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Recovery Potential Assessment for the Laurentian South designatable unit of Atlantic Cod (*Gadus morhua*): the southern Gulf of St. Lawrence cod stock (NAFO Div. 4T-4Vn(Nov-Apr))

Évaluation du potentiel de rétablissement de la morue franche (*Gadus morhua*) de l'unité désignable du Sud laurentien : morue franche du sud du golfe du Saint-Laurent (division 4T-4Vn (nov.-avril) de l'OPANO)

Douglas P. Swain, Luc Savoie and Éliane Aubry

Fisheries and Oceans Canada / Pêches et Océans Canada
Gulf Fisheries Centre / Centre des Pêches du Golfe
P.O. Box 5030 / C.P. 5030
Moncton, NB / N.-B.
E1C 9B6

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ABSTRACT

In 2010, the Laurentian South designatable unit (DU) of Atlantic Cod (*Gadus morhua*) was assessed by the Committee on the Status of Endangered Wildlife in Canada as Endangered. The southern Gulf of St. Lawrence cod stock (management unit 4T – 4Vn(Nov-Apr)) is a component of this DU. The southern Gulf cod stock is at the lowest level observed in the 61-year record and is declining. Abundance of mature cod in 2008-2010 is estimated to average 37% of the average level in the mid to late 1990s and 10% of the average level in the mid 1980s. A limit reference point (LRP) has been established for southern Gulf cod based on the spawning stock biomass (SSB) below which the probability of poor recruitment is high. The LRP is estimated to be 80,000 t. Estimated SSB has been below the LRP since 2003. Estimated SSB in 2010 is 49% of the LRP. Southern Gulf cod are widely distributed over the Magdalen Shallows in summer, though the area occupied by adult sizes of cod in September declined from an average of about 64,500 km^2 in the 1980s to an average of about 47,000 km^2 in the 2000s. An index of geographic range, the minimum area containing 95% of cod, decreased by 50% between the 1980s and the 2000s for adult cod. Nonetheless, given the broad distribution of waters suitable for cod in the southern Gulf and the Cabot Strait, habitat is not considered to be limiting for this population. Southern Gulf cod do not have any known dwelling-place similar to a den or nest during any part of their life. Productivity of southern Gulf cod is currently unusually low. The instantaneous rate of natural mortality (M) of cod aged 5 years and older (5+ cod) increased to very high levels in the late 1980s and early 1990s, averaging 0.66 over the 1994-2009 period. Predation by grey seals is thought to be an important component of this high natural mortality. Other components of productivity are also currently low. Weight-at-age has been at a low level since the early 1980s. Recruitment rate (recruits per unit of SSB) was exceptionally high in the mid to late 1970s but declined to a low level in the 1990s and 2000s, comparable to the rates observed in the 1950s and 1960s. If these conditions persist in the future, this stock is expected to continue to decline, even with no fishing. Under these conditions, the probability of reaching the LRP would be zero. With no fishing, at current levels of other components of productivity, 5+ M would need to be reduced to 0.5 to halt the decline in SSB and to 0.4 in order to have a high probability (90%) of exceeding the LRP in 20 years. During the small directed fishery for southern Gulf cod in 2007 and 2008, fishing mortality is estimated to have been 0.106 for fully-recruited ages, a small fraction of natural mortality, but still unsustainable given current stock productivity. With the closure of the directed fishery in 2009, fully-recruited fishing mortality dropped to 0.014, a negligible level with no detectable effect on population projections. The only additional action that can be taken to improve the chances for recovery of southern Gulf cod would appear to be action to reduce the rate of natural mortality on adult (5+) cod.

RÉSUMÉ

En 2010, l’unité désignable (UD) du Sud laurentien de la morue franche (*Gadus morhua*) a été évaluée par le Comité sur la situation des espèces en péril au Canada comme étant en voie de disparition. Le stock de morue du sud du golfe du Saint-Laurent (unité de gestion 4T-4Vn (Nov-Avr)) est une composante de cette UD. Le stock de morue du sud du Golfe est à son plus bas niveau en 61 ans et continue à diminuer. L’abondance moyenne des morues matures de 2008 à 2010 est estimée à 37% de la moyenne du milieu à la fin des années 1990 et à 10% de la moyenne du milieu des années 1980. Un point de référence limite (PRL) a été établi pour la morue du sud du Golfe basé sur la biomasse du stock reproducteur (BSR) en-dessous de lequel la probabilité d’un faible recrutement est élevée. Le PRL est estimé à 80 000 t. L’estimation de la BSR est en-dessous de la PRL depuis 2003. En 2010, l’estimation de la BSR représente 49% de la valeur du PRL. En été, la morue du sud du Golfe est largement distribuée à travers la région du Plateau madelinien. Toutefois, la région occupée par la morue de taille adulte en septembre a diminué d’une moyenne d’environ 64 500 km^2 dans les années 1980 à une moyenne d’environ 47 000 km^2 dans les années 2000. L’indice de la distribution géographique, définit comme la zone minimale contenant 95% des morues, a diminué de 50% entre les années 1980 et 2000 pour la morue adulte. Néanmoins, considérant la vaste étendue d’eau convenable à la morue dans le sud du Golfe et le Détroit de Cabot, l’habitat n’est pas considéré limité pour cette population. La morue du sud du Golfe n’a pas de structure d’habitat connu similaire à un den ou un nid durant sa vie. La productivité de la morue du sud du Golfe est présentement anormalement basse. Le taux de mortalité naturelle (*M*) instantané des morues de 5 ans et plus (5+) a augmenté à des niveaux très élevés à la fin des années 1980 et début des années 1990, atteignant une moyenne de 0.66 pour la période de 1994 à 2009. La prédation par le phoque gris est considérée comme une composante importante de cette mortalité naturelle élevée. D’autres composantes de la productivité sont présentement faibles. Le poids selon l’âge est à un bas niveau depuis le début des années 1980. Le taux de recrutement (recrues par unité de BSR) était exceptionnellement élevé au milieu des années 1970, mais a diminué à un bas niveau dans les années 1990 et 2000, comparables aux taux observés dans les années 1950 et 1960. Si ces conditions persistent, il est à prévoir que ce stock continuera à diminuer, même sans pêche. Sous ces conditions, la probabilité d’atteindre le PRL est nulle. Sans pêche et aux niveaux présents des autres composantes de la productivité, la *M* de la morue de 5+ a besoin d’être réduite à 0,5 pour freiner le déclin dans la BSR et à 0,4 pour avoir une forte probabilité (90%) d’excéder le PRL dans 20 ans. Durant la petite pêche dirigée sur la morue du sud du Golfe en 2007 et 2008, la mortalité par la pêche a été estimée à 0,106 pour les âges pleinement recrutées, une petite fraction de la mortalité naturelle, mais demeure insoutenable étant donné la productivité actuelle du stock. Avec la fermeture de la pêche dirigée en 2009, la mortalité par la pêche des morues pleinement recrutés a chuté à 0,014, un niveau négligeable qui n’a pas eu d’effet perceptible sur les projections de ces populations. La seule autre mesure qui pourrait être prise afin d’améliorer les chances de rétablissement de la morue du sud du Golfe semble être une mesure visant à réduire le taux de mortalité naturelle des morues adultes (5+).

INTRODUCTION

Atlantic Cod was reassessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010 due to evidence of further declines in some stocks, most notably the southern Gulf of St. Lawrence stock. Atlantic Cod was previously assessed as four designated units (DU): Maritimes (Special Concern), Laurentian North (Threatened), Newfoundland and Labrador (Endangered) and Arctic (Special Concern). In the recent re-assessment, the Maritimes DU was divided into two units, the Laurentian South DU and the Southern DU, both assessed as Endangered (COSEWIC 2010).

This document provides information on one component of the Laurentian South DU, the cod stock in the southern Gulf of St. Lawrence (Northwest Atlantic Fisheries Organization [NAFO] Divisions 4T and 4Vn [November-April]). Information is provided on its recent and current status in terms of abundance, biomass and range, its life history, threats to its survival and recovery, and the feasibility of its recovery.

BACKGROUND

The southern Gulf of St. Lawrence (sGSL) cod stock undertakes fairly well-defined seasonal migrations (Fig. 1). The stock overwinters in dense aggregations in relatively warm water along the southern slope of the Laurentian Channel in the Cabot Strait area. In April and early May the stock migrates into the southern Gulf to spawn and feed, returning to the overwintering grounds in November.

Southern Gulf cod have been fished since the sixteenth century or earlier. Annual landings varied between 20,000 and 40,000 t in the early to mid 20th century (Fig. 2). Landings began to increase in the mid 1940s, peaking at 104,000 t in 1956. Except for a brief period in the mid 1970s, landings remained high, near or above 60,000 t, in most years until the early 1990s when the stock collapsed and the fishery was closed. Following a moratorium on directed fishing from September 1993 to May 1998, the fishery was re-opened with a total allowable catch (TAC) of 3,000 t in 1998 and 6,000 t in 1999-2002. The directed fishery for cod was again closed in 2003, but re-opened in 2004 with a TAC of 3,000-4,000 t, declining to 2,000 t in 2007 and 2008. The directed fishery has been closed since May 2009.

CURRENT AND HISTORICAL ABUNDANCE AND BIOMASS

INDICES OF ABUNDANCE AND BIOMASS

Trends in relative abundance and biomass of this stock are monitored by a stratified-random bottom-trawl survey conducted in September since 1971 using research vessels, a second stratified-random bottom-trawl survey conducted in August since 2003 using commercial fishing vessels, and a longline sentinel fishery program conducted since 1995. The area sampled by the August and September surveys extends from depths under 20 m to depths over 350 m (Fig. 3), and covers virtually all of the zones occupied by sGSL cod in August and September (see Swain et al. 2012). Indices reported here for the September survey are based on the strata sampled since 1971 (415-439); those reported for the August survey are based on all strata except 402.

Two trawls have been used in the September survey, the Yankee 36 trawl from 1971 to 1985 and the Western IIA trawl from 1985 to the present. In addition, four different vessels have been used to conduct this survey. Whenever the gear and/or vessel changed, comparative fishing experiments were conducted to calibrate the new vessel/gear to the old vessel/gear in order to maintain the consistency of the time series (Nielsen 1994; Benoît and Swain 2003; and Benoît 2006). A fifth uncalibrated vessel was used to conduct the 2003 September survey. This survey started late and only about half the target sampling intensity was achieved, with three strata sampled by only one fishing set and two strata missed altogether. Although estimates were obtained for the missed strata using a generalized linear model, indices from the 2003 September survey are generally not used to calibrate population models for this stock (and have been excluded from calibration of the population models described below).

The abundance and biomass indices from the 2010 September survey were the lowest observed in the 40-year record (Fig. 4). Trawlable abundance of mature cod averaged 32 million in the 2005-2010 September surveys, 49% of the average for 1993-1997 and 15% of the average for the 1980s (Fig. 5). Abundance and biomass indices from the August sentinel trawl survey were also the lowest on record in 2010 (Fig. 6). The 2010 indices were about 30% of the values observed at the start of this time series in 2003. Standardized catch rates in the longline sentinel program declined steadily after 2004, with each year setting a new record for the lowest value observed (Fig. 7). The 2010 catch rate was 20% of the 2004 catch rate. In summary, all three indices indicate that the stock has been declining since the early to mid 2000s and is currently at the lowest level observed. Further details on these indices are given in Swain et al. (2009b).

POPULATION MODELS

Methods

Abundance and biomass of the sGSL cod stock was estimated using a population model calibrated using various indices of relative abundance. In addition to age-disaggregated indices from the three survey time series described above, several additional sentinel indices covering the 1995-2002 period and a commercial catch rate index (1982-1993, with a time trend in catchability) were used to calibrate the population model. Further details on the calibration indices are given in Swain et al. (2009b). Data up to and including 2009 were used to fit the model.

The population model used here differs from the models used in previous assessments of this stock in a number of respects. The most important difference relates to the treatment of the instantaneous rate of natural mortality (*M*). Previous assessments of this stock have used a single age-aggregated (2+ years) value of *M* in a given year. Recent assessments have assumed that 2+ *M* was 0.2 in 1971-1979 and 0.4 in 1994-1997, and estimated *M* in blocks of years for the remainder of the time series. In the model used here separate values of *M* are estimated or assumed for two age groups, ages 2-4 and 5+ years. *M* was assumed to be 0.65 for ages 2-4 yr and 0.15 for ages 5+ yr in 1971-1976, and estimated for other years. The value of 0.15 was chosen based on the results of independent studies which estimated *M* to be 0.07 to 0.2 in the 1970s and earlier (Swain et al. 2009b, p. 26-27). Information on an appropriate starting value for the younger age class was lacking. The value of 0.65 was chosen based on the formula given by Gislason et al. (2010) for estimating *M* from length and growth characteristics. A limited sensitivity analysis indicated that the initial fixed value of *M* chosen for age 2-4 (0.5 or 0.65) had no noticeable effect on estimates of 5+ *M* and little effect on estimates of spawning stock biomass (SSB). After 1976, *M* was estimated as a random walk or in blocks of years. Results were similar between the two approaches, and the random-walk results are presented here. Additional differences from previous models include the use of a 12+ group and fitting of the sequential population analysis (SPA) using AD Model Builder (ADMB; http://admbproject.org/) instead of ADAPT. Further details, including model fits and the reasons for the changes in model structure, are given Swain (2012).

In the random walk models, *M* was modeled as follows:

$M_{j,y} = M\text{fix}_j$ if y=1971-1976

$M_{j,y} = M_{j,y-1} * \exp(M\text{dev}_{j,y})$ if y>1976

where *y* indexes year and *j* indexes age class (2-4 or 5+).

For the *M*-block models, the objective function to be minimized was:

$$\mathrm{f}_1 = 0.5 \cdot \sum_{a,y,i} (\log(I_{a,y,i} \,/\, (q_{a,i} N_{a,y})) / s_{a,y,i})^2 + \sum_{a,y,i} \log(s_{a,y,i})$$

where

$$s_{a,y,i} = (\log(1 + cv_{a,y,i}^2))^{0.5}$$

where *I* is an abundance index, *N* is estimated population abundance, *q* is catchability, *cv* is the coefficient of variation for index *i, a* indexes age, *y* indexes year and *i* indexes abundance indices. *cv* was set to a constant value of 0.3, and thus had no effect on the minimization.

For the random walk models, the objective function to be minimized was:

$$\mathrm{f}_2 = \mathrm{f}_1 + 0.5 \cdot (\sum_{j,y} M\text{dev}_{j,y}^2) / sd^2$$

The value of *sd* affects the degree to which the random walk is constrained. If it is too large, estimated *M* will tend to fluctuate erratically in response to year-effects. For the analyses presented here, *sd* was set at 0.075.

Models were extended back to 1950 using the catch at age for 1950-1970 and assuming that *M* in 1950-1970 was 0.65 for ages 2-4 and 0.15 for ages 5+ years.

Results

For ages 2-4 years, estimated *M* declined in the late 1980s and early 1990s (Fig. 8). Estimated *M* for ages 5+ showed the opposite trend over time, increasing in the late 1970s and early 1980s to a level near 0.35 and again in the late 1980s and early 1990s to a level fluctuating between 0.6 and 0.75. Results were similar between the random walk model and the *M*-block model.

The biomass of cod aged 5 years and older declined between the mid 1950s and mid 1970s; 5+ biomass in the mid 1970s had declined to about 25% of the biomass in the mid 1950s (Fig. 9). This decline was not apparent in spawning stock biomass (SSB) due to a decline in the age at maturity in the 1960s (see below); maturation at a younger age compensated for the loss of older spawners. Both SSB and 5+ biomass increased sharply in the late 1970s, reflecting the recruitment of unusually strong year-classes (see below). However, both decreased equally sharply in the late 1980s and early 1990s, due mainly to a sharp increase in the mortality of older (5+) fish. Estimated biomass was roughly stable from the mid 1990s to the early 2000s, but declined steadily from the early 2000s to the present and is now at the lowest level observed in the 61-yr record. Estimated SSB at the beginning of 2010 is 34% of the average level in the mid to late 1990s and 11% of the average level in the 1980s. Estimated 5+ biomass at the beginning of 2010 is 33% of the average level in the mid to late 1990s, 12% of the average level in the 1980s, and 11% of the average level in the mid 1950s.

Estimated 5+ abundance declined from about 180 million cod in the mid 1950s to 50 million cod in the mid 1970s (Fig. 10). Again, very little variation in estimated mature abundance occurred over this period due to the decline in age at maturation in the 1960s. Mature and 5+ abundance increased sharply in the late 1970s due to the recruitment of unusually strong year-classes. Estimated abundance in the mid 1980s averaged about 600 million mature individuals and 365 million 5+ cod. Abundance has been declining since the mid 1980s; this decline was very rapid in the late 1980s and early 1990s, but has been slower since the early 1990s. The 2009 abundance estimates, 60.7 million mature individuals and 46.7 million 5+ cod, are the lowest in the 61-yr record. Average mature abundance in 2008-2010 is estimated to be 37% of the average level in the mid to late 1990s and 10% of the average level in the mid 1980s. Average 5+ abundance in 2008-2010 is estimated to be 37% of the average level in the mid to late 1990s, 14% of the average level in the mid 1980s, and 27% of the average level in the mid 1950s.

The 2003-2005 and 2007 year-classes are estimated to be the weakest in the 61-yr record (Fig. 11). Estimated age-2 abundance in the last five years of the analysis (2005-2009) averaged 49% of the average level in the mid to late 1990s, 9% of the level in the 1980s and 32% of the level in the 1950s. Year-classes produced in the mid to late 1970s were unusually strong given the low SSB that produced them (see below). Total 2+ abundance in recent years is estimated to be the lowest on record.

CURRENT AND HISTORICAL POPULATION RANGE

Current and historical trends in population range are based on catch rates in the September research vessel survey, the longest time series available for this analysis. Catch rates in the August sentinel trawl survey provide additional information on cod distribution in recent years. September and August are during the feeding season of southern Gulf cod, the season when cod are most widely distributed in the southern Gulf. This is also the season when density-dependent effects on population range are most likely to occur due to competitive interactions for food resources (Swain and Kramer 1995; Swain 1999).

Cod are widely distributed over the Magdalen Shallows in September (Fig. 12). In the 1970s, cod densities tended to be highest in western regions of the Magdalen Shallows in September, particularly in the Shediac Valley and Chaleur Bay. Distribution expanded into intermediate depths and into eastern regions of the southern Gulf in the 1980s. In addition to the increase in overall abundance, this reflected a spreading out of cod distribution at high abundance (Swain and Wade 1993; Swain and Sinclair 1994; Swain 1999). In the 1990s, distribution in September contracted back into shallower waters, though distribution was shifted eastward relative to the 1970s. Distribution was even more restricted in the 2000s, with areas of high density restricted to narrow bands extending from Miscou to northwestern Prince Edward Island (P.E. I.) and to the north and east of the Magdalen Islands.

Distribution in August was similar to that in September in the 2000s, though densities in August tended to be relatively higher off Gaspé and relatively lower north of P.E.I. compared to the distribution in September (Fig. 13). A reduction in the extent of areas of moderate to high cod density is evident between August 2003 and August 2010.

Distribution in September is broadly similar between small and large cod, though large cod tend to be distributed somewhat further offshore in deeper water (Fig. 14).

