(-m)), where m is natural mortality of fully recruited (grey line, squares) and recruit size scallops (green line, squares), from 1986 to 2012. Dashed lines are the upper and lower 95% credible limits on the estimates.

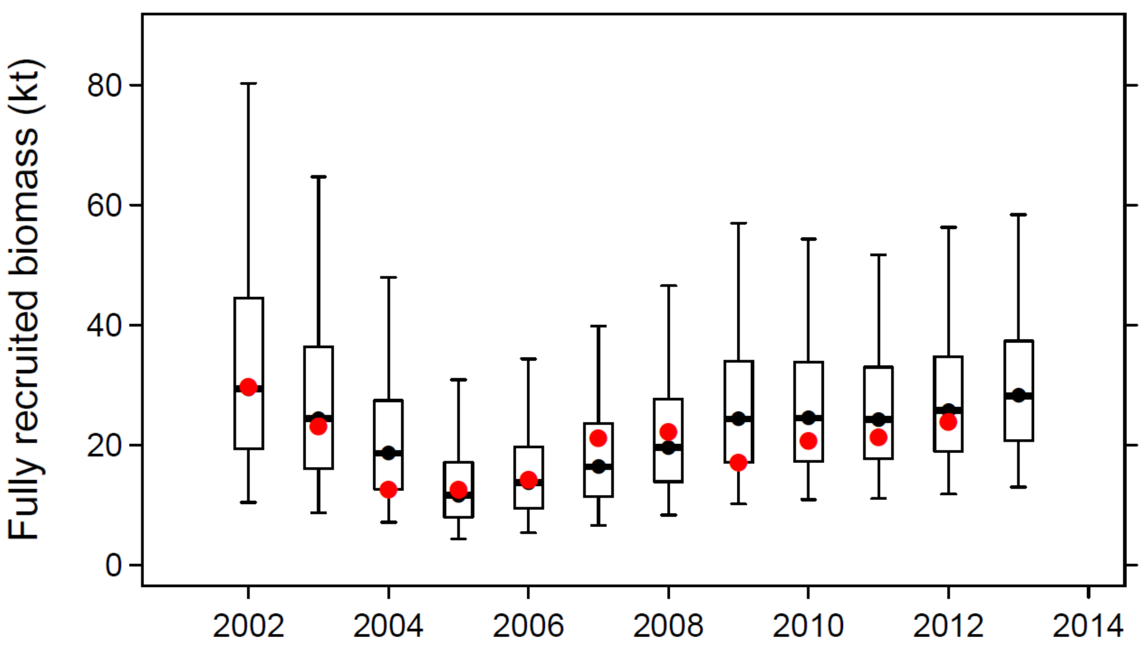


Figure 21. Evaluation of the model projection performance for Georges Bank 'a'. Box and whisker plots summarize posterior distribution of fully recruited biomass (kt) in year t based on model fit to year t-1 (e.g., 2006 prediction based on data up to 2005), from 2002 to 2014. Red dot represents the estimate of the biomass in year t using data up to and including year t.

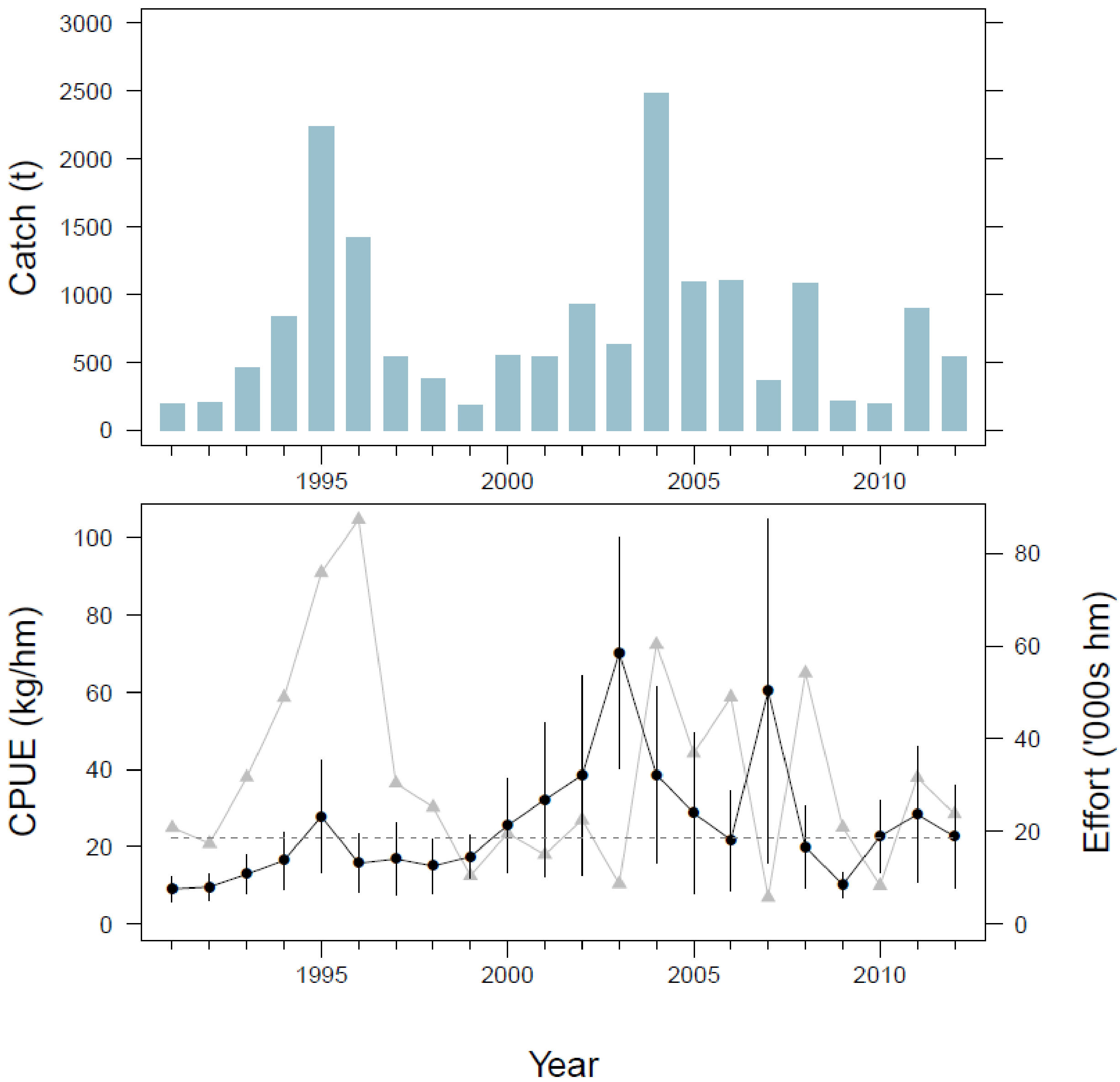


Figure 22. Summary of fishery inputs based on survey year (June–May). Upper panel shows landings in tons of meat (abductor muscle). Lower panel shows catch per unit effort (●, black filled circle) and total effort (▲; grey filled triangle) for the scallop fishery on Browns Bank north during the survey year (June to May; 1985-2012). Vertical lines are ± (plus or minus) one standard error from jackknife estimates of CPUE.