Area occupied (A_t) by cod in September in year *t* was calculated for two size classes of cod as follows:

$$A_t = \sum_{k=1}^{S} \sum_{j=1}^{N_k} \sum_{i=1}^{n_j} \frac{a_k}{N_k n_j} I \quad \text{where } I = \begin{cases} 1 \text{ if } Y_{ijkl} > 0 \\ 0 \text{ otherwise} \end{cases}$$

where Y_{ijkl} is the number of fish in length class *l* caught in tow *i* at site *j* in stratum *k*, a_k is the area of stratum *k*, N_k is the number of sites sampled in stratum *k*, n_j is the number of tows conducted at site *j*, and *S* is the number of strata. The size classes examined were ≤38 and ≥39 cm TL, roughly corresponding to juveniles and adults (since the decline in size at maturation in the 1960s). Area occupied was highest in the 1980s and lowest in the 2000s (Fig. 15). For juvenile sizes, area occupied declined from an average of about 60,000 km^2 in the 1980s to an average of about 46,000 km^2 in the 2000s. For adult sizes, area occupied declined from an average of about 64,500 km^2 in the 1980s to an average of about 47,000 km^2 in the 2000s.

Area occupied (as defined above) will decrease as population size decreases even if there is no increase in geographic concentration (Swain and Sinclair 1994). In order to describe changes in geographic concentration, the minimum area containing 95% of cod was also calculated for each size class, following Swain and Sinclair (1994). First, catch-weighted cdf's of cod catch were calculated in each year:

(5) $$F(c) = 100 \frac{\sum_{i=1}^{n} w_i y_i I}{\sum_{i=1}^{n} w_i y_i} \qquad \text{where} \quad I = \begin{cases} 1 & \text{if} \quad y_i \le c \\ 0 & \text{otherwise} \end{cases}$$

where *c* is a level of cod catch (i.e., number per standard tow), w_i is the weighting factor for tow *i* (i.e., the proportion of the survey area in the stratum fished by tow *i* divided by the number of tows made in that stratum), *n* is the number of trawl tows in the survey, and y_i is the number of cod caught in tow *i*. *F*(c) is an estimate of the percent of cod that occur at a local density of *c* or less. Cumulative area in relation to cod catch was also calculated as follows:

(6) $$G(c) = \sum_{i=1}^{n} \alpha_i I \qquad \text{where} \quad I = \begin{cases} 1 & \text{if } y_i \le c \\ 0 & \text{otherwise} \end{cases}$$

where α_i is the area of the stratum fished by tow *i* divided by the number of tows made in that stratum. We evaluated *F* at intervals of 0.01, and calculated the density c_{05} corresponding to $F = 5$. $G(c)$ is the estimated area containing the most sparsely distributed 5% of cod (including areas where no cod were caught). Thus, the minimum area containing 95% of cod (D_{95}) is given by:

(7) $$D_{95} = A_S - G(c_{05})$$

where A_S is 70,075 km^2, the total survey area.

The decline between the 1980s and the 2000s was more extreme for D_{95} than for area occupied, particularly for the adult size class (Fig. 16). For the adult sizes, D_{95} decreased by 50% from an average of about 44,000 km^2 in the 1980s to an average of about 22,000 km^2 in the 2000s.

LIFE-HISTORY VARIATION

TOTAL MORTALITY (*Z*)

Model-independent estimates of the total instantaneous rate of mortality *Z* were obtained from survey catch rates at age. Following Sinclair (2001), analyses of covariance were conducted in moving 5-yr windows, with log catch rate as the dependent variable, year-class as a factor and age as the covariate. The year-class term controlled for variation in year-class strength. The covariate slope provides an estimate of *Z*. Analyses were restricted to ages 7-11 yr. Relative F, catch-at-age divided by survey trawlable abundance at age (Sinclair 1998), was also calculated for the same age range and averaged over the same moving 5-yr windows.

Based on the RV survey catch rates at age, *Z* increased sharply in the late 1980s, peaking at values greater than 1 and then dropped sharply with the closure of the fishery in 1993 (Fig. 17). These changes in *Z* reflected changes in fishing mortality. However, *Z* remained high following the closure of the fishery in 1993. Based on the RV data, estimated *Z* was about 0.45-0.55 during the mid to late 1990s, increasing sharply in the 2000s to values between 0.75 and 0.95. The August sentinel trawl data also indicated high *Z* in the 2000s. The most recent estimates of Z from survey catch rates are about 0.6-0.75.

The estimates of *Z* during the fishing moratorium in 1994-1997 indicate that *M* was 0.4 or higher during this period. Estimated *Z* in 1994-1997 was 0.57 (95% CI: 0.47-0.66). Relative fishing mortality (ages 7-11 yr) during this period averaged 0.025. The very high *Z* estimates for recent years suggest that natural mortality may have increased to even higher levels, though the uncertainty in the recent estimates is high due to possible year effects in the survey data.

Earlier studies obtained estimates for *M* of southern Gulf cod ranging from 0.07 to 0.1-0.2 in the 1970s and earlier (Dickie 1963; Beverton 1965; Myers and Doyle 1983). The low estimates of *Z* in the 1970s relative to the high estimates of relative fishing mortality (Fig. 17) also suggest that *M* was very low in this earlier period.

NATURAL MORTALITY (*M*) FROM POPULATION MODELS

The population models described here provide direct estimates of *M*. As noted above, these models indicate opposing trends in *M* for young and older cod (Fig. 8). For cod aged 2-4 years, estimated *M* declined in the late 1980s and early 1990s; for cod aged 5+ years, estimated *M* increased sharply in the late 1980s and early 1990s, and averaged 0.66 over the 1994-2009 period.

In addition to natural mortality, these estimates will also include any mortality due to discarded or unreported catch. The decline in estimated *M* of young cod in the late 1980s and early 1990s may partly reflect a decline in unreported fishing mortality (e.g., due to discarded catch) associated with changes in management measures in the late 1980s and early 1990s and with the sharp decline in fishing effort following the closure of directed fishing for cod in September

1993. On the other hand, reduced mortality of small fish in the 1990s and 2000s is widespread throughout the marine fish community in the southern Gulf (Benoît and Swain 2008; Swain et al. 2009a) and may be associated with release from predation following the collapse of large demersal fishes (Benoît and Swain 2011).

Increases in estimated *M* of larger (ages 5+ years) cod in the late 1980s and early 1990s may be partly due to increases in unreported catch during this period. For example, using a modelling approach that incorporated censoring of the catch data, Bousquet et al. (2010) estimated that unreported catch was substantial for this stock in the 1988-1992 period. However, fishing effort in the southern Gulf declined to very low levels in the mid to late 1990s and the 2000s, and very little of the high estimated *M* in these periods can be attributed to unreported catch (Swain et al. 2011a).

AGE AND SIZE AT MATURATION

Age and length at 50% maturity declined sharply in cohorts of southern Gulf cod produced in the 1950s and 1960s (Fig. 18). This reflects changes in maturation reaction norms (Fig. 19), and likely represents an evolutionary response to intensified fishing (Swain 2011a). Maturation reaction norms have changed little among cohorts produced since the early 1970s, despite severe reductions in fishing effort and mortality in the 1990s and 2000s. The high natural mortality of adult cod in the 1990s and 2000s may be a cause of the continued early maturation in this population, now replacing fishing mortality as the agent of selection favouring early maturity.

FECUNDITY

In comparisons between the cod stocks in the southern Gulf, Sydney Bight (4Vn), eastern Scotian Shelf (4VsW) and Georges Bank, McIntyre and Hutchings (2003) concluded that southern Gulf cod had relatively high size-specific fecundity, high gonadosomatic index and large eggs. They suggested that the higher reproductive allotment among southern Gulf cod may represent a selection response to slower growth and later maturation, resulting in higher pre-reproductive mortality and fewer lifetime reproductive events.

McIntyre and Hutchings (2003) also compared size-specific fecundity between southern Gulf cod collected in 1955, 1956, 1980, 1998 and 1999. Fecundity did not differ significantly between years, except for relatively low fecundity at length in 1998.

GROWTH AND CONDITION

Weight-at-age of southern Gulf cod dropped sharply in the late 1970s and early 1980s (Fig. 20). This reflected a density-dependent decline in growth rate as cod abundance increased during this period, combined with a change in the direction of size-selective fishing mortality (Hanson and Chouinard 1992; Sinclair et al. 2002a,b). Weight-at-age has remained low since the mid 1980s, despite good conditions for growth in recent years (i.e., low cod abundance, high prey abundance and relatively warm water temperatures) and a severe reduction in size selection due to fishing. The continued small size-at-age of southern Gulf cod may be partly due to a genetic response to size-selective fishing in the 1980s and early 1990s (Swain et al. 2007). Other hypotheses yet to be examined are that it reflects the phenotypic response to continued size-selective mortality (now natural mortality rather than fishing mortality) and\or changes in cod behaviour in response to increased risk of predation.

Condition of southern Gulf cod in September was relatively high in the early to mid 1970s, low from the late 1970s to the mid 1980s, near the longterm average from the late 1980s to the mid 2000s, and slightly below the longterm average in recent years (Fig. 21). Southern Gulf cod feed little in the winter and thus show a strong seasonal cycle in condition, with condition at its lowest level in spring (Schwalme and Chouinard 1999). Seasonal variation in the condition of southern Gulf cod has been monitored since September 1991. Condition in the spring tended to be lower in the 1990s than in the 2000s (Fig. 22).

RECRUITMENT

Year-classes of southern Gulf cod produced in the mid to late 1970s were unusually strong (Fig. 23). This strong recruitment fueled the rapid recovery of this stock from its earlier collapse in the 1970s. The recruitment rate in this period is thought to be abnormally high, reflecting reduced predation on cod eggs and larvae following the collapse of pelagic fish stocks in the southern Gulf in the early 1970s (Swain and Sinclair 2000). Pelagic fish stocks recovered in the 1980s, and recruitment rates of cod returned to a lower level.

LIMIT REFERENCE POINT

A limit reference point (LRP) for southern Gulf cod was established at the national workshop on gadoid reference points in November 2002 (Rivard and Rice 2002). The LRP for this stock is based on the SSB below which population productivity is seriously impaired. Three types of criteria were examined: 1) $B_{recover}$, the lowest historical SSB from which the stock has readily recovered; 2) the SSB where expected recruitment is half the maximum (RK_{50}, BH_{50}, NP_{50}); and 3) the point below which the population is unlikely to produce average recruitment under good early life history stage survival conditions ($Sb_{50/90}$). The estimates for the various methods clustered around a narrow band between 70,000 and 80,000 t, and it was concluded that the best estimate of the LRP for this stock was 80,000 t of SSB (Chouinard et al. 2003). The stock is estimated to have been below the LRP since 2003. Estimated SSB in 2010 is 49% of the LRP.

PROJECTED POPULATION TRAJECTORY AT CURRENT PRODUCTIVITY

Population projections were undertaken to examine the consequences of current productivity conditions, defined here as the conditions that occurred between 1994 and 2009 (i.e., since the initial closure of cod-directed fisheries in September 1993). These projections should not be interpreted as forecasts of future stock status because they depend on assumptions about future productivity. The southern Gulf population was projected forward, taking into account uncertainty in estimated abundance at age and uncertainty and variability in estimated components of productivity in the current period.

METHODS

Projections were based on the population model with *M* for ages 2-4 and 5+ modelled as random walks. The population was projected for 40 years, a time span corresponding to slightly over three generations for this population (about 36 yr). These projections are calculated assuming that current productivity conditions persist 40 years into the future. For the purposes of these projections, current productivity conditions are defined as those occurring since 1994. All components of productivity (i.e., recruitment rate, weight-at-age and natural mortality) have varied around a relatively constant level over this period (Figs. 8, 20, and 23). Note that these projections do not estimate the probability that the population will be at a particular level at a particular time in the future; instead, they estimate this probability assuming that current productivity conditions were to persist into the future.

A stock-recruit relationship is required for projections. Productivity of this population with respect to recruitment has varied over time (Fig. 24). Recruitment rates were unusually high from the mid 1970s to the early 1980s. Under current productivity conditions (1990-2007 year-classes), the stock-recruit relationship appears to be linear; during this period, a Beverton-Holt model and a simple linear regression model fit the data equally well (Fig. 24). While the slope of the linear relationship is highly significant ($P<0.0001$), the intercept does not differ from 0 ($P=0.16$). Thus, projections were conducted assuming a constant average recruitment rate over the range of SSB estimated to have produced the 1990-2007 year-classes, and a recruitment rate randomly selected from those observed in the 1994-2009 period (1992-2007 year-classes) was applied to SSB to obtain the abundance of age-2 recruits. In cases where SSB exceeded the maximum observed during this period, it was set at the maximum observed to predict recruitment. This corresponds to the recruitment model described by the solid black line and the dashed-dotted black line in Figure 24. (SSB did not reach this maximum in any projections assuming current productivity.)

Projections were based on 2,000 saved MCMC (Markov chain Monte Carlo) simulations of the population model (200,000 simulations with every 100th simulation saved). For each projection scenario, 2,000 iterations were performed. For each iteration, one of the MCMC simulations was randomly selected. The iteration was started from the estimates of abundance at age in 2010 in the selected MCMC simulation. For each year of the projection iteration, a recruitment rate and values of *M* for ages 2-4 and 5+ were randomly selected from the 1994-2009 values in the selected MCMC simulation and a vector of weight-at-age was randomly selected from the 1994-2009 values. In addition, an “expanding-window” approach, in which the “selection window” expanded backwards in time (as far as 1994) as the projection expanded into the future, was examined. This approach produced results very similar to those in which the random selection of components of productivity was from the entire 1994-2009 window in all projection years, and was examined for one projection scenario only. Three projection scenarios were examined: 1) fishing mortality (*F*) =0; 2) fully-recruited $F = 0.014$, corresponding to fishing effort in 2009 when there was no directed fishery; and 3) fully-recruited *Fs*=s0.106, corresponding to fishing effort in 2007-2008 when there was a small directed fishery with a TAC of 2,000 t. The partial recruitment vectors used in scenarios 2 and 3 were those estimated for 2009 and 2007-2008, respectively.

RESULTS

If current productivity conditions were to persist in the future, the population is projected to continue to decline, even with no fishery removals (Figs. 25, 26). Under current (i.e., 1994-2009) productivity conditions, there is no possibility that the southern Gulf cod stock will recover to its LRP (Fig. 26).

The extent to which various levels of fishing mortality would jeopardize survival of this population was assessed by comparing projected population trajectories at these levels of *F* to the trajectory with $F = 0$ (Figs. 26, 27). In 2009, the directed fishery for southern Gulf cod was closed and removals from this stock were restricted to bycatch in fisheries directing for other species and to removals by scientific monitoring programs. This level of removals resulted in a fully recruited *F* of 0.014. This level of *F* has a negligible impact on projected SSB and mature abundance. Projections at this level of *F* are essentially indistinguishable from projections at $F = 0$ (Fig. 26a), and the probability that SSB will fall below various thresholds differs negligibly between F = 0.014 and F = 0 (Fig. 27). For example, the probability that projected SSB will fall below 5,000 t by 2050 is about 32% in both cases (Fig. 27). Removals at the small level of the cod directed fisheries in 2007 and 2008 (TAC of 2,000 t) resulted in a fully recruited F of 0.106. This level of F accelerated projected population declines and thus decreased the probability of population survival (Fig. 26b). For example, the probability that projected SSB will fall below 5,000 t by 2050 is 63% at this higher level of F, about twice the probability given F = 0 or F due to bycatch only (Fig. 27).

POPULATION PROJECTIONS AT HIGHER LEVELS OF PRODUCTIVITY

Projections were also conducted at lower levels of 5+ M in order to determine the reduction in 5+ M required to obtain stable or increasing SSB at current levels of other components of productivity. Projections were conducted as described above except that selected values of 5+ M were reduced to a level 60 – 90% of the selected level. Fishing mortality was set at 0. A reduction to 75% of the current level (0.50) is required to halt declines in SSB while a reduction to 70% of the current level (0.46) would produce increasing SSB (Figs. 28, 29). With a reduction to 65% or 60% of the current level (0.43 or 0.40), the probability of exceeding the LRP in 20 years would be 60% or 90% respectively, given the productivity conditions used in these projections and the uncertainties in the estimates of abundance at age and natural mortality. These results are similar to those obtained with a different model in analyses examined at the review of seal impacts (Swain 2011b); with that model, a reduction in 5+ M to 63% of the current level resulted in a 70% probability of reaching the LRP in 20 years.

The projections above assume that M of cod aged 2-4 years remains at the relatively low levels estimated for the 1994-2009 period. If M of these young cod were to return to the higher levels assumed or estimated for 1971-1990, considerably greater reductions in 5+ M would be required to achieve increasing SSB given the low weights-at-age and recruitment rates observed in the 1994-2009 period (Fig. 30).

SEASONAL DISTRIBUTION AND HABITAT ASSOCIATIONS

Cod are widely distributed in the southern Gulf, occupying a range of depths, temperatures and bottom types. The depths and temperatures occupied by southern Gulf cod vary seasonally (Swain et al. 1998), ontogenetically (Swain 1993; Swain and Kramer 1995; Swain et al. 1998) and with cod abundance (Swain 1993; Swain and Kramer 1995; Swain 1999). Younger cod tend to occupy shallower warmer waters in summer and shallower colder waters in winter compared to older cod. Southern Gulf cod occupy warmer deeper waters in winter than in summer. During the feeding season in summer and early fall, southern Gulf cod tend to occupy relatively warm shallow waters when abundance is low and shift their distribution into colder waters at intermediate depths when abundance is high. This shift in distribution is thought to result from the interplay between density-dependent food resources and density-independent metabolic costs associated with water temperature (Swain and Kramer 1995). The median temperatures occupied by southern Gulf cod generally vary from about 1 to 3.5°C in summer (depending on age and time period) and 5 to 6°C in winter. Given the broad distribution of waters suitable for cod in the southern Gulf and the Cabot Strait, habitat is not considered to be limiting for this population. Southern Gulf cod do not have any known dwelling-place similar to a den or nest during any part of their life.

During the overwintering period, seasonal migrations and spawning, southern Gulf cod are highly aggregated in certain areas. In early winter, southern Gulf cod are highly aggregated along the slope of the Laurentian Channel in the vicinity of St. Paul’s Island (Fig. 31). Additional concentrations occur further to the southeast along the slope of the Channel in 4Vn and into 4Vs, particularly in heavy ice years. Southern Gulf cod are also highly aggregated during their migrations into the Gulf in the spring and out of the Gulf in the fall. Two migration routes are used, one through the Cape Breton Trough and one along the south slope of the Laurentian Channel (Fig. 1). Based on the distribution of fishing effort in the 1980s and early 1990s (Fig. 32), it is thought that the route through the Cape Breton Trough was the dominant route, though there are indications that the Laurentian slope route may be becoming more important.

The spring migration occurs in April and May. The fall migration occurs in November, with the timing of peak migration shifting from late November – early December in the early 1980s to the beginning of November in the mid to late 1990s (Comeau et al. 2002). Cod are also aggregated during spawning. The principle spawning ground is thought to occur in the Shediac Valley area off Miscou (Fig. 1). Powles (1958) reported that the spawning period of cod in the southern Gulf lasted from May to September, with peak spawning in late June. Other studies suggest that peak spawning occurs somewhat earlier, in late May (Jean 1963; Lett 1980). Schwalme and Chouinard (1999) reported that reductions in gonadosomatic indices associated with spawning occurred in June and July. Due to the concentration of a high proportion of the population in these limited areas in particular seasons, the population is particularly susceptible to threats at these places and times.

THREATS, LIMITING FACTORS AND MITIGATION MEASURES

FISHING

The estimated fishing mortality exerted on southern Gulf cod increased throughout the 1950s, 1960s and early 1970s (Fig. 33). This resulted in the first collapse of the stock in the 1960s and early 1970s and in apparent genetic changes in life history (i.e., early age at maturation). As abundance increased due to exceptional recruitment, fishing mortality then declined, particularly on the younger commercially-available ages. Fishing mortality increased rapidly in the late 1980s and early 1990s, particularly on older ages, and the stock collapsed a second time. Since the stock collapse in the early 1990s, fishing mortality has been relatively low, particularly during the moratoria on directed fishing in 1994-1997, 2003 and since 2009. During the directed fisheries in 1998-2002 and 2004-2008 fishing mortality, though relatively low, was still too high for the stock to sustain given its high level of 5+ *M*. On the other hand, the fishing mortality associated with bycatch of cod since the closure of cod-directed fishing in 2009 is negligible.

NATURAL MORTALITY

The lack of recovery (and continued decline) of southern Gulf cod is primarily due to high natural mortality of older (5+) cod. The mortality patterns experienced by cod, with *M* declining for young (small) cod and increasing for older (larger) cod, are seen throughout the marine fish community in the southern Gulf (Benoît and Swain 2008; Swain et al. 2009a; Benoît and Swain 2011). A comprehensive suite of hypotheses has been examined to determine which factors are most likely to be important causes of the elevated *M* of 5+ cod (Swain et al. 2011a). The factors examined were: unreported catch, emigration, disease, contaminants, poor fish condition, life-history change, parasites, and predation (in particular predation by grey seals). The conclusions, based on the weight of evidence, were as follows.

A significant portion of the losses attributed to *M* in the late 1980s and early 1990s may instead be due to unreported catch, but the contribution of unreported catch to estimated *M* from the mid 1990s to the present can only be negligible.

The hypothesis that the losses represent emigration rather than mortality can be rejected.

While data are limited, there is no evidence to support the hypothesis that disease is a major contributor to the elevated *M*.

The hypothesis that contaminant-induced mortality is a significant component of the elevated *M* is not supported by the evidence.

Life-history change (early maturation) in combination with poor fish condition may have contributed to moderate increases in *M* (by 0.1-0.2) in the early to mid 1980s, but *M* due to these causes would have declined when fish condition subsequently improved. Neither life history change (early maturation, early senescence) nor poor fish condition are supported as important causes of the current high level of *M* in the 2000s.

Parasite-induced mortality related to direct damage to organs and tissues or depletion of energy reserves is small in this population. However, it is possible that parasite infection may contribute the elevated *M* by increasing the susceptibility of heavily infected fish to predators.

The sharp increase in *M* of 5+ cod as their abundance collapsed in the late 1980s and early 1990s is consistent with the predator-pit hypothesis for the cause of this high *M*. Given the diets, distributions and abundances of potential predators of large cod, grey seals are most likely to be the predominant predator producing this pit. The available diet information indicates that grey seals consume large cod (>40 cm in length), that they appear to show positive selection for large cod over small cod, and that when foraging in the vicinity of cod aggregations large cod can be one of the dominant components of the diet. Due to data gaps, the quantity of large cod consumed by grey seals is uncertain. However, some assumptions for filling data gaps lead to consumption estimates that account for a high proportion of the *M* of 5+ cod. There is also indirect (correlative) evidence that grey seal predation plays a role in the elevated *M* of adult cod and other large demersal fish (e.g., Chouinard et al. 2005a). The hypothesis most strongly supported by the weight of evidence is that a major component of the current high *M* of 5+ southern Gulf cod is due to predation by grey seals.

OTHER LIMITING FACTORS

Weight-at-age

Weight-at-age of southern Gulf cod has been low since the mid 1980s. This low weight-at-age contributes to the production deficit currently experienced by this stock. The causes of continued low weight-at-age in this stock are unclear. Much of the decline in length-at-age observed in the late 1970s and early 1980s reflected the phenotypic response to a change in size-selective mortality, presumed to be exerted by the fishery (Sinclair et al. 2002a,b). Size selection due to the fishery should now be low given the low level of fishing mortality since 1994. The decline in weight-at-age was also partly due to a density-dependent decline in growth rate as cod abundance increased to very high levels in the early 1980s. Given the low cod abundance (and high prey abundance) in the 1990s and 2000s, a density-dependent increase in growth rate might now be expected, but is not evident in the weights- or lengths-at-age. Declines in growth in some other cod stocks in the late 1980s and early 1990s were partly attributed to direct or indirect effects of cold water temperatures (Castonguay et al. 1999; Swain et al. 2003). Water temperatures in the southern Gulf in summer are now relatively warm and should promote good growth of cod. One possibility is that weight-at-age remains low in southern Gulf cod due to a genetic response to the strong selection against fast growth imposed in the 1980s and early 1990s (Swain et al. 2007). Another possibility is that continued low weight-at-age is a result of increased predation by grey seals, due to selective predation of fast-growing behavioural types and/or due to behavioural changes associated with increased risk of predation.

Recruitment rate

Recruitment rate is currently low compared to the levels observed from the mid 1970s to the early 1980s, and thus contributes to the current low productivity of this stock. The exceptional recruitment rates in the earlier period are thought to be unusually high, resulting from reduced predation on cod eggs and larvae by pelagic fish (which had collapsed in the mid 1970s). Pelagic fish, in particular fall-spawning herring, are currently at a relatively high level of abundance in the southern Gulf, providing one explanation for the lower rates now than in the 1970s. Nonetheless, some increase in recruitment rate at low stock size might be expected due to density-dependent compensatory effects, but this has not been observed.

MITIGATION MEASURES

Following the closure of the directed cod fishery in 2009, removals by the commercial fishery have been reduced to a very low level (< 150 t) and have no detectable effect on the probability of survival or recovery of this stock. There is also a small recreational fishery, but removals by this fishery are thought to amount to 10-15 t, lower than the removals for scientific purposes (i.e., the sentinel programs) and again sufficiently low that their effect on the probability of survival or recovery of this stock is negligible.

The only additional action that can be taken to improve the chances for recovery of this stock would appear to be action to reduce the rate of natural mortality on adult (5+) cod, the main factor contributing to the continued stock decline. A review of the weight of evidence for potential causes of the high 5+ *M* of southern Gulf cod supported a conclusion that predation by grey seals was likely the greatest contributor to the current elevated mortality of large (5+) cod (DFO 2010). Due to significant potential biases in the diet information for grey seals, it was not possible to quantify their consumption of large cod. Thus, it was not possible to provide a quantitative estimate of their contribution to *M*. Nonetheless, a number of scenarios were examined regarding the grey seal removals that would be required to reduce 5+ *M* to a level that would allow recovery (Swain et al. 2011b). Stochastic projections indicated that there would be a high probability of reaching the LRP in 20 years if 5+ *M* were reduced to 63% of its current level, assuming that other components of productivity were to remain at their current levels (Swain 2011b). The projections presented here, based on a different population model and using slightly different procedures, came to a similar conclusion. In a scenario where it was assumed that predation by grey seals accounted for 11% of current 5+ *M*, it was not possible to reduce *M* to a level that would permit recovery by removal of grey seals. In a second scenario it was assumed that predation by grey seals accounted for 49% of 5+ *M*. This scenario is more consistent with the conclusion, based on weight of evidence, that predation by grey seals is a major component of the current high *M* of 5+ cod. In this scenario, seal removal could reduce *M* to levels that would allow recovery, but the necessary removals were substantial. To reduce *M* to a level that would permit recovery to the LRP in 20 years with a high probability (70% chance, given the assumptions of the projections), the number of grey seals foraging in the areas occupied by southern Gulf cod would need to be reduced by 70% to an estimated 31,000 animals. If seal predation contributes a higher proportion of *M*, or particular seals specialize in predation on cod and it is possible to target those seals, the necessary removals would be lower.

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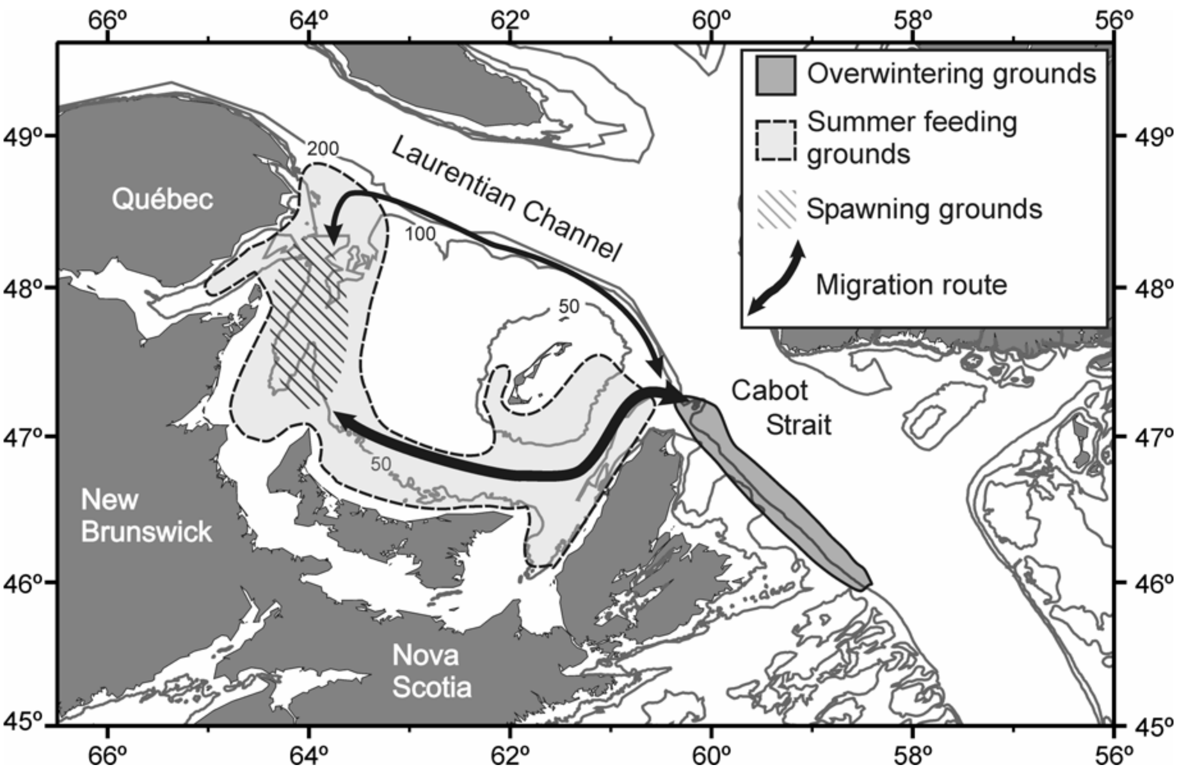


Figure 1. Seasonal distribution of southern Gulf of St. Lawrence cod.

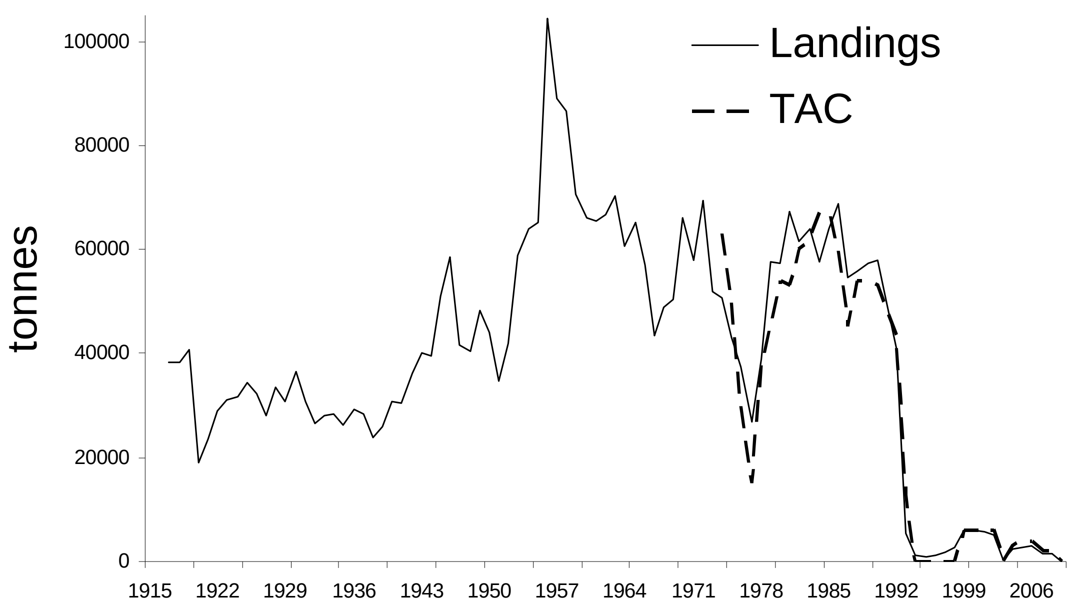


Figure 2. Landings (t) and total allowable catch (TAC) of southern Gulf of St. Lawrence cod.

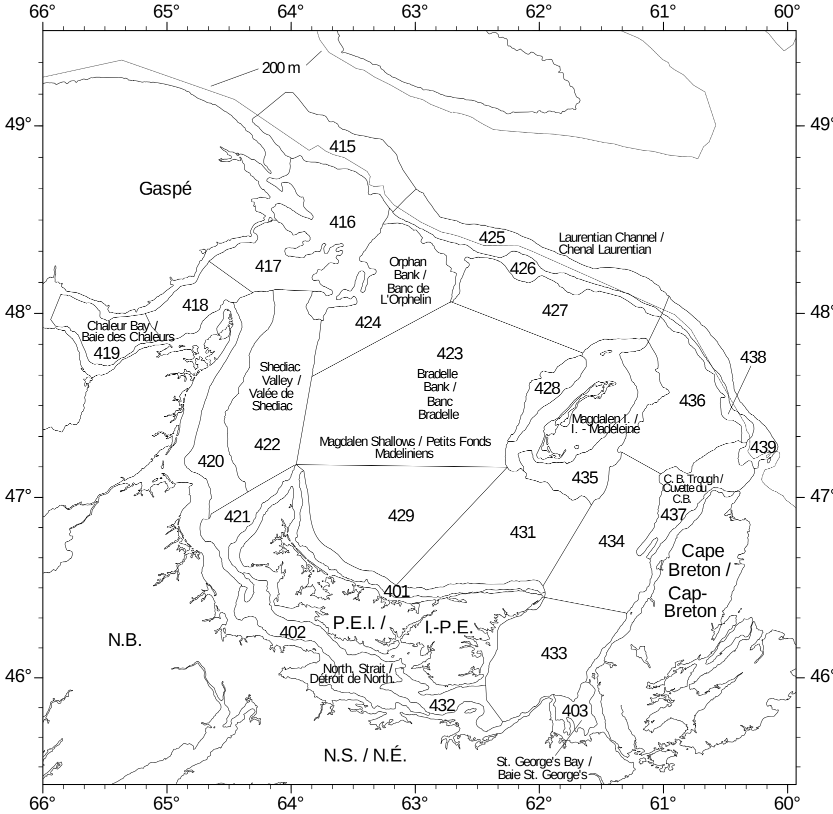
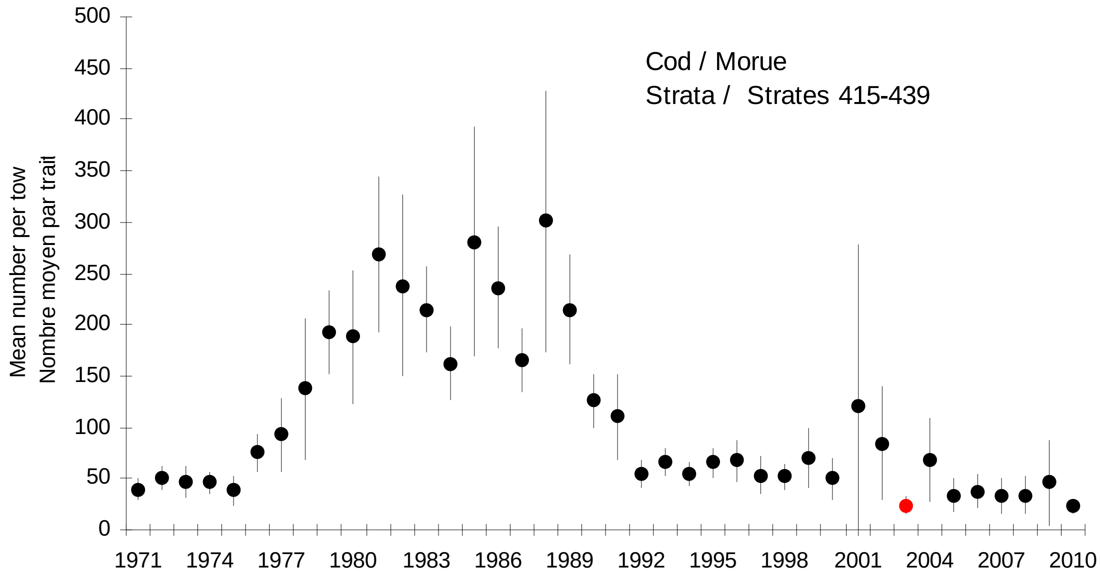


Figure 3. Stratification scheme used for the August sentinel and September research surveys of the southern Gulf of St. Lawrence



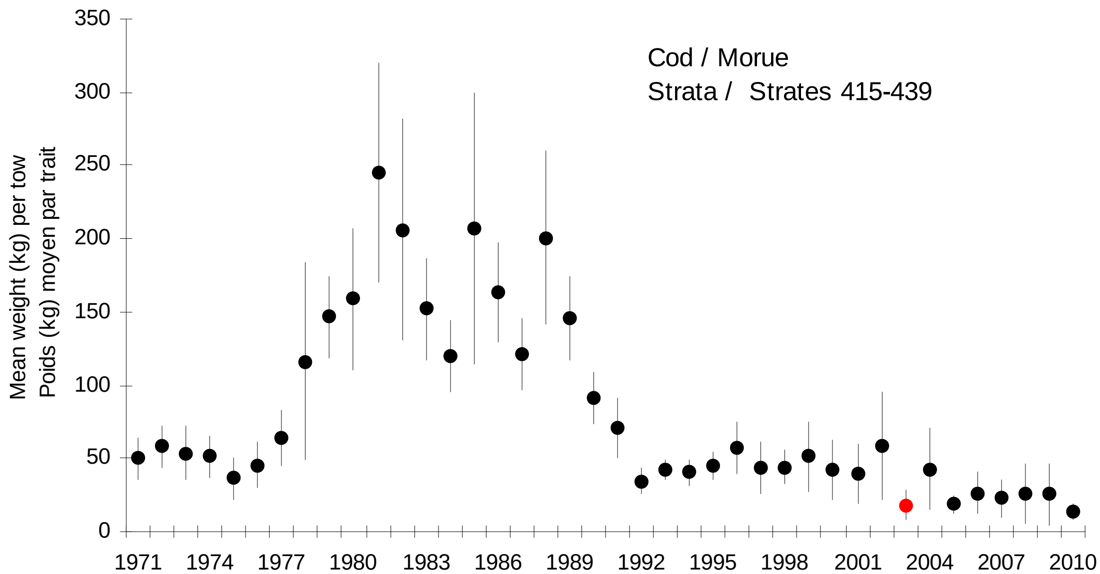


Figure 4. Mean number and weight of cod per tow in the September research vessel survey of the southern Gulf of St. Lawrence. Vertical lines are ±2SE. The 2003 survey (denoted by the red symbol) started late, had a low sampling intensity with some strata sampled by only one tow or missed entirely, and was conducted by an uncalibrated vessel (the Wilfred Templeman); the mean values in missed strata were estimated as described in Chouinard et al (2005b).