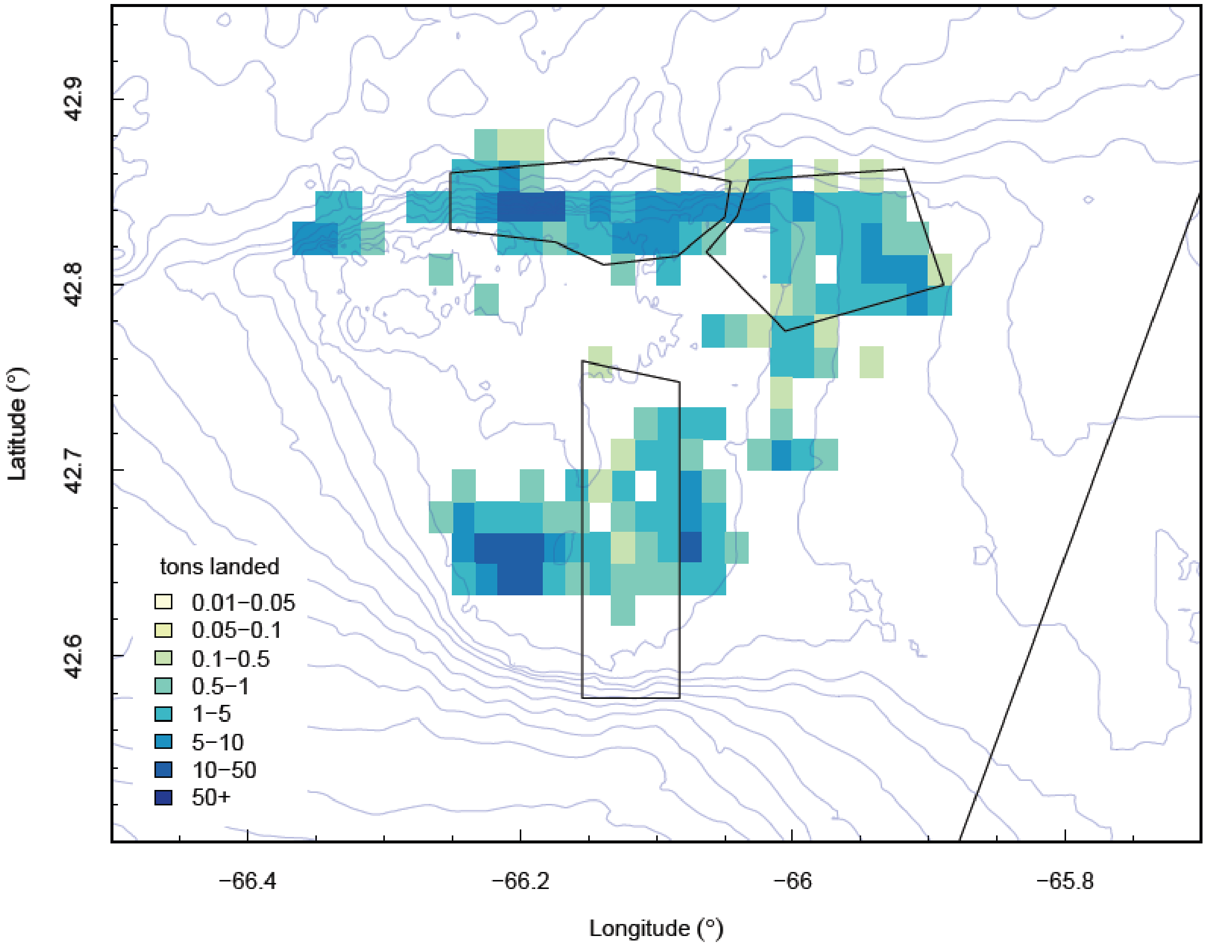


Figure 23. Spatial distribution of landings from Browns Bank north in 2012. Landings reported in commercial fishing logs are summed for each one minute square. Industry-managed closure areas that were in place in the past are shown for spatial reference.

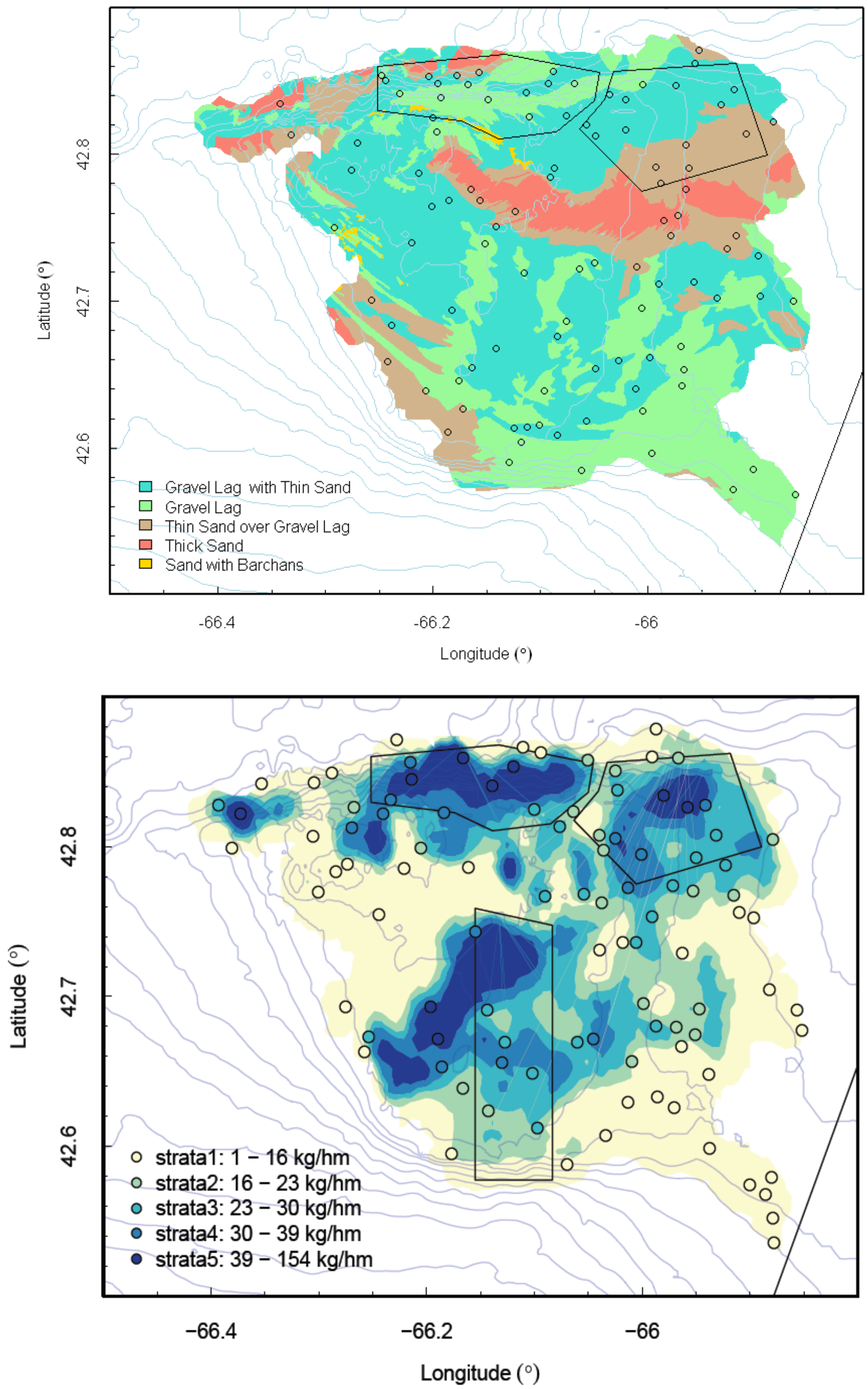


Figure 24. Comparison of stratification schemes for the Browns Bank north survey. Upper panel is based on bottom type (2012) and the lower panel is based on historical catch rate from 2002–2012 (2013).

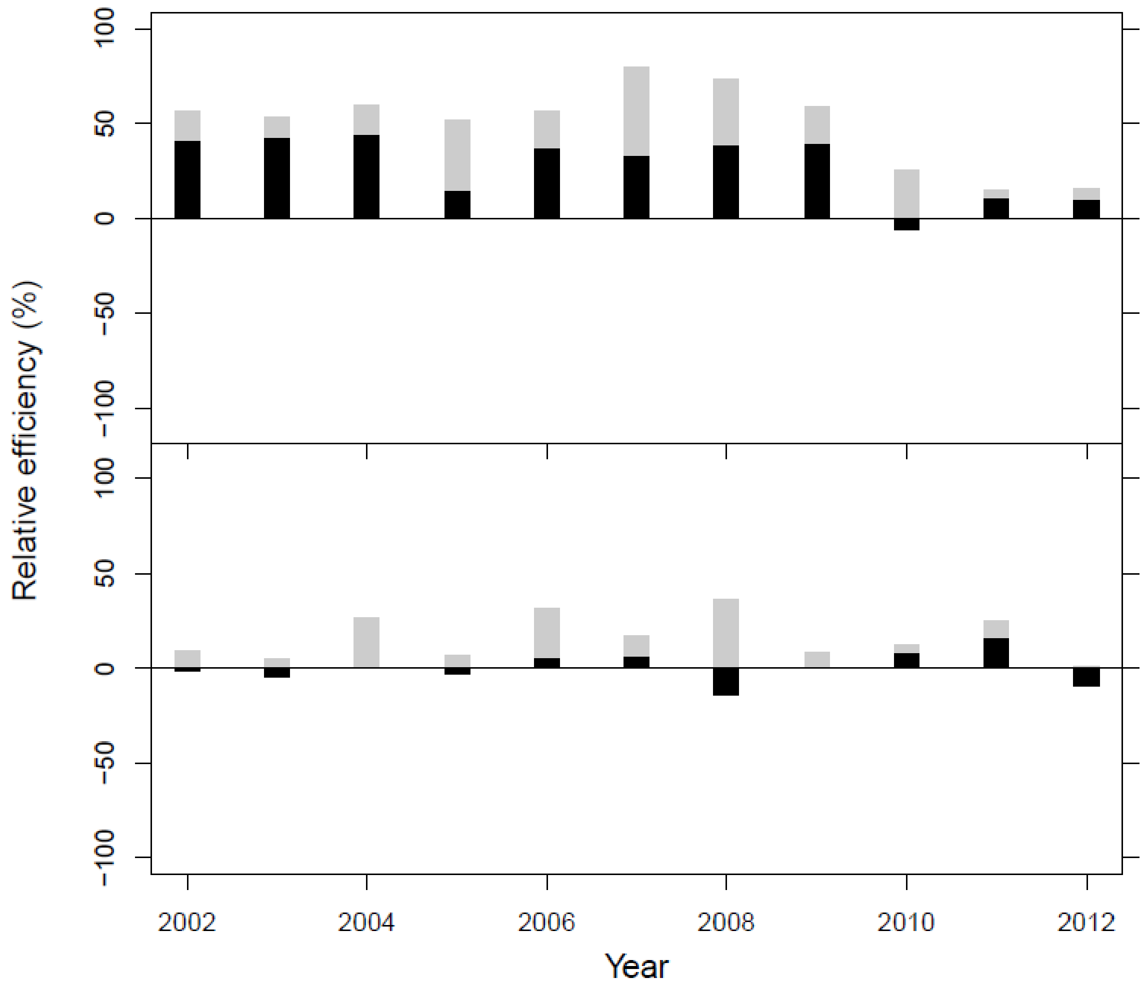


Figure 25. Realized (■; black filled square) and potential (■; grey filled square) relative efficiencies of the historical catch rate design for the survey of sea scallops (Placopecten magellanicus) on Browns Bank north (2002-2012).The upper panel shows the efficiencies relative to the bottom type stratified design and the lower panel shows the efficiencies relative to simple random sampling.

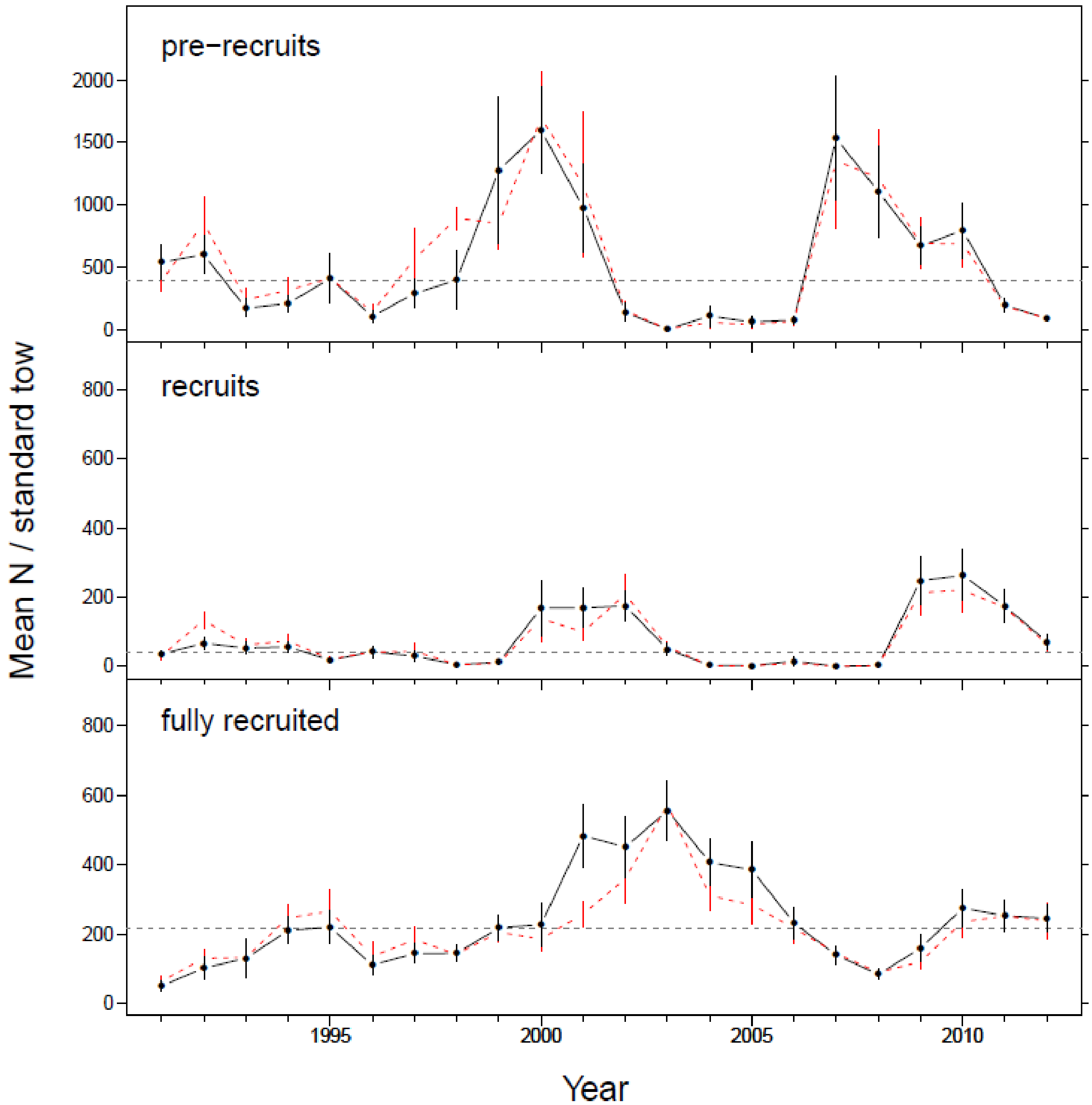


Figure 26. Stratified mean abundance per standard tow (800 m x 2.44 m drag) of scallops from May survey of Browns Bank north (1991-2012). Upper panel shows pre-recruits, middle panel shows recruits and lower panel shows full-recruited. Horizontal dashed lines are the long-term medians and vertical lines are ± (plus or minus) one standard error. Red dashed line represents the indices using the bottom type stratification scheme.

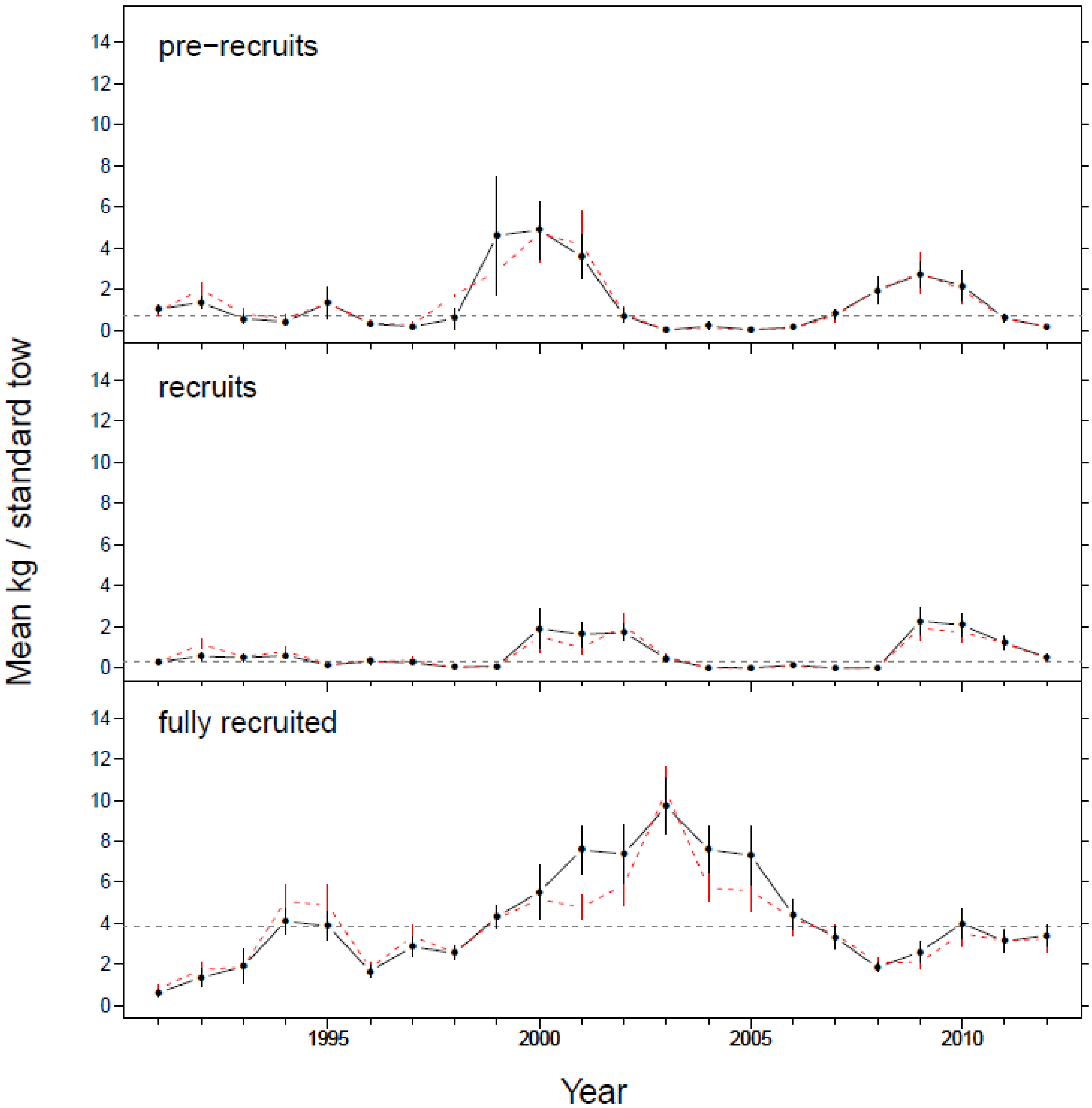


Figure 27. Stratified mean biomass per standard tow (800 m x 2.44 m drag) of scallop abductor muscles from May survey of Browns Bank north (1991-2012). Upper panel shows pre-recruits, middle panel shows recruits and lower panel shows full-recruited. Horizontal dashed lines are the long-term medians and vertical lines are ± (plus or minus) one standard error. Red dashed line represents the indices using the bottom type stratification scheme.