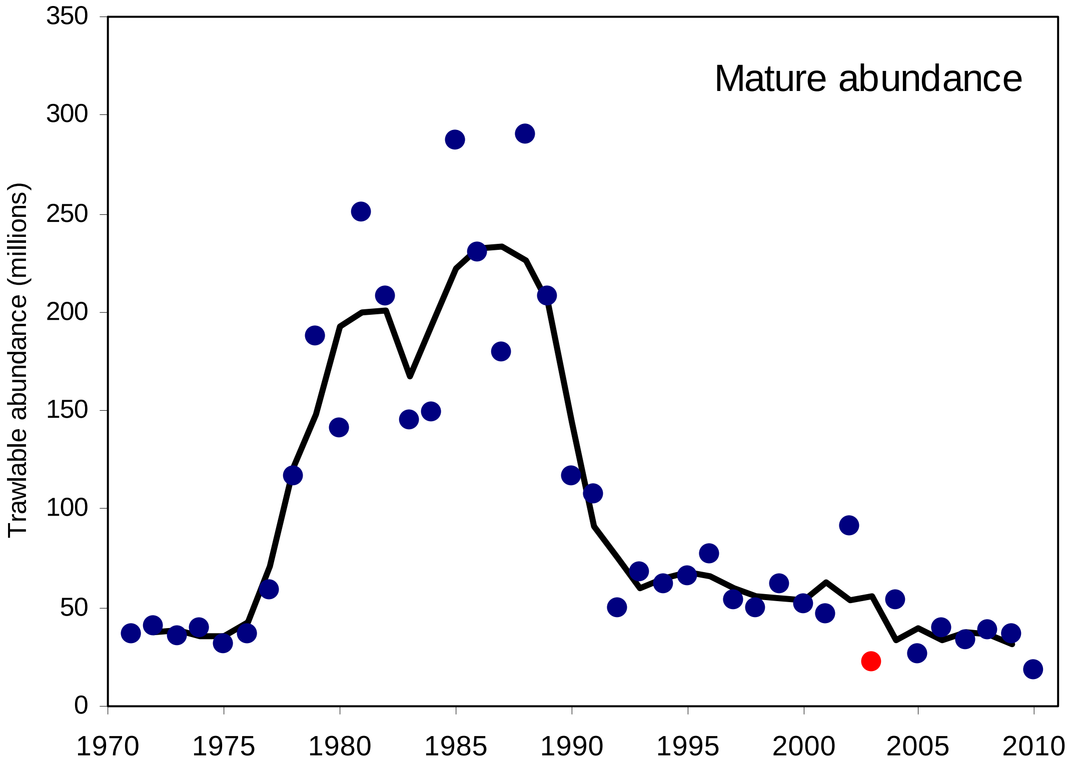
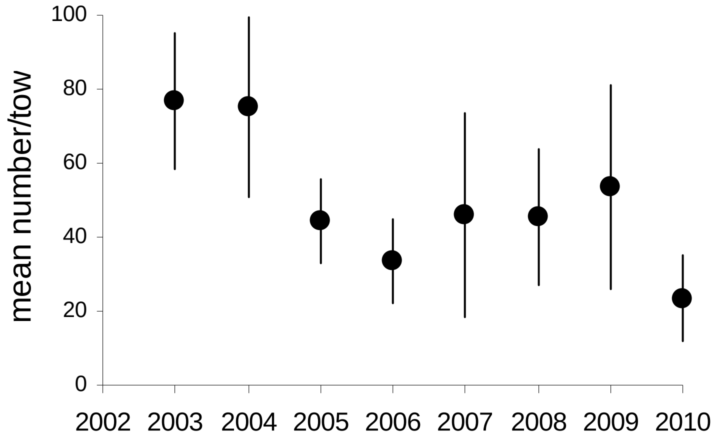


Figure 5. Index of the abundance of mature cod from the September RV survey. The line is a 3-year moving average. The 2003 index, denoted by red symbols, is normally excluded from population model calibration for the reasons outlined in the text.



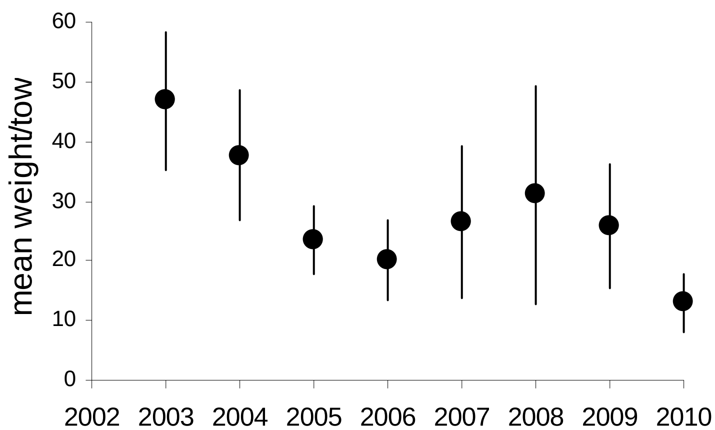


Figure 6. Stratified mean catch rates of cod in the August sentinel trawl survey of the southern Gulf of St. Lawrence. Catch rates have been adjusted for estimated differences in fishing efficiency between vessels.

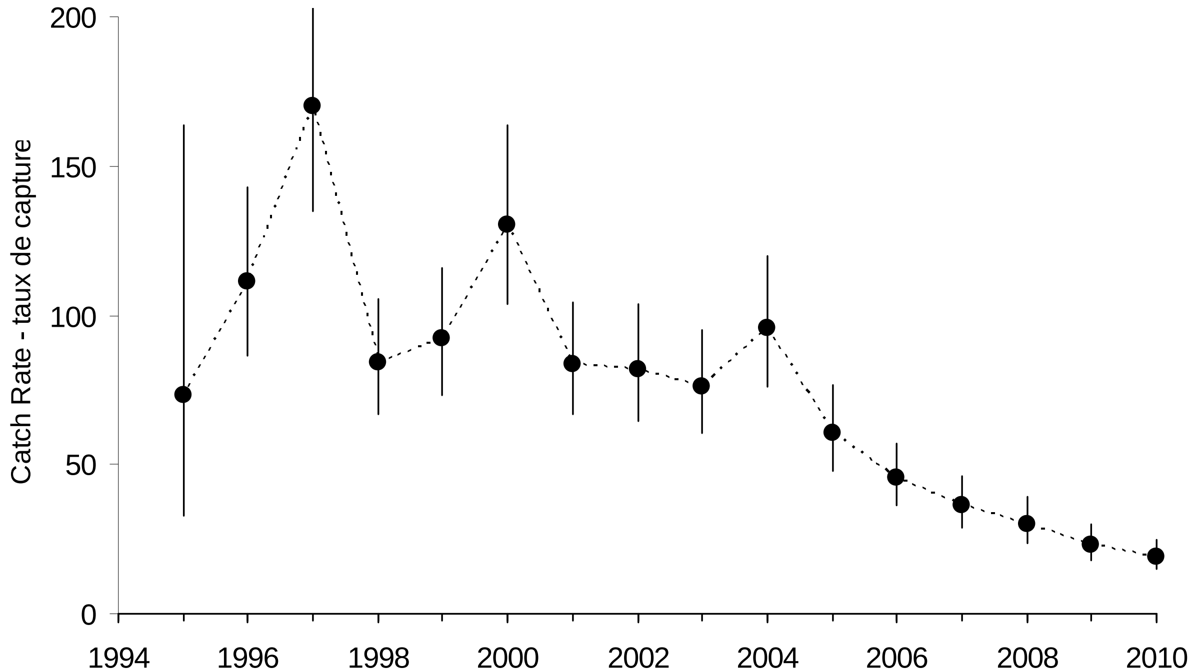


Figure 7. Standardized catch rates in the longline sentinel surveys in the southern Gulf of St. Lawrence, 1995 to 2009. Error bars indicate approximate 95% confidence intervals.

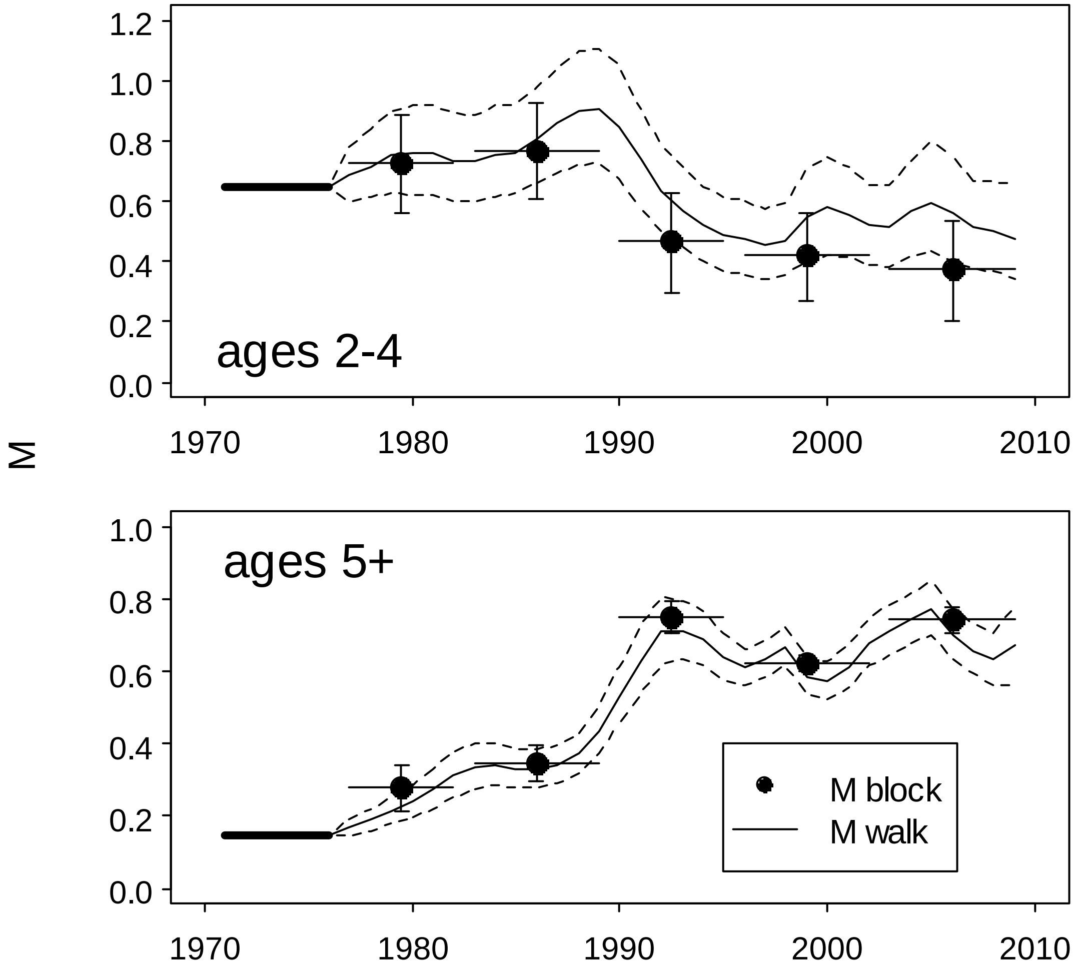


Figure 8. Estimated instantaneous rate of natural mortality (M) for southern Gulf cod aged 2-4 and 5+ years. Lines show the results of the random-walk model and circles the results of the M-block model. Solid lines and circles are the median of 2,000 MCMC realizations; dashed lines and error bars are the 2.5th and 97.5th percentiles of these MCMC realizations. Light horizontal lines indicate the year-blocks for M estimates and heavy horizontal lines indicate assumed values.

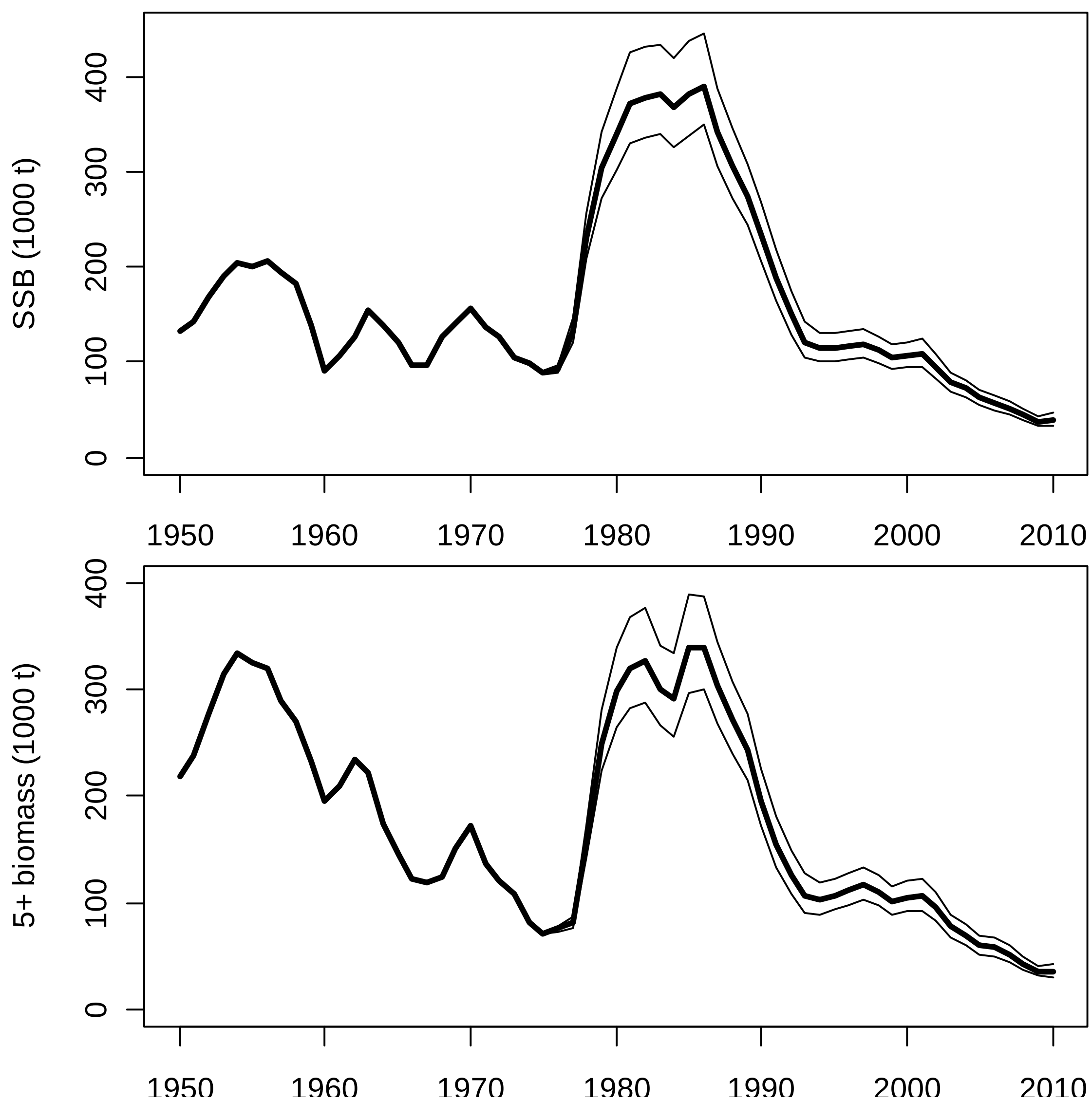


Figure 9. Estimated spawning stock biomass (SSB) and 5+ biomass of southern Gulf (4T) cod based on a population model with separate random walks in age 2-4 and 5+ M. Heavy lines are the median of 2,000 MCMC realizations; light lines are the 2.5th and 97.5th percentiles of these MCMC realizations.

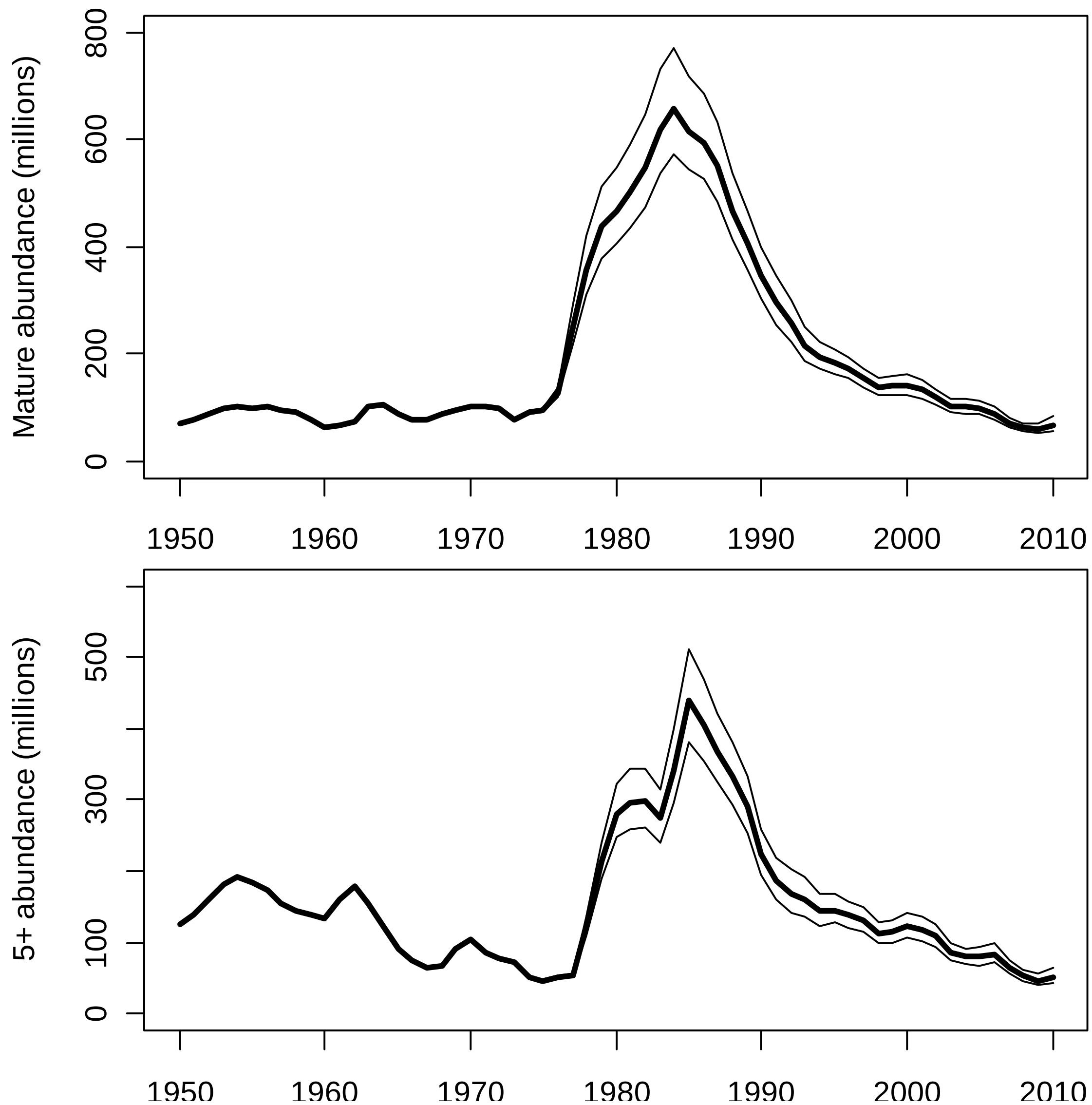


Figure 10. Estimated mature and 5+ abundance of southern Gulf (4T) cod based on a population model with separate random walks in age 2-4 and 5+ M. Heavy lines are the median of 2,000 MCMC realizations; light lines are the 2.5th and 97.5th percentiles of these MCMC realizations.