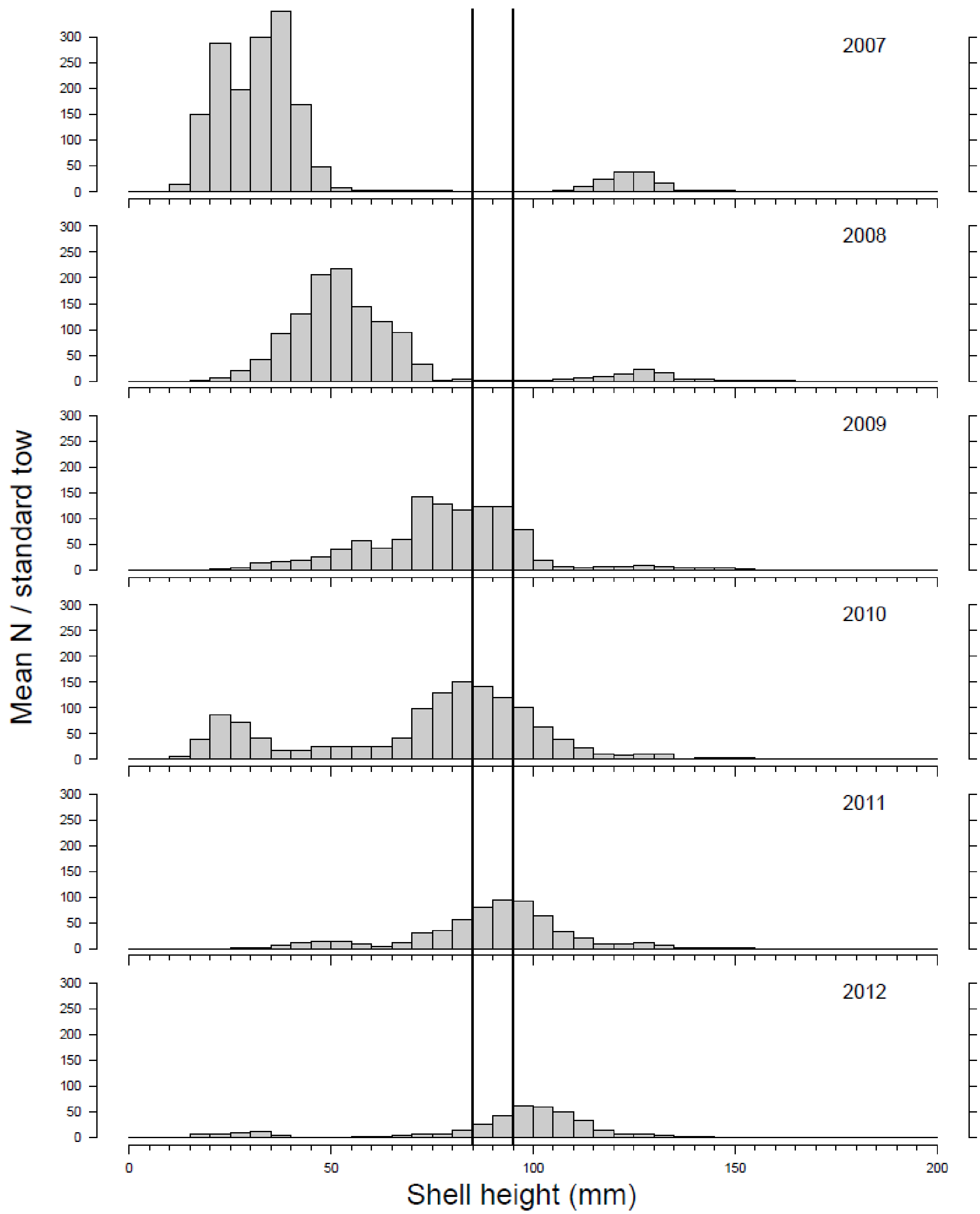


Figure 28. Shell height (mm) frequency plot showing the mean number of scallops per standard tow (800 m x 2.44 m drag) from spring survey of Browns Bank north (2007-2012) for each 5 mm bin. Vertical lines divide the pre-recruit, recruit and fully-recruited size classes.

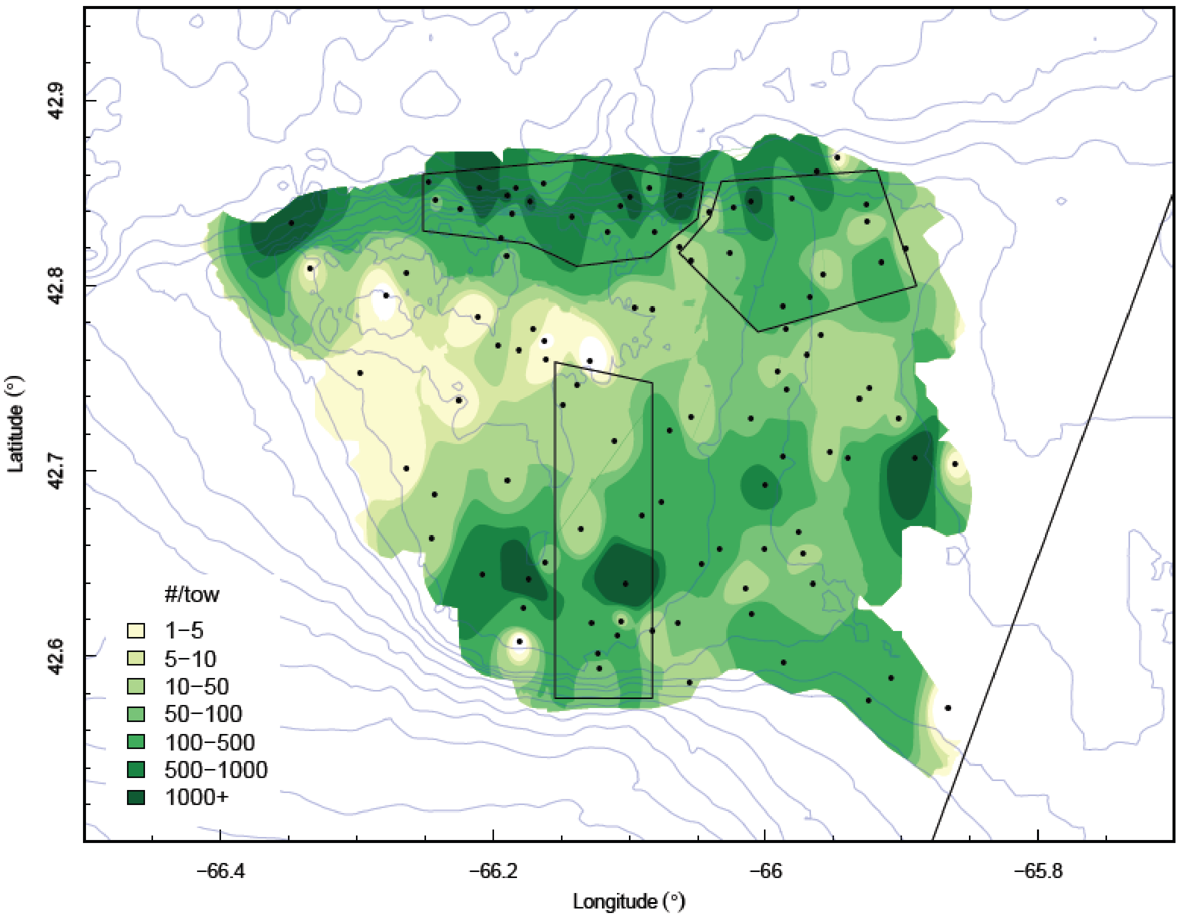


Figure 29. Distribution of fully recruited (≥95 mm shell height) scallops from the survey of Browns Bank north in May 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

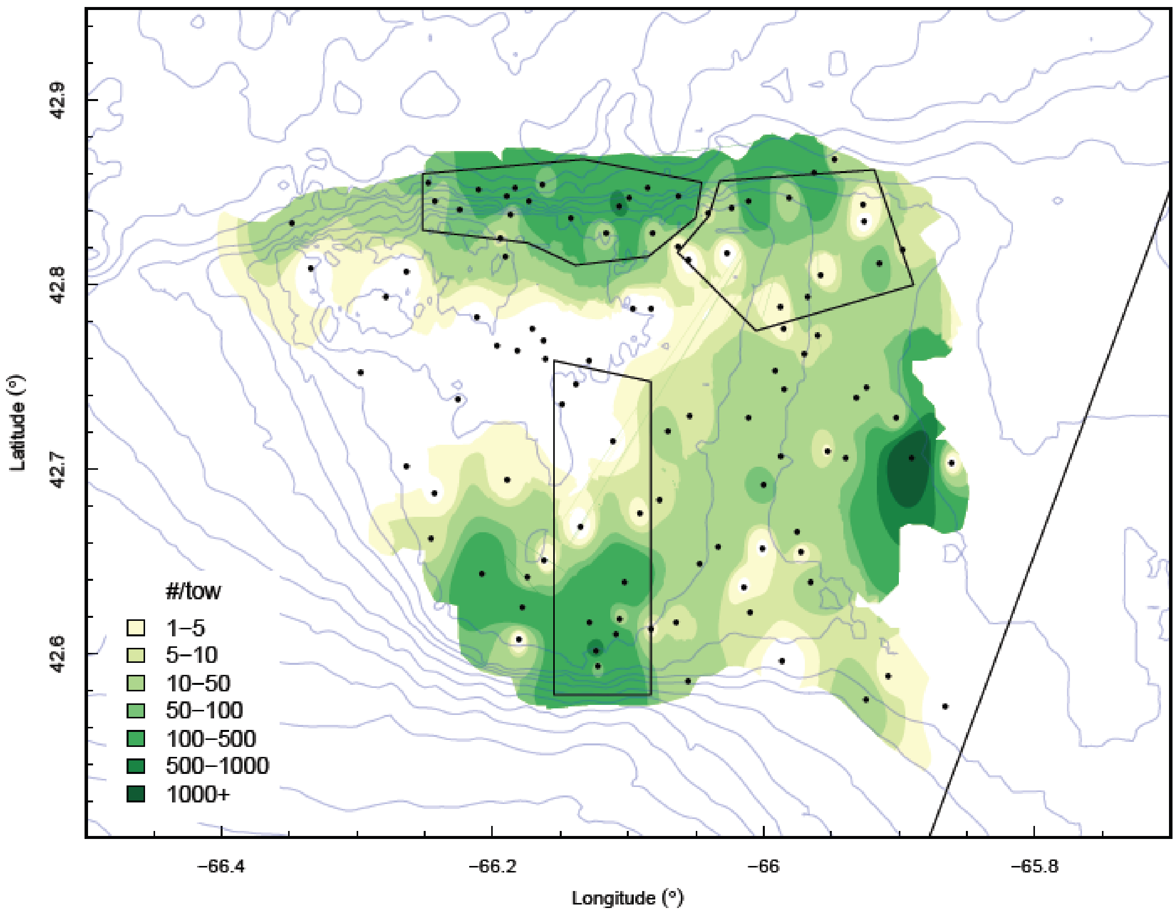


Figure 30. Distribution of recruit (85-95 mm shell height) scallops from the survey of Browns Bank north in May 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.

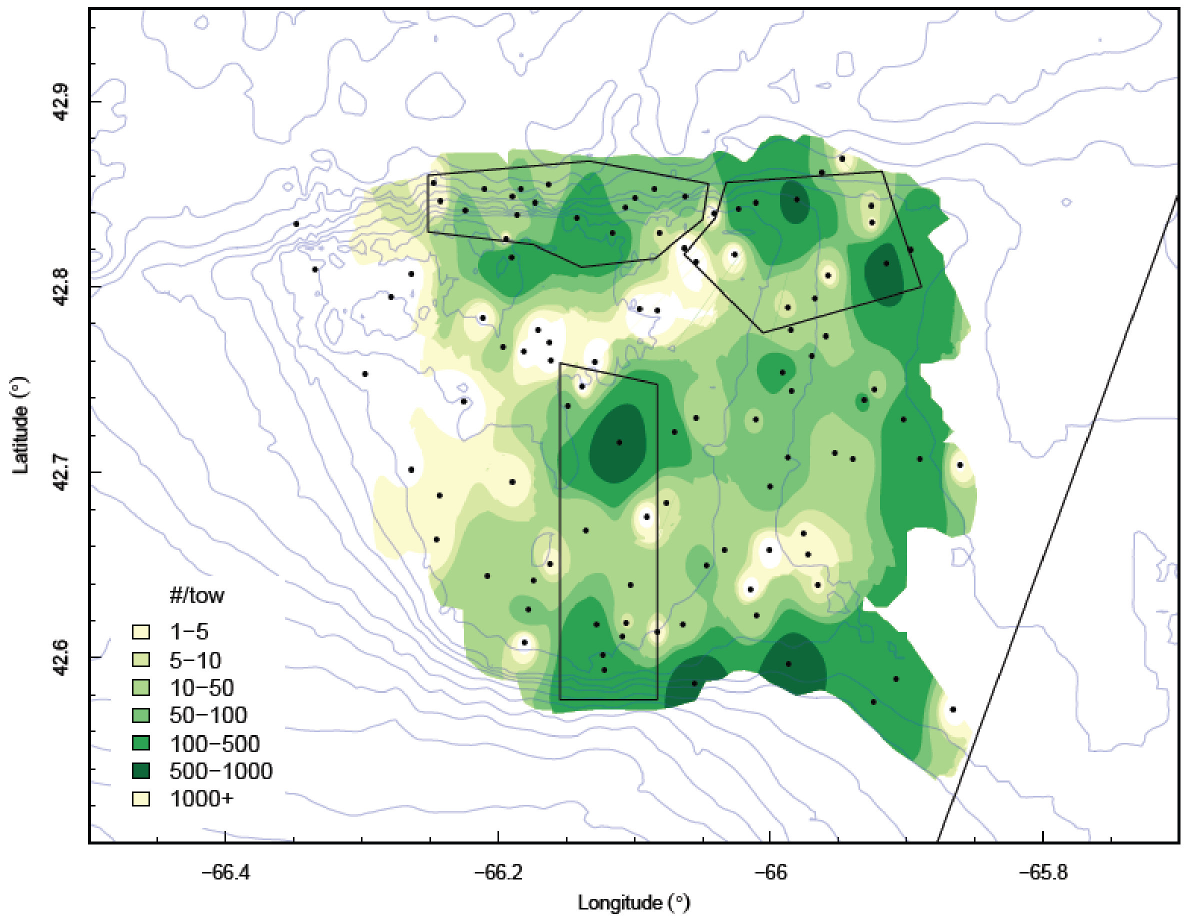
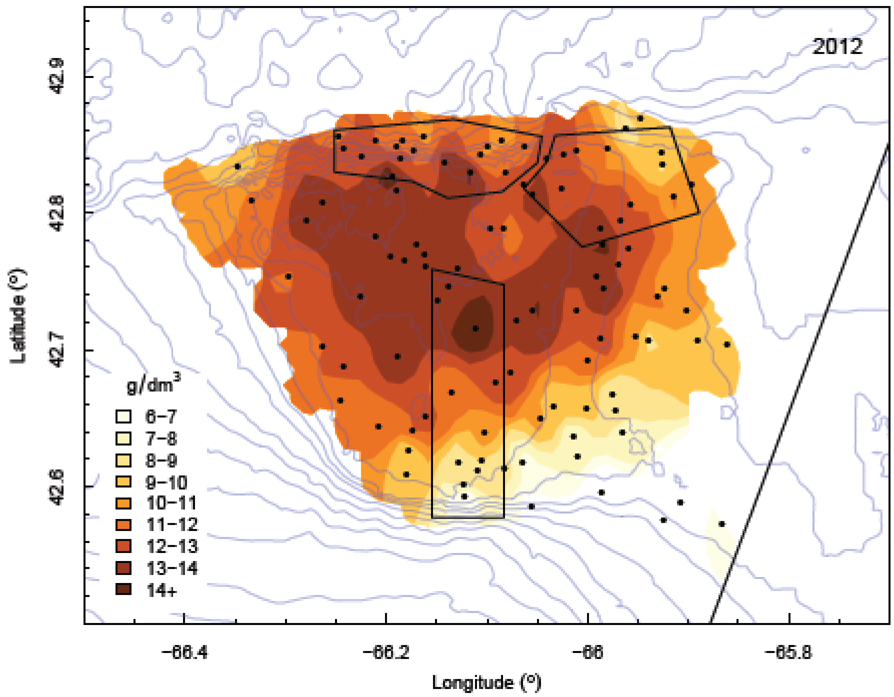


Figure 31. Distribution of pre-recruit (<85 mm shell height) scallops from the survey of Browns Bank north in May 2012. Inverse distance weighted interpolation was used on the standardized number of scallops per tow to produce a contoured color image. Recent industry-managed closure areas are provided for spatial reference only.



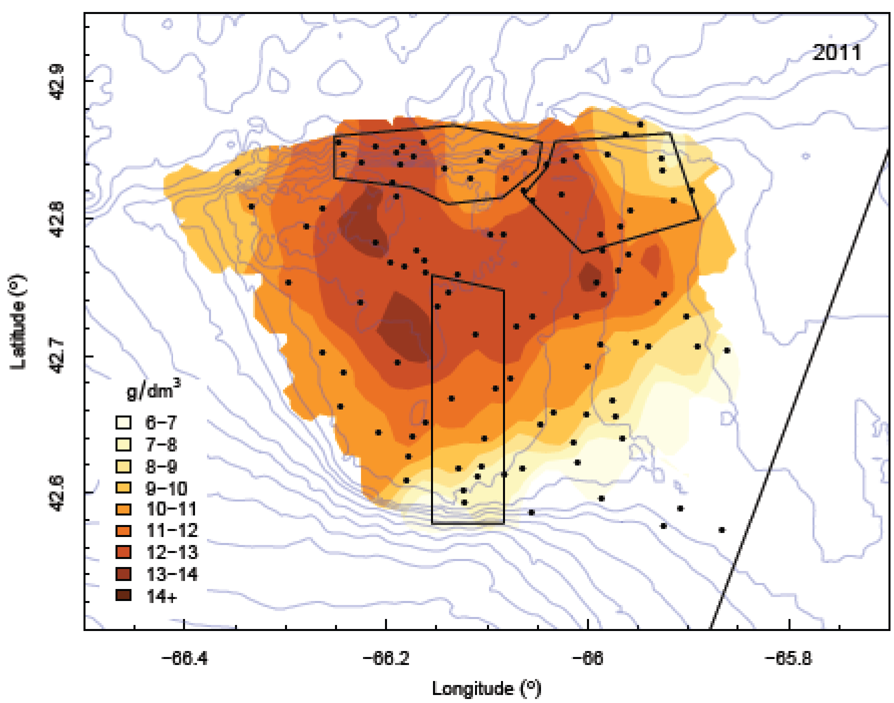


Figure 32. Spatial distribution of condition factor (g/dm^3) from the May survey on Browns Bank north for 2012 (upper) and 2011 (lower).