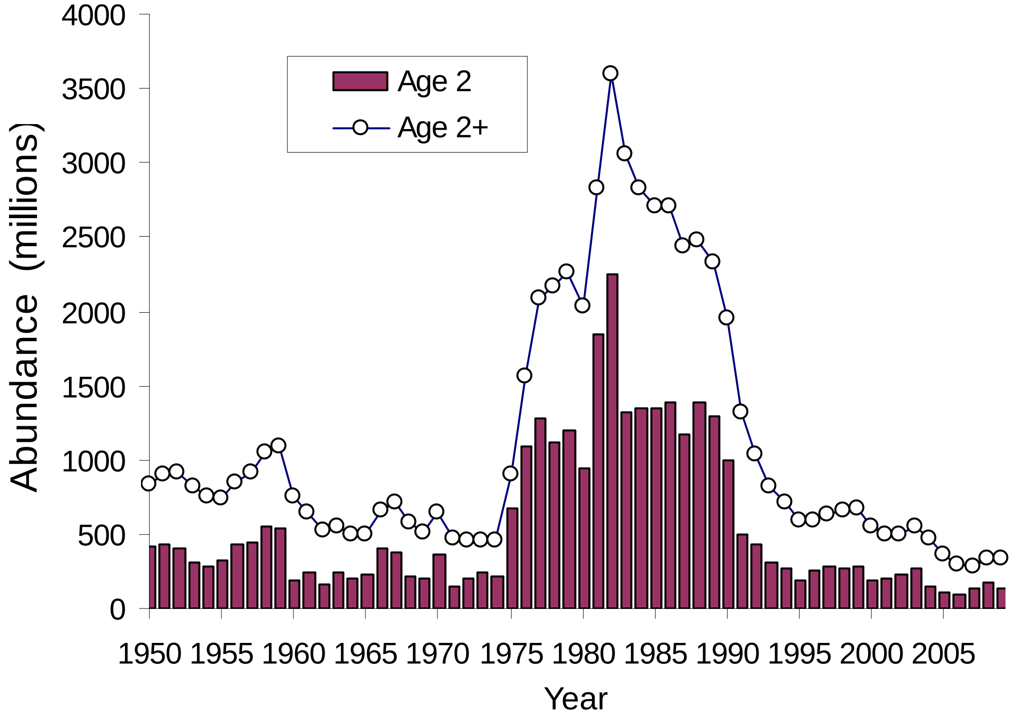


Figure 11. Estimated recruitment (age 2) and total (2+) abundance of southern Gulf cod.

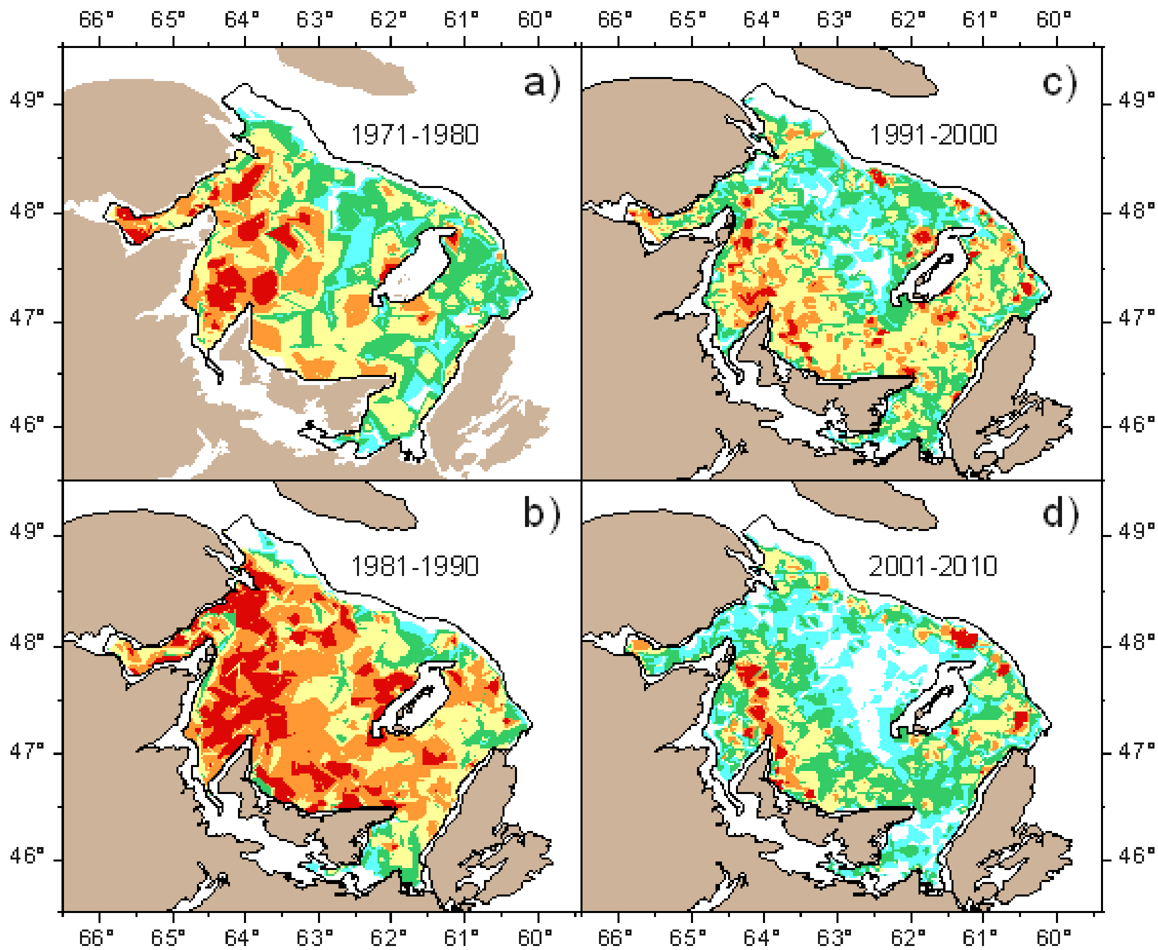


Figure 12. Geographic distribution of Atlantic cod catches (10 year intervals) from the September survey of the southern Gulf of St. Lawrence. Contour intervals are the 10th (blue), 25th (green), 50th (yellow), 75th (orange) and 90th (red) percentiles of nonzero catches (fish/tow).

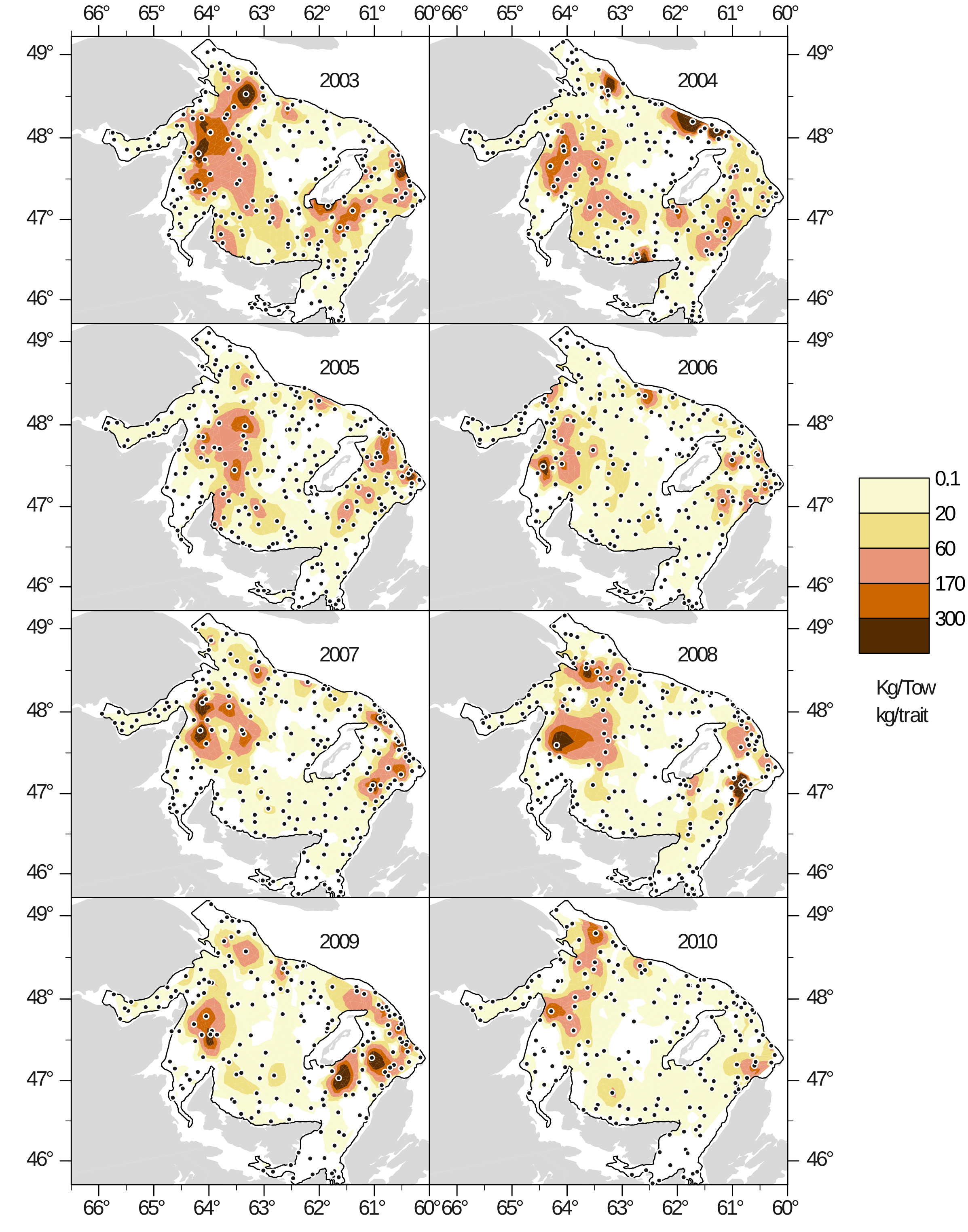


Figure 13. Cod catches in the August mobile sentinel survey of the southern Gulf of St. Lawrence.

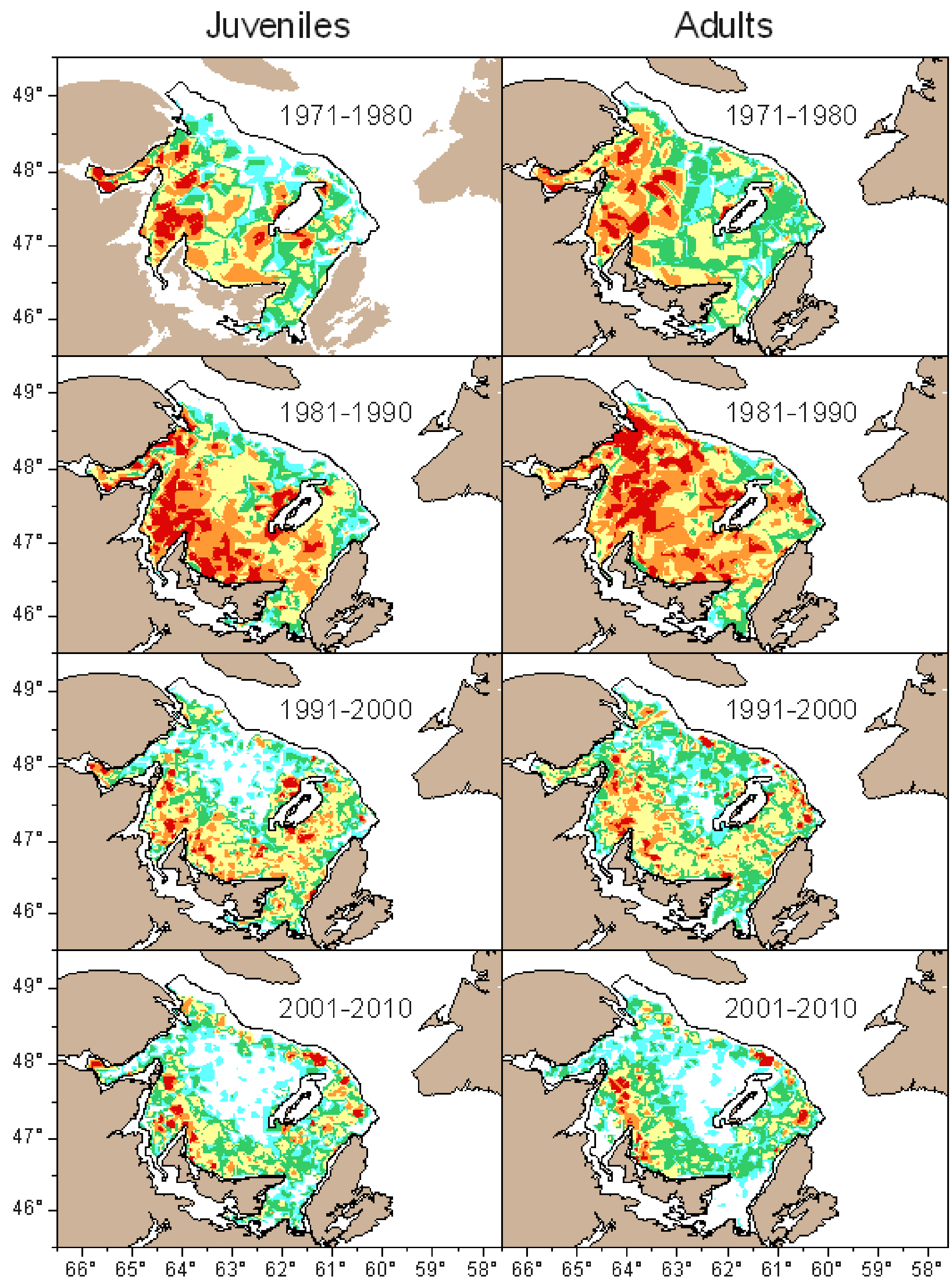


Figure 14. Geographic distribution of two size classes (≤38 and ≥39 cm TL) of Atlantic cod (10 year intervals) in September in the southern Gulf of St. Lawrence. Contour intervals are the 10th (blue), 25th (green), 50th (yellow), 75th (orange) and 90th (red) percentiles of nonzero catches (fish/tow). The two size classes correspond roughly to juvenile and adult cod (after the decline in size at maturity in the 1960s).

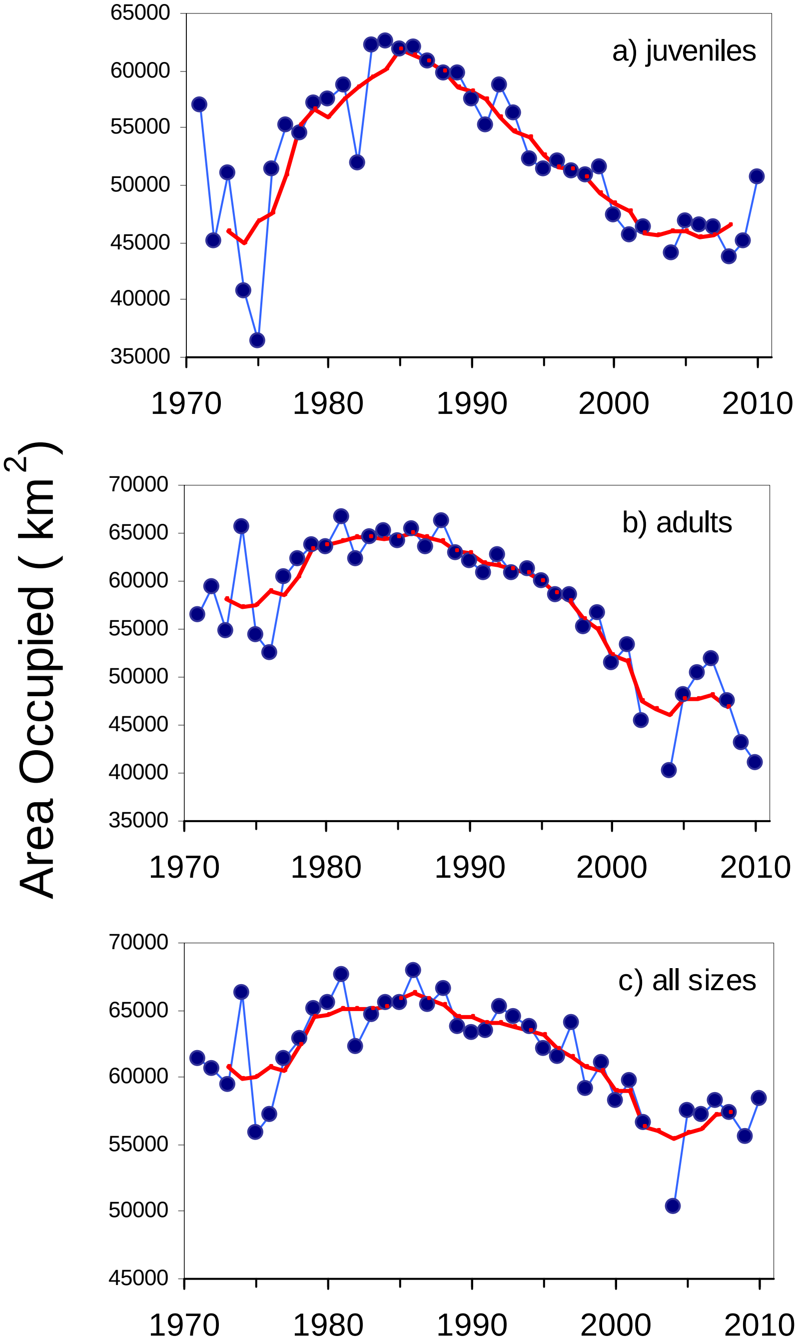


Figure 15. Indices of area occupied by southern Gulf cod in September for two size classes (≤38 and ≥39 cm TL, roughly corresponding to juveniles and adults). The red line is a 5-yr running average.

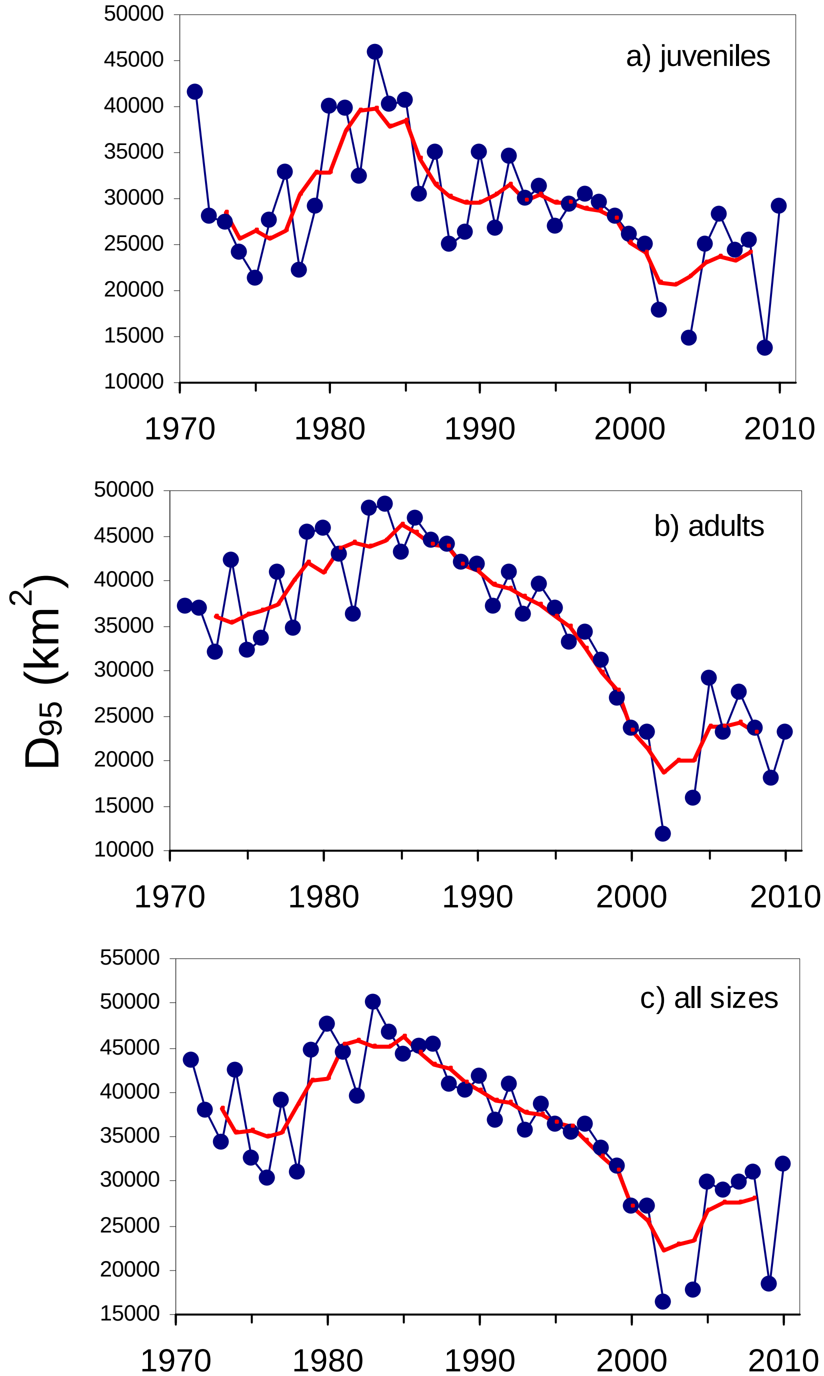


Figure 16. Indices of geographic range of southern Gulf cod in September for two size classes (≤38 and ≥39 cm TL, roughly corresponding to juveniles and adults). D95 is the minimum area containing 95% of cod. The red line is a 5-yr running average.