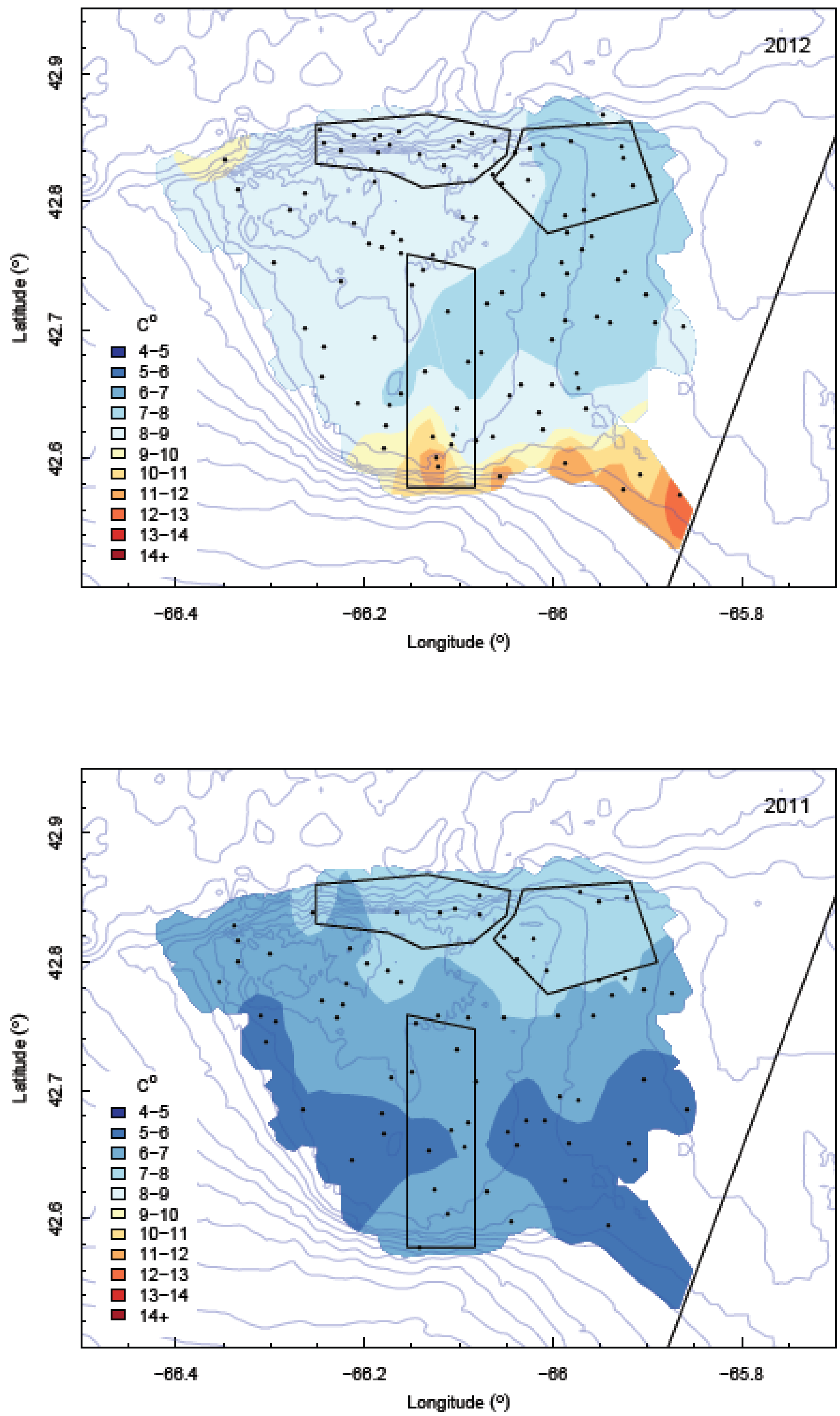


Figure 33. Spatial distribution of bottom temperature (C°) from the May survey on Browns Bank north for 2012 (upper) and 2011 (lower).

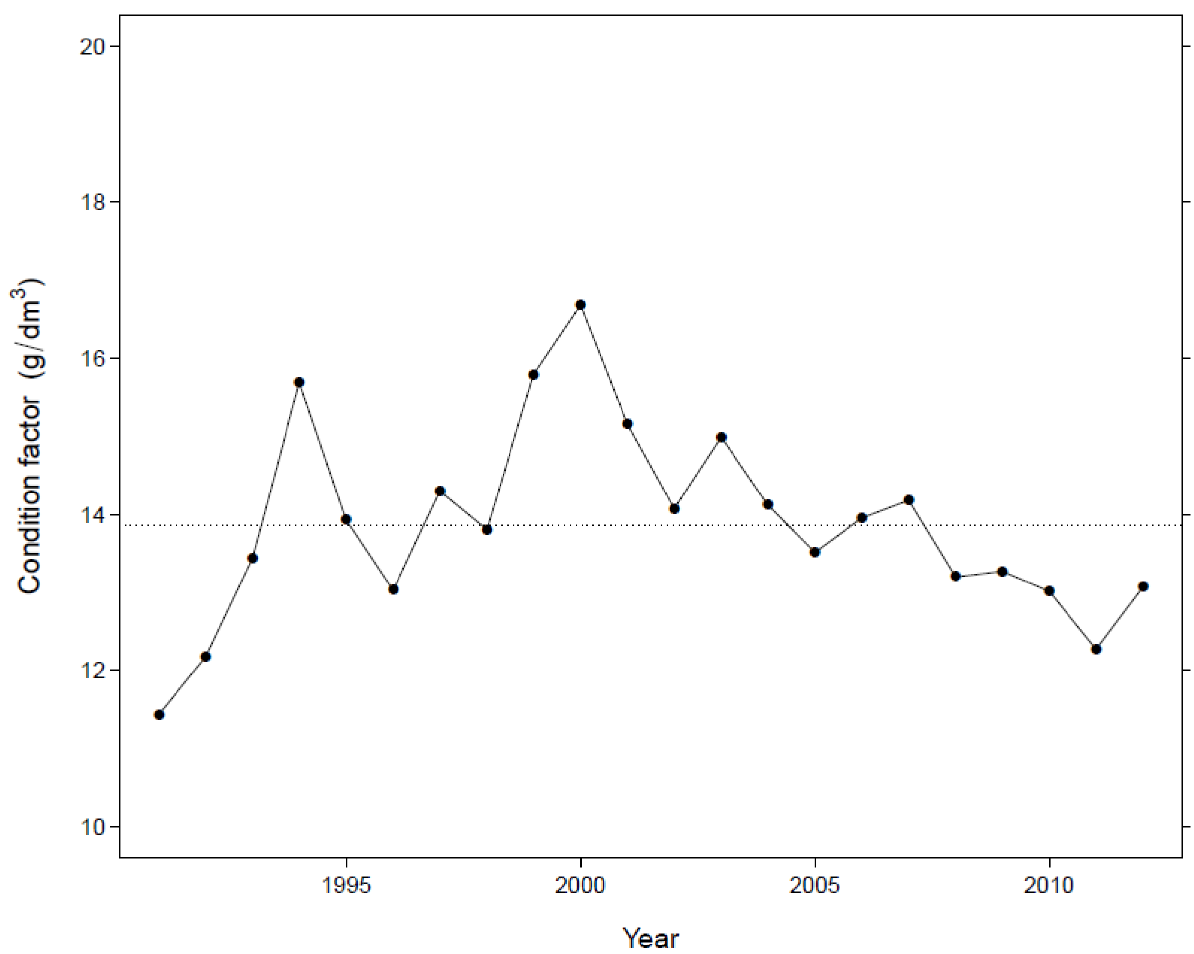


Figure 34. Browns Bank north trend in condition factor (g/dm^3) from the annual May surveys (1991-2012). Horizontal dotted line is the long-term mean.

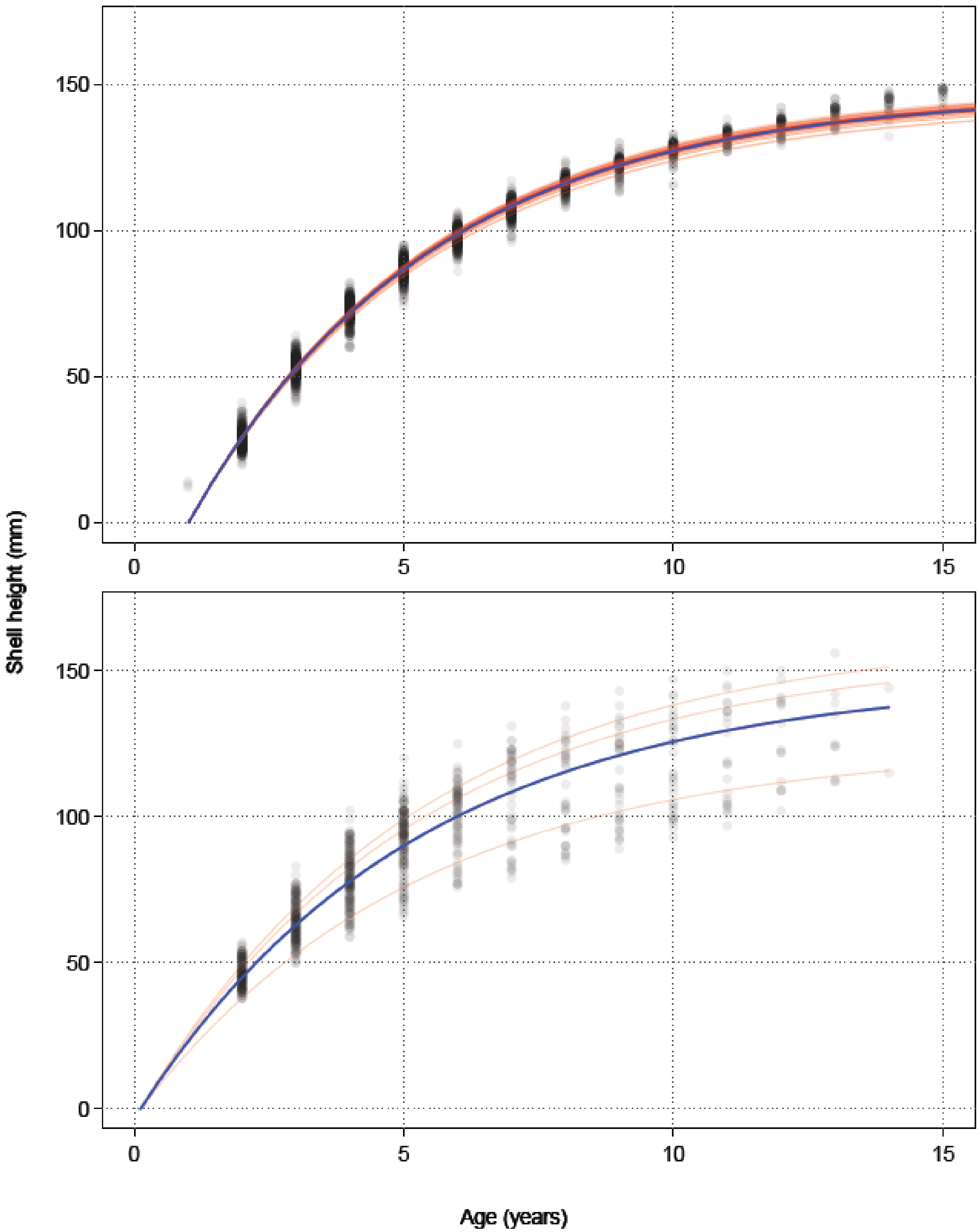


Figure 35. Von Bertlanffy model fit to age data collected on the May survey on Browns Bank north in 1996-2003 (upper panel; ages 1-16) and in 2012 (lower panel; ages 0-14) with station as a random effect.

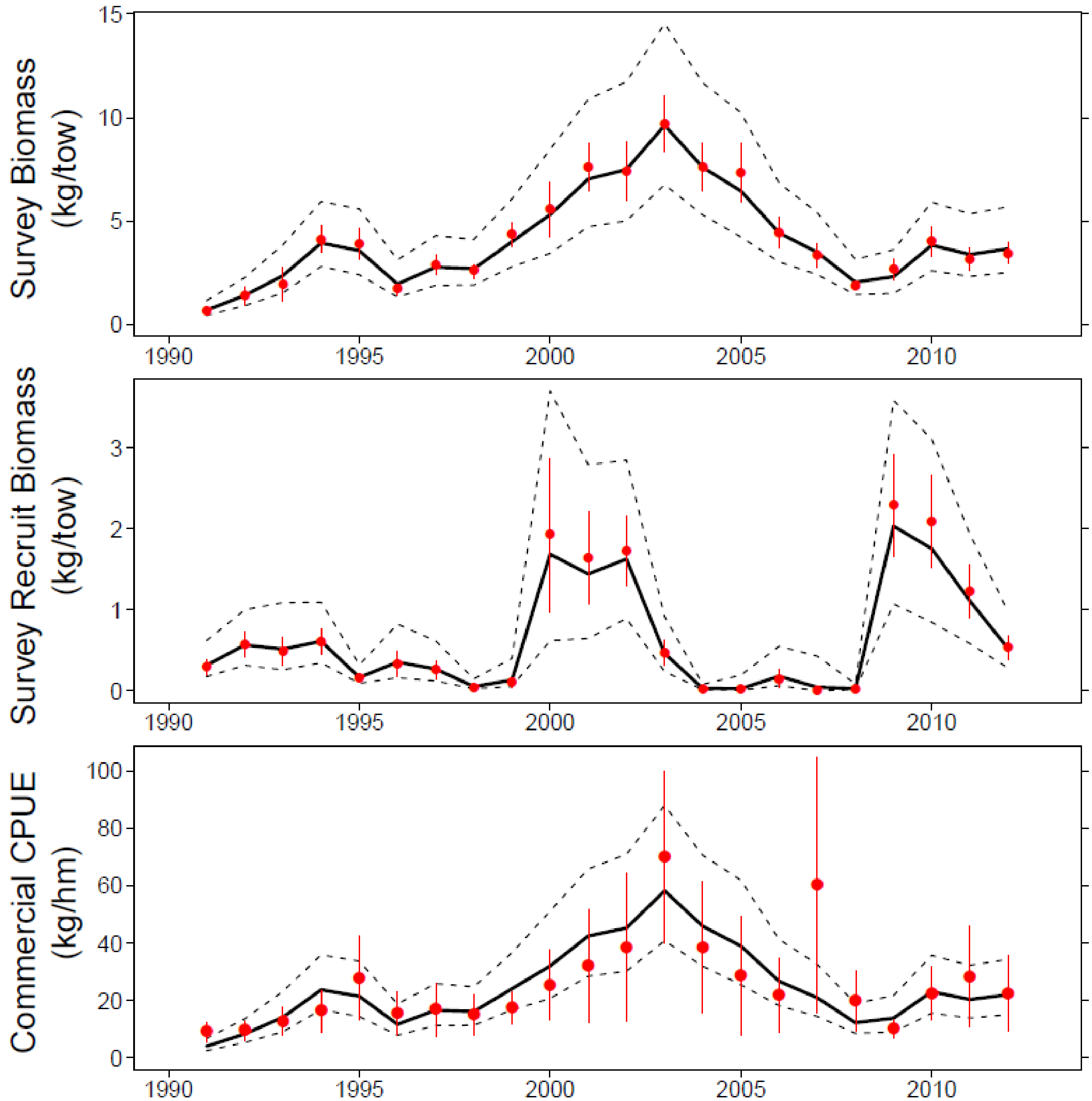


Figure 36. Fit of the stock assessment model to observed biomass indices(upper panel: survey biomass (kg/tow); middle panel: survey recruitment biomass (kg/tow); lower panel: commercial CPUE (kg/hm) (●; red filled circle) for Browns Bank north. Dotted lines represent 95% credible limits and vertical error bars represent ± (plus or minus) one standard error.

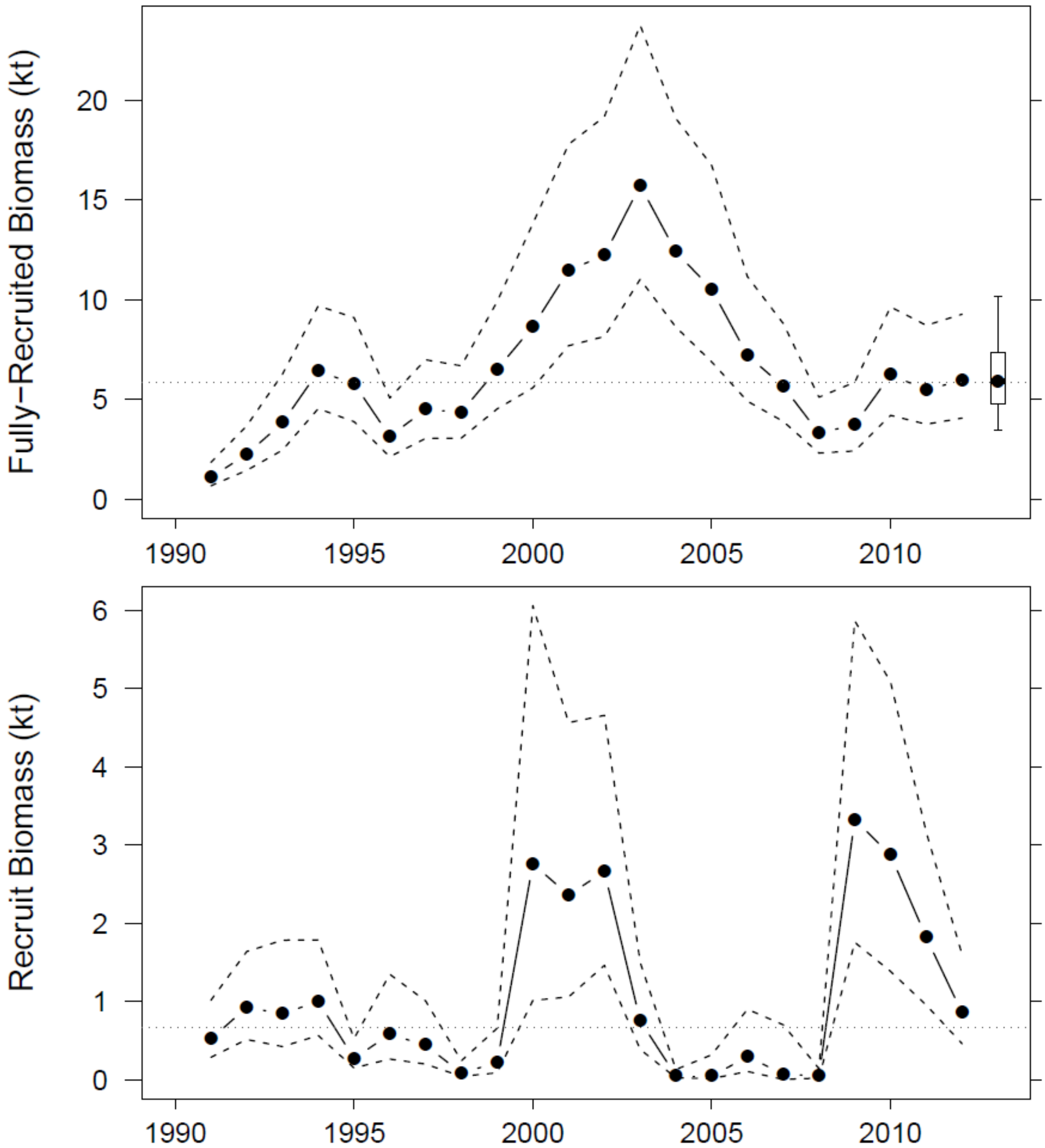


Figure 37. Biomass estimates (kt) for fully recruited (upper panel) and recruit (lower panel) scallops from the stock assessment model fit to the Browns Bank north survey and commercial (1991-2012). Dashed lines are the upper and lower 95% credible limits on the estimates. The predicted fully recruited biomass for 2013, assuming the interim catch (750 t), is displayed as a box plot with median, 50% credible limits (box) and 80% credible limits (whiskers). Horizontal dotted line represents the 21 year median.