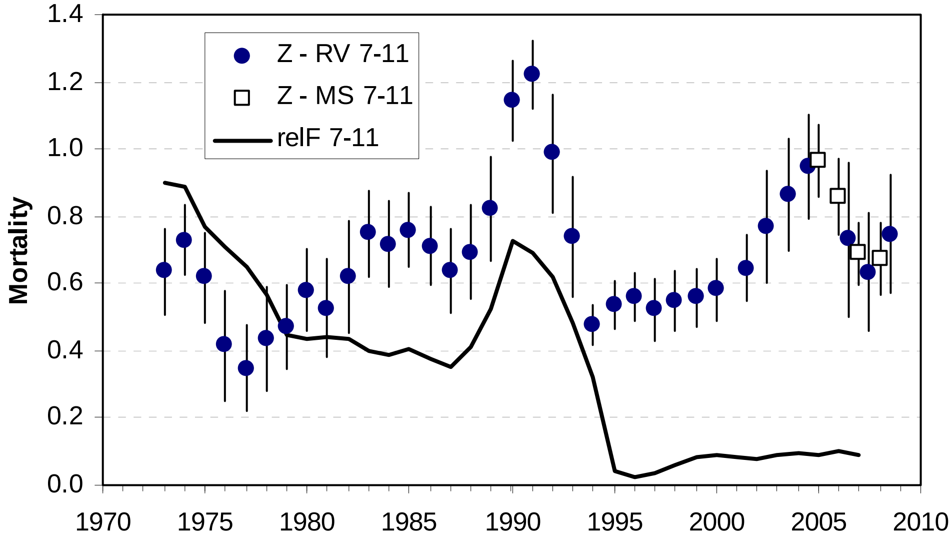


Figure 17. Estimated total mortality (Z) in moving 5-yr windows for cod aged 7-11 yr, based on catch rates in the September RV survey (filled circles) and mobile sentinel survey (open squares). Vertical lines are approximate 95% confidence intervals. The line is relative fishing mortality for ages 7-11, averaged over the same 5-yr periods.

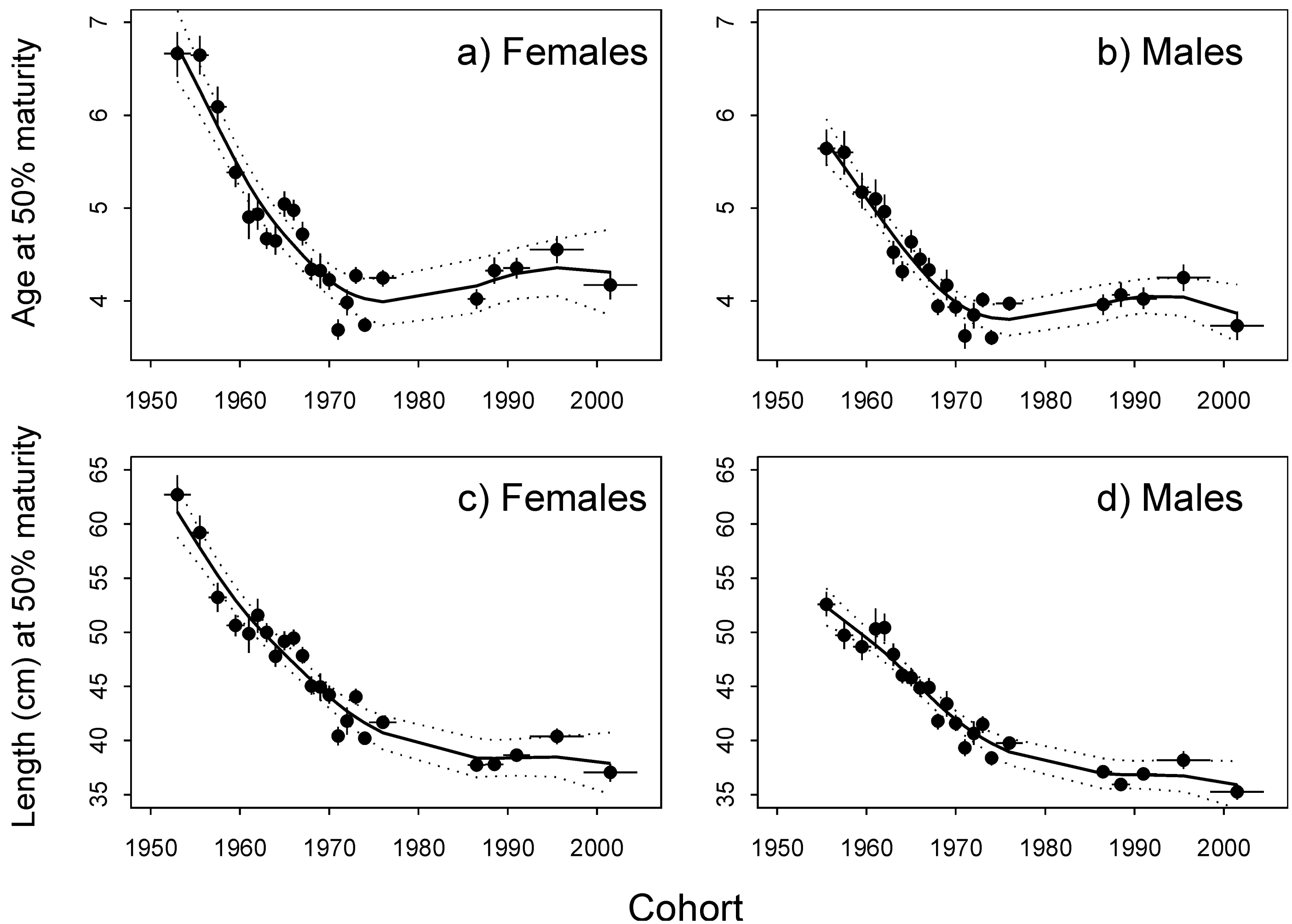


Figure 18. Age and length at 50% maturity for female and male cod in the southern Gulf of St. Lawrence. Vertical lines are 95% confidence intervals. Horizontal lines indicate the range of cohorts grouped together for an estimate. Time trends are summarized by a smoothing spline (heavy line) ± 2 SE (dotted lines). Lengths have been adjusted to September values. (from Swain 2011a).

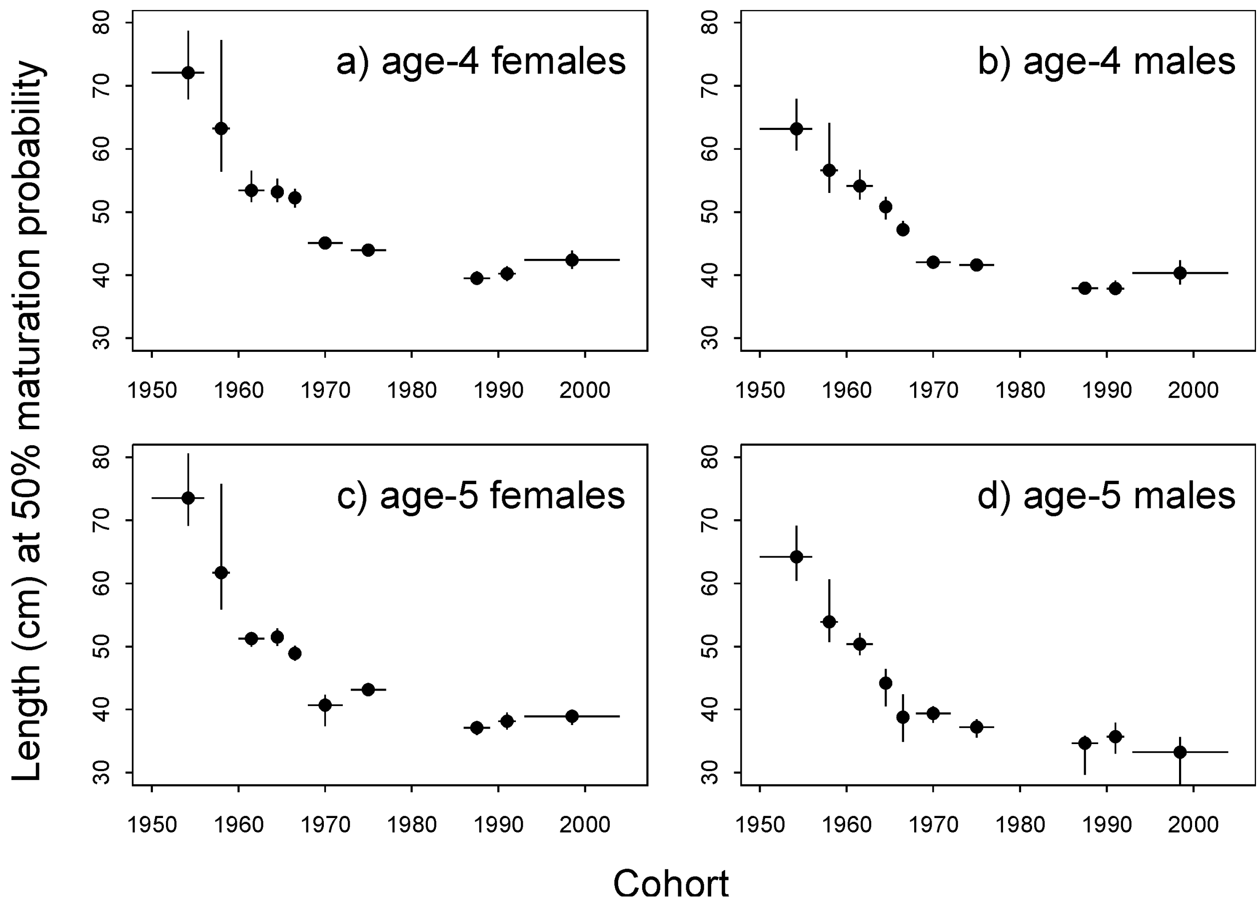


Figure 19. Temporal trends in maturation reaction norm midpoints for southern Gulf of St. Lawrence cod at ages 4 and 5 years. Vertical lines are 95% confidence intervals. Horizontal lines indicate the range of cohorts grouped together for an estimate. (from Swain 2011a).

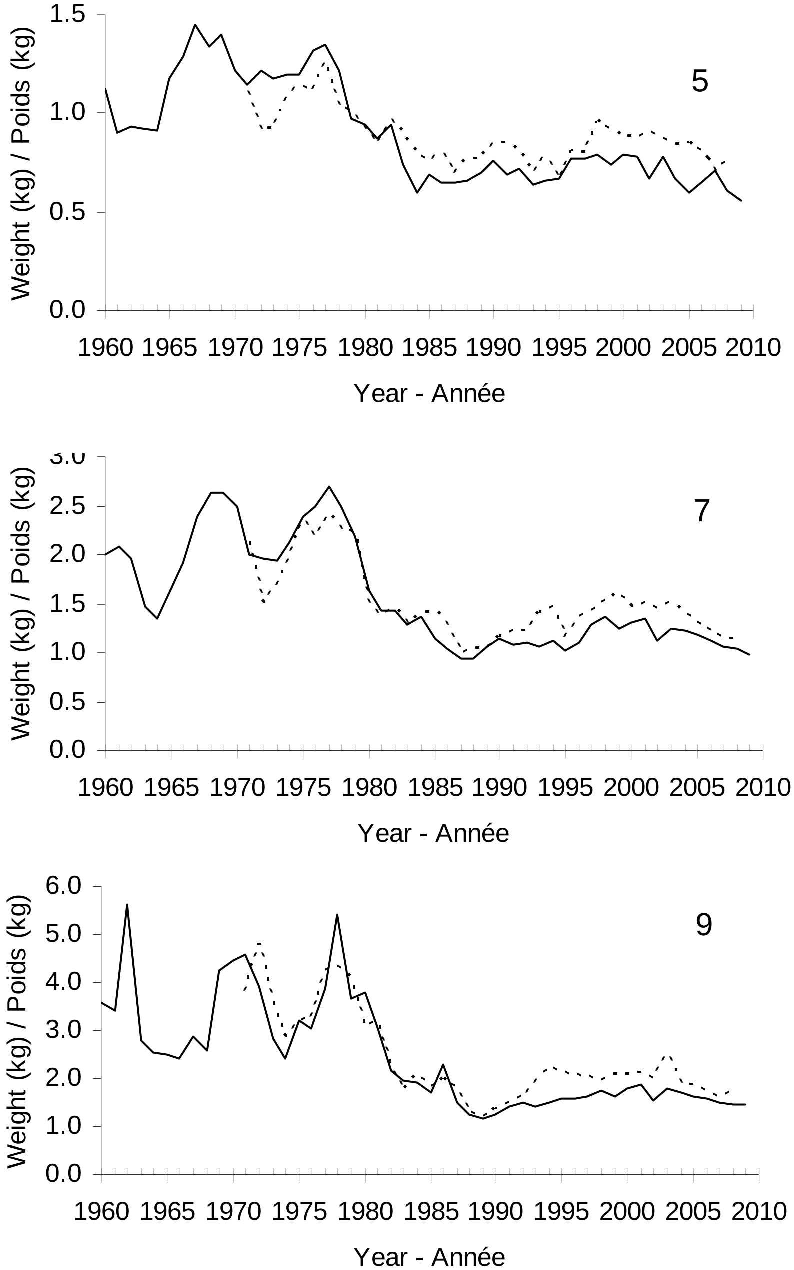


Figure 20. Trends in mean weights (kg) at ages 5 (upper), 7 (middle) and 9 (lower) of southern Gulf of St. Lawrence cod from September research vessel surveys (solid lines) and the commercial fishery (dashed lines). Data from 1960 to 1970 are from non stratified-random surveys.

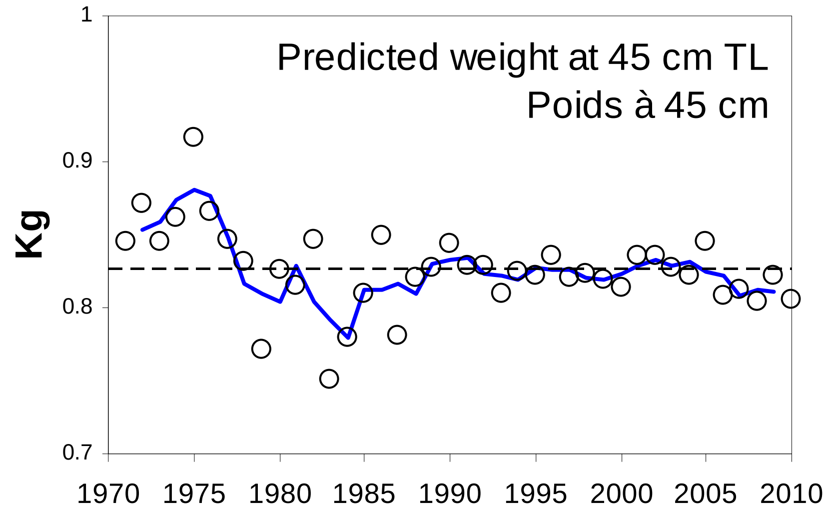


Figure 21. Condition index for cod derived from length and weight data collected during the September trawl surveys in the southern Gulf of St. Lawrence. The index is the predicted weight of a 45 cm cod based on the annual length-weight relationships. The solid blue line is a 3-yr moving average and the dashed line is the 40-yr mean.

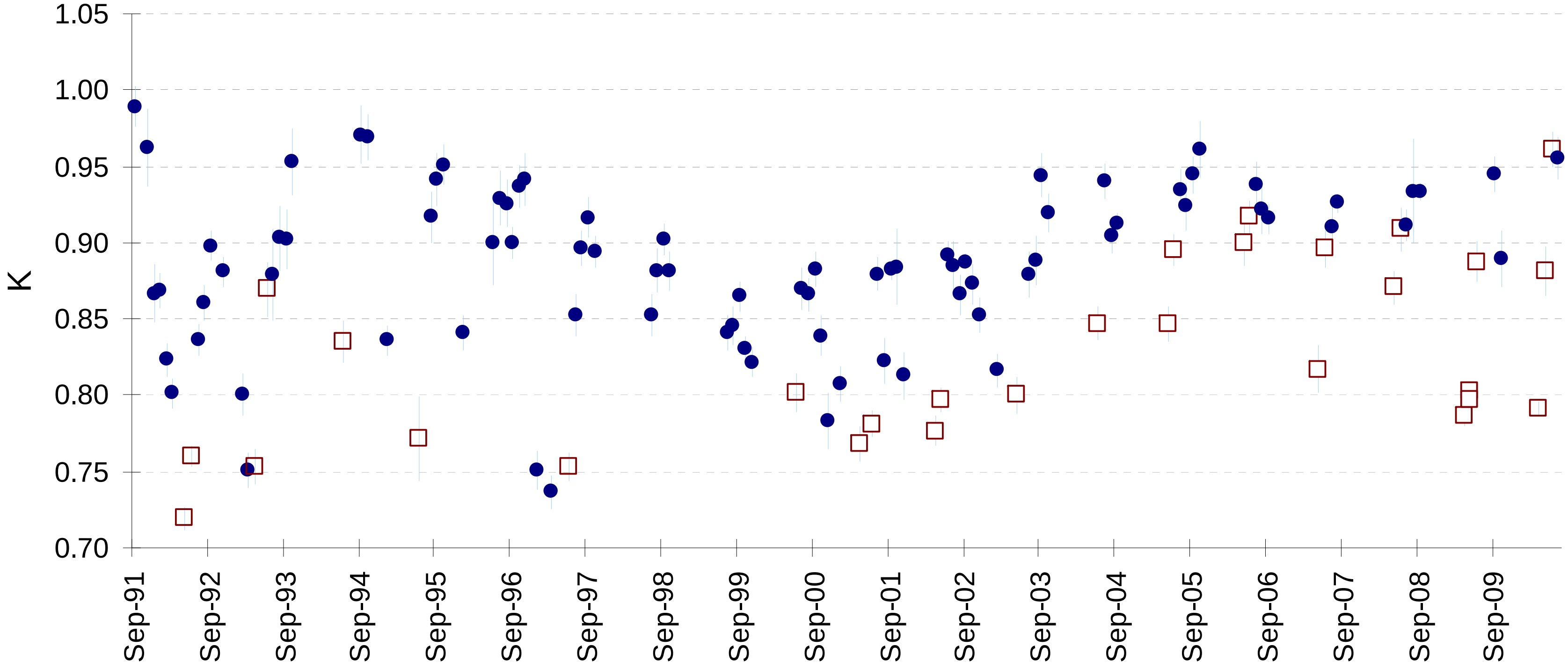


Figure 22. Seasonal and interannual variation in condition factor (K) of southern Gulf of St. Lawrence cod. Vertical lines are 95% confidence intervals. Squares indicate samples collected in April May or June.