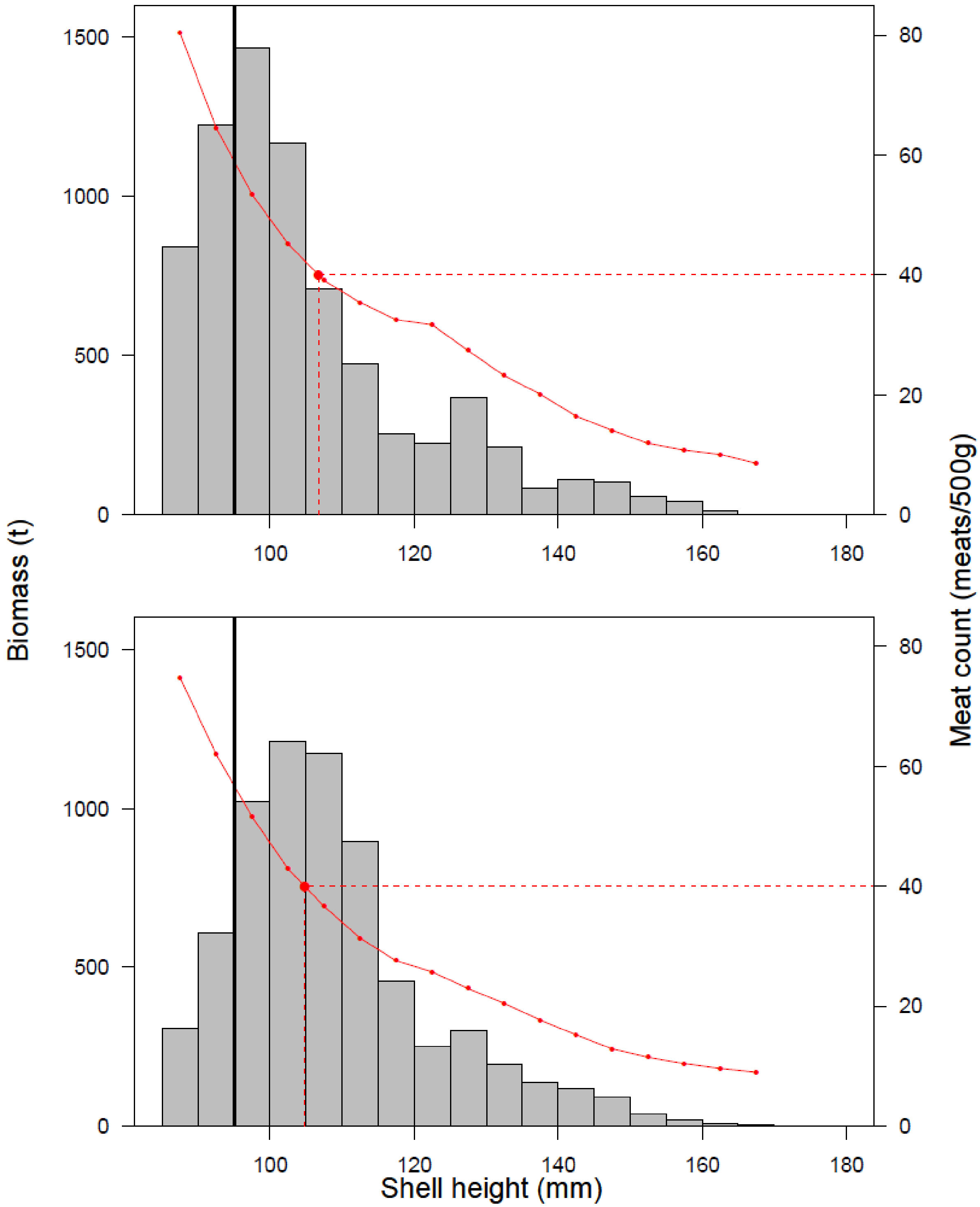


Figure 38. Breakdown of 2011 (upper panel) and 2012 (lower panel) estimated recruit and fully recruited biomass (t) for Browns Bank north by shell height (mm). The solid red line is the observed meat count (meats/500 g) at shell height in the May survey. The dashed red line indicates what shell height corresponds to the meat count regulation of 40 per 500 g.

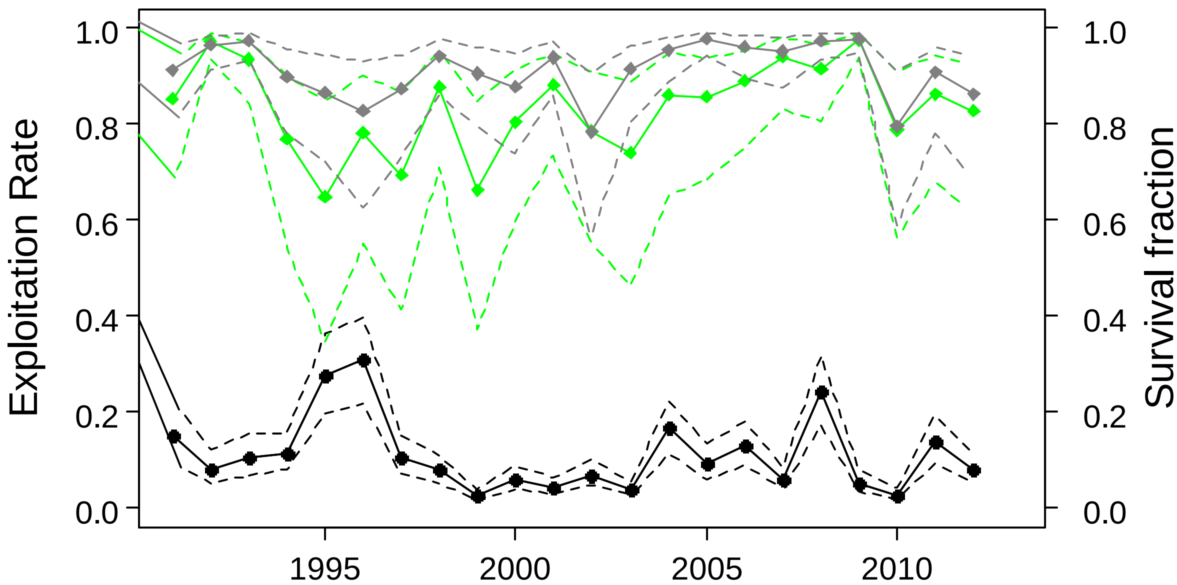


Figure 39. Annual trends in exploitation (black line, circles) and survival estimates (exp(-m)), where m is natural mortality of fully recruited (grey line, squares) and recruit size scallops (green line, squares) from 1991 to 2012. Dashed lines are the upper and lower 95% credible limits on the estimates.

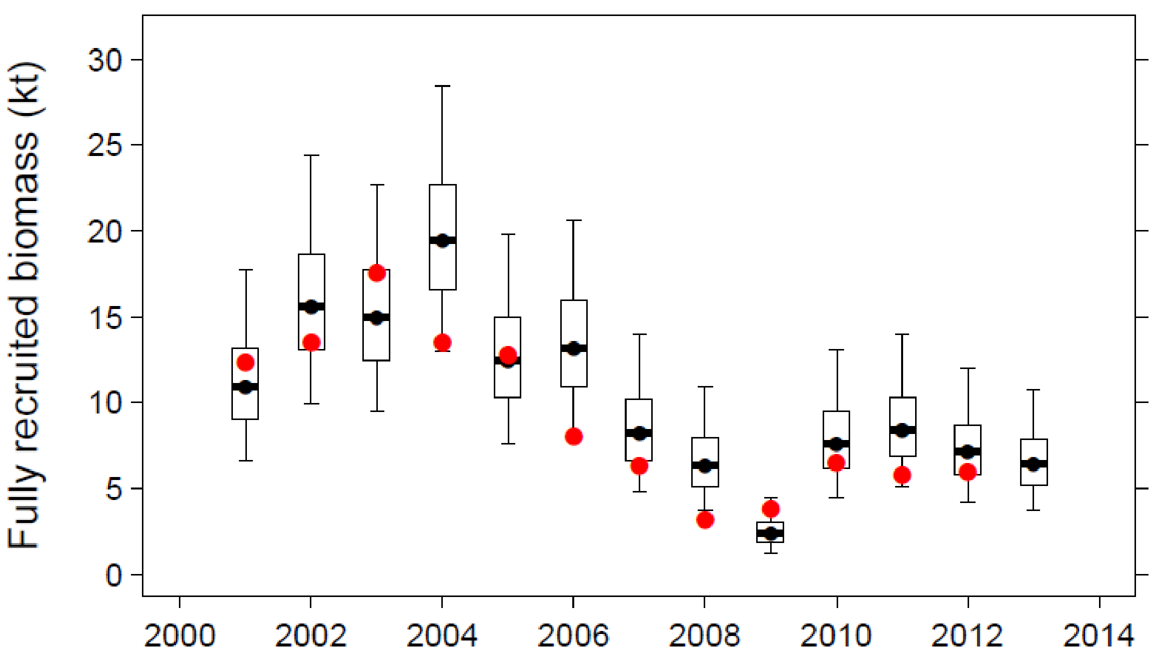


Figure 40. Evaluation of the model projection performance for Browns Bank north (2001-2013). Box and whisker plots summarize posterior distribution of fully recruited biomass in year t based on model fit to year t-1 (e.g., 2006 prediction based on data up to 2005). Red dot represents the estimate of the biomass in year t using data up to and including year t.