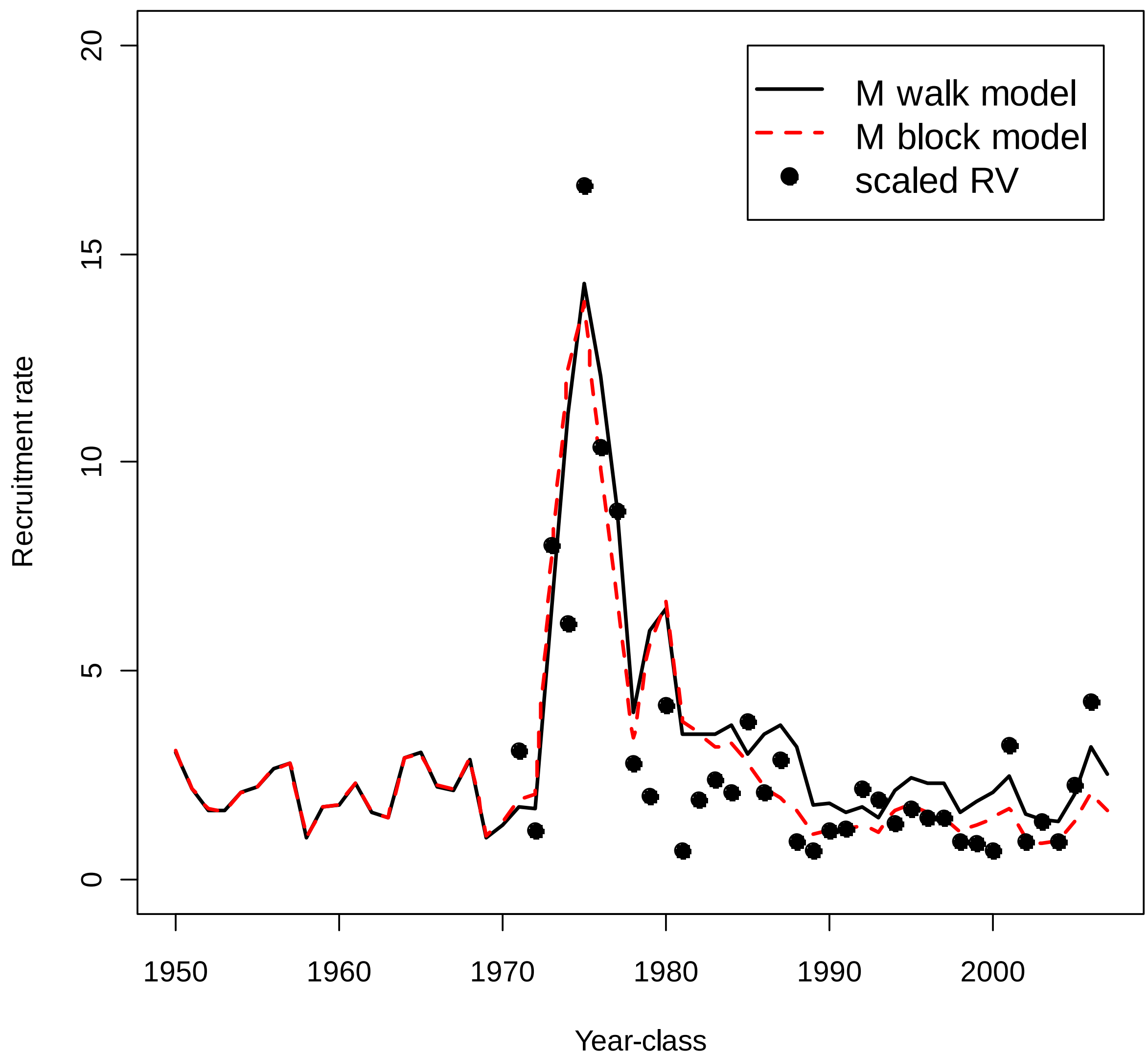


Figure 23. Recruitment rate (number of recruits divided by the SSB that produced them) of southern Gulf cod based on population models (lines) and the September survey data (circles). The survey rates are scaled to a level comparable to those produced by the models.

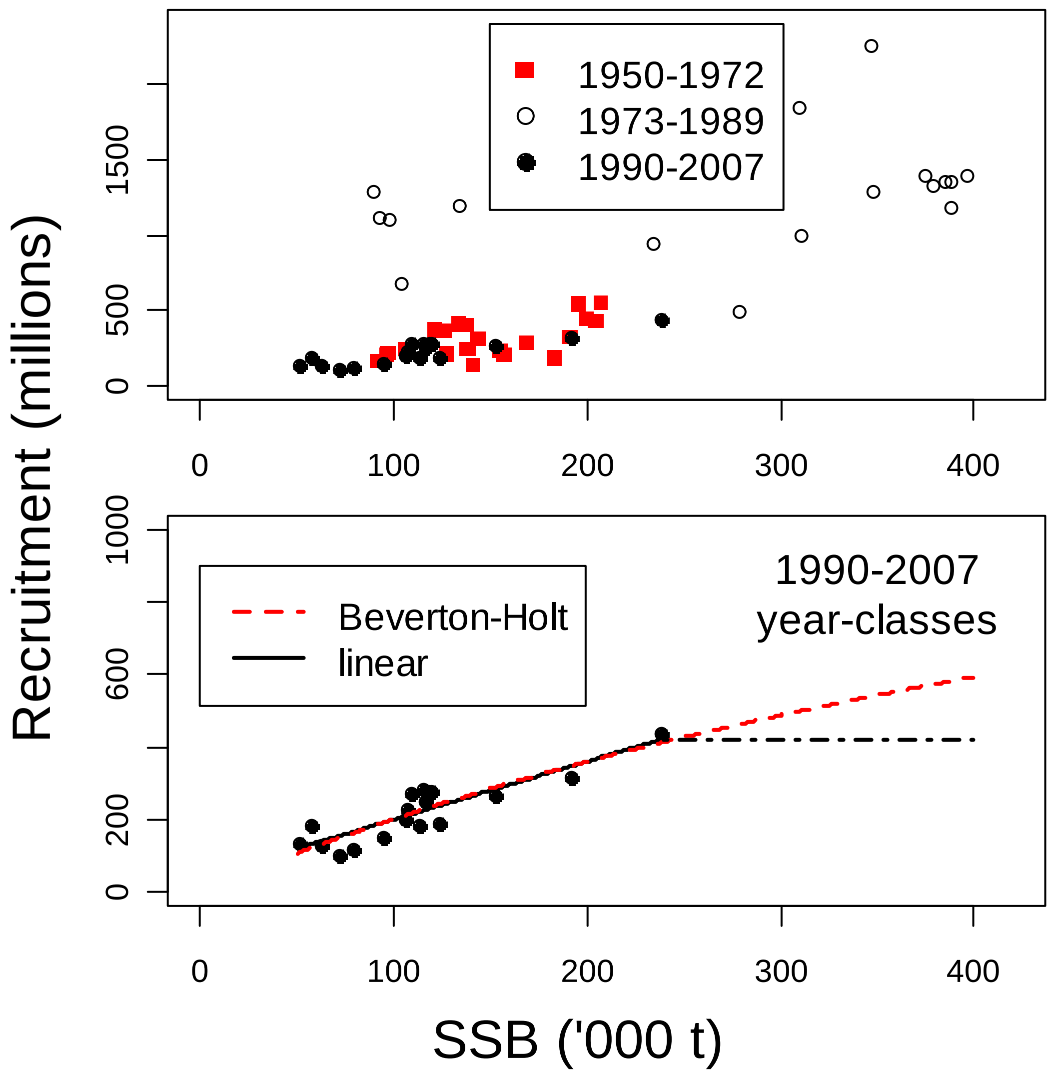


Figure 24. Stock-recruit relationship for southern Gulf cod. Recruitment is at age 2.

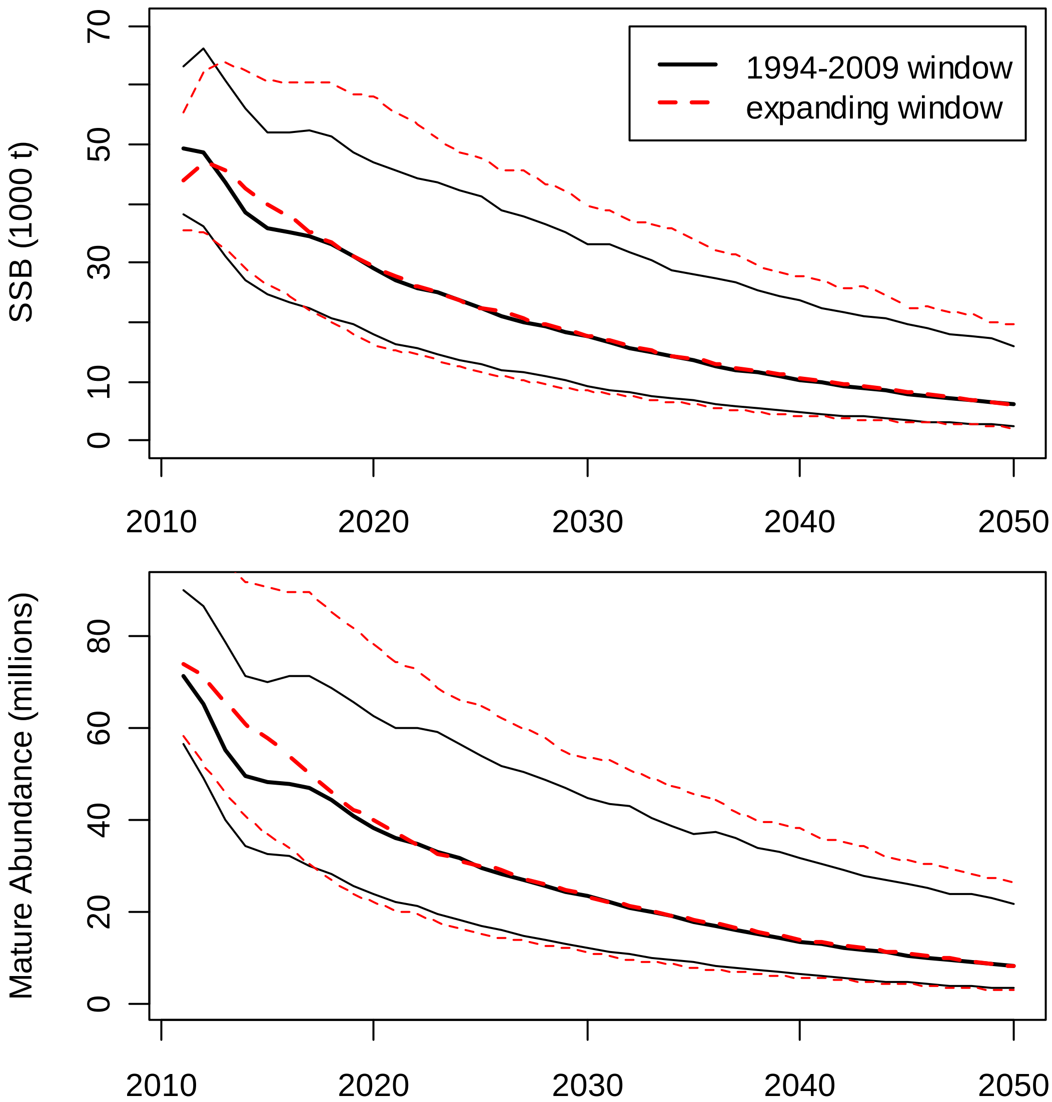


Figure 25. Projected spawning stock biomass (SSB) and mature abundance of southern Gulf cod with no fishery removals (neither directed nor bycatch) under the assumption that current productivity conditions persist in the future. Productivity parameters are sampled from either the full 1994-2009 window or from an expanding window from 2009 to 1994.

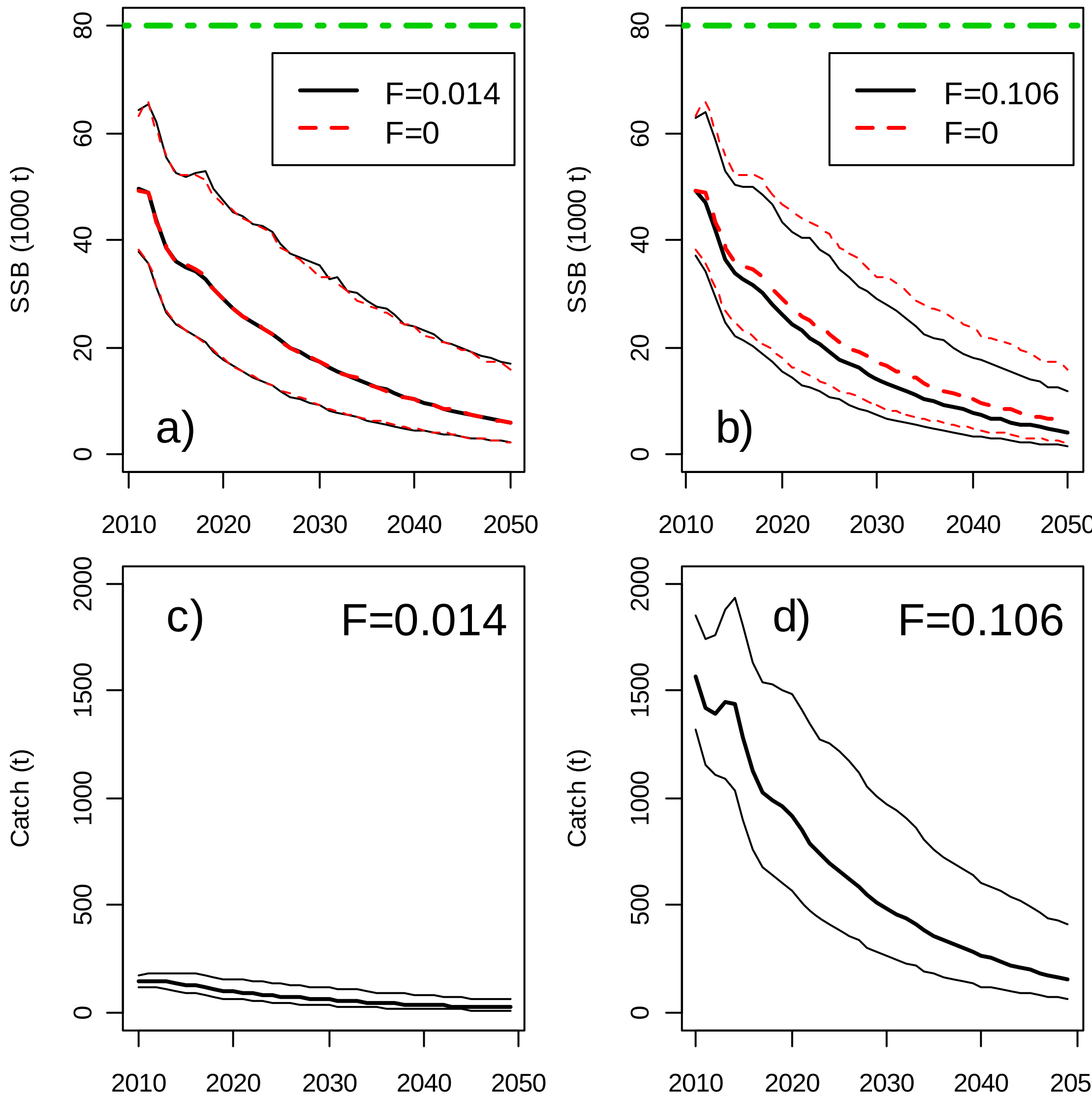


Figure 26. Projected spawning stock biomass (SSB) and catch of southern Gulf cod under three fishing mortality (F) scenarios. F=0.014 is the fully-recruited F estimated for 2009, when there was no directed fishery. F=0.106 is the average fully-recruited F estimated for 2007 and 2008, when there was a directed fishery with a TAC of 2,000 t (with average landings of about 1,550 t). Heavy lines show the median projection and light lines the 2.5th and 97.5th percentiles of projections. The green dashed-dotted line is the limit reference point for this stock

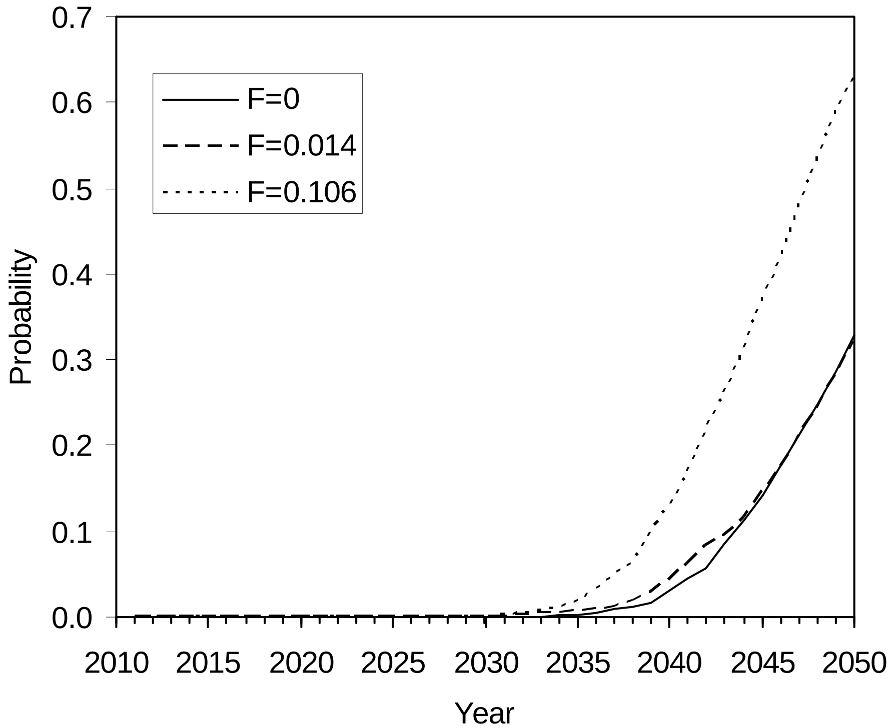


Figure 27. Probability that the projected SSB of southern Gulf cod will fall below 5,000 t at various levels of fully-recruited F.

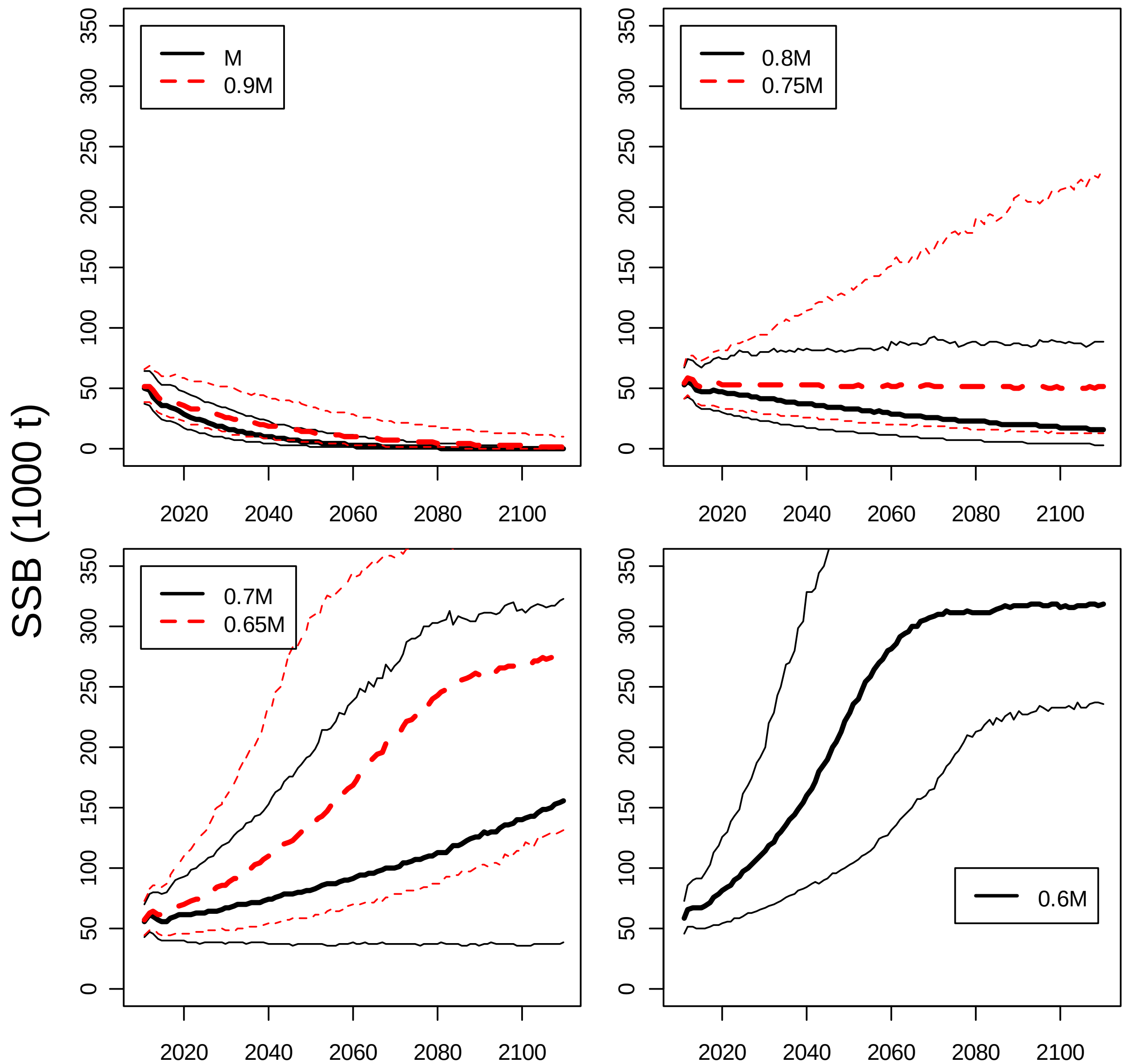


Figure 28. Projected spawning stock biomass (SSB) of southern Gulf cod at reduced levels of 5+ M, assuming that other components of productivity were to remain at current levels. Fishing mortality is set at 0. Heavy lines show the median projection and light lines the 2.5th and 97.5th percentiles of projections.

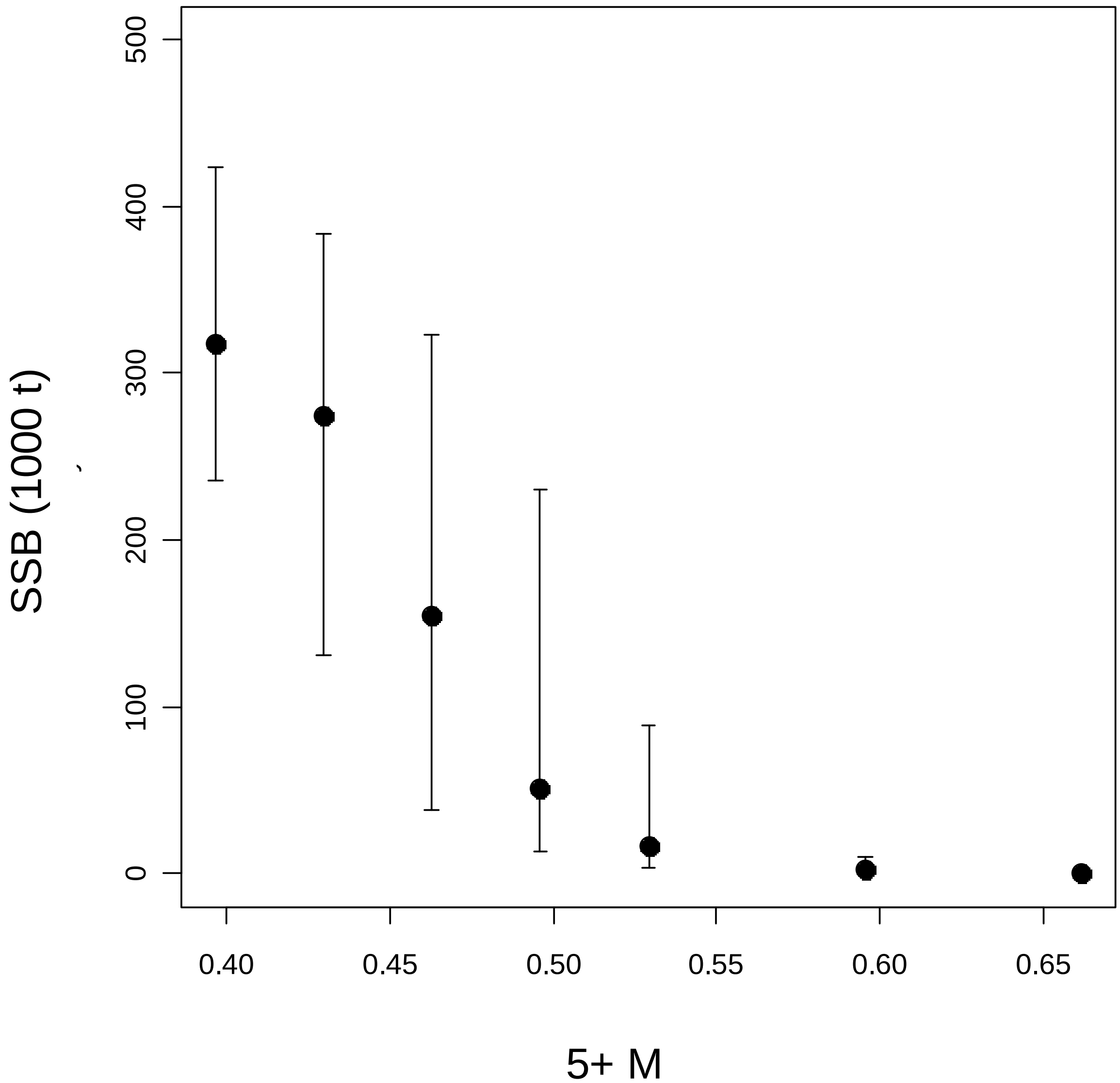


Figure 29. Projected spawning stock biomass (SSB) of southern Gulf cod after 100 years at various levels of 5+ M with other components of productivity at current (1994-2009) levels. Fishing mortality is set at 0. The circles show the median value and the error bars the 2.5th and 97.5th percentiles.

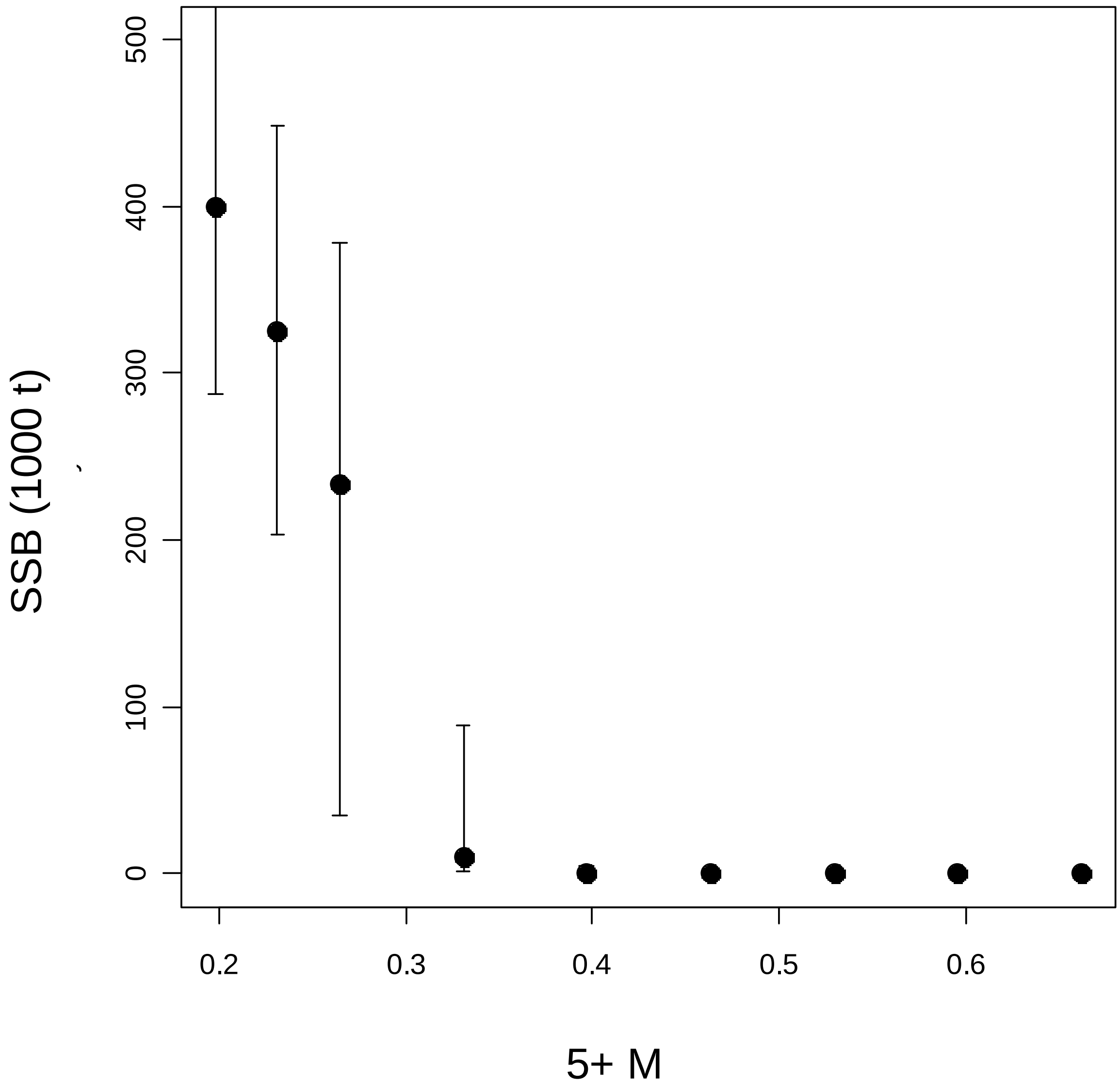


Figure 30. Projected spawning stock biomass (SSB) of southern Gulf cod after 100 years at various levels of 5+ M with recruitment rate and weight-at-age at current (1994-2009) levels and M of 2-4 year old cod at 1971-1990 levels. The circles show the median value and the error bars the 2.5th and 97.5th percentiles.

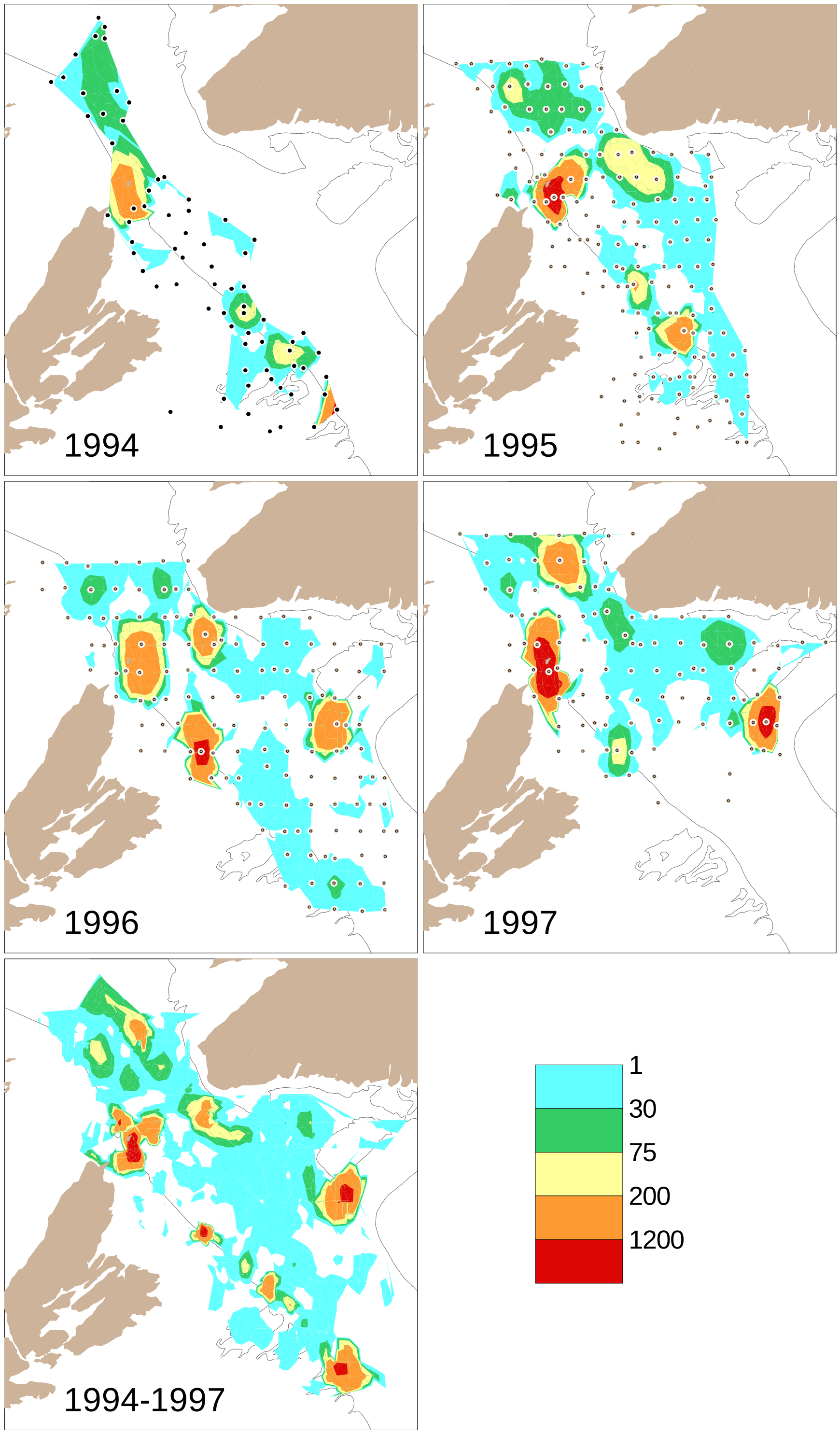


Figure 31. Distribution of catches (fish/tow) of cod 35 cm and longer in January surveys of the Cabot Strait. Cod on the south side of the Laurentian Channel are southern Gulf cod. The aggregation apparent at the southern extreme of the study area with all years combined is due to a single tow in the 1994 survey.

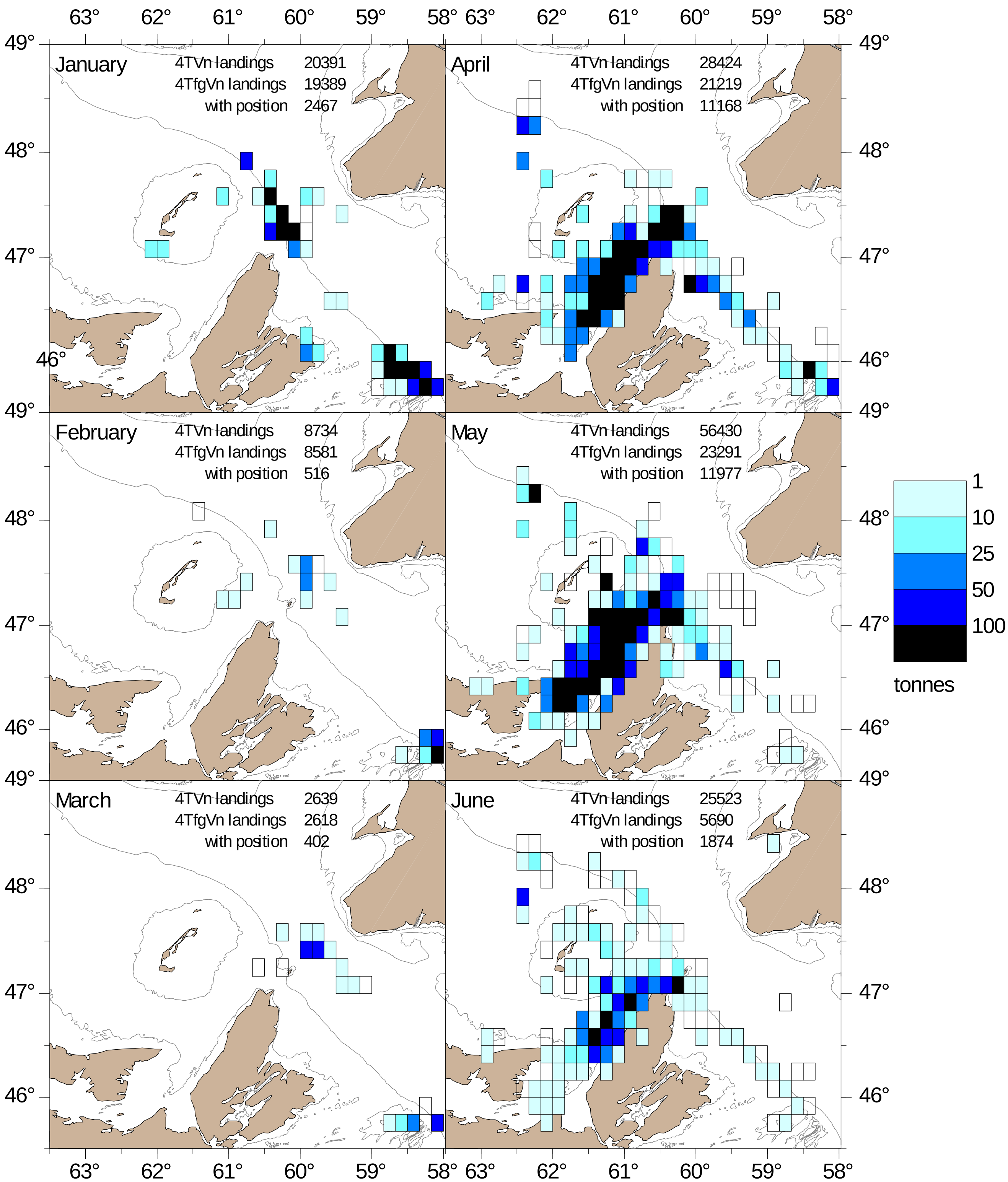


Figure 32. Distribution of cod catches by mobile gear in 4TfgVn (1986 to 1990).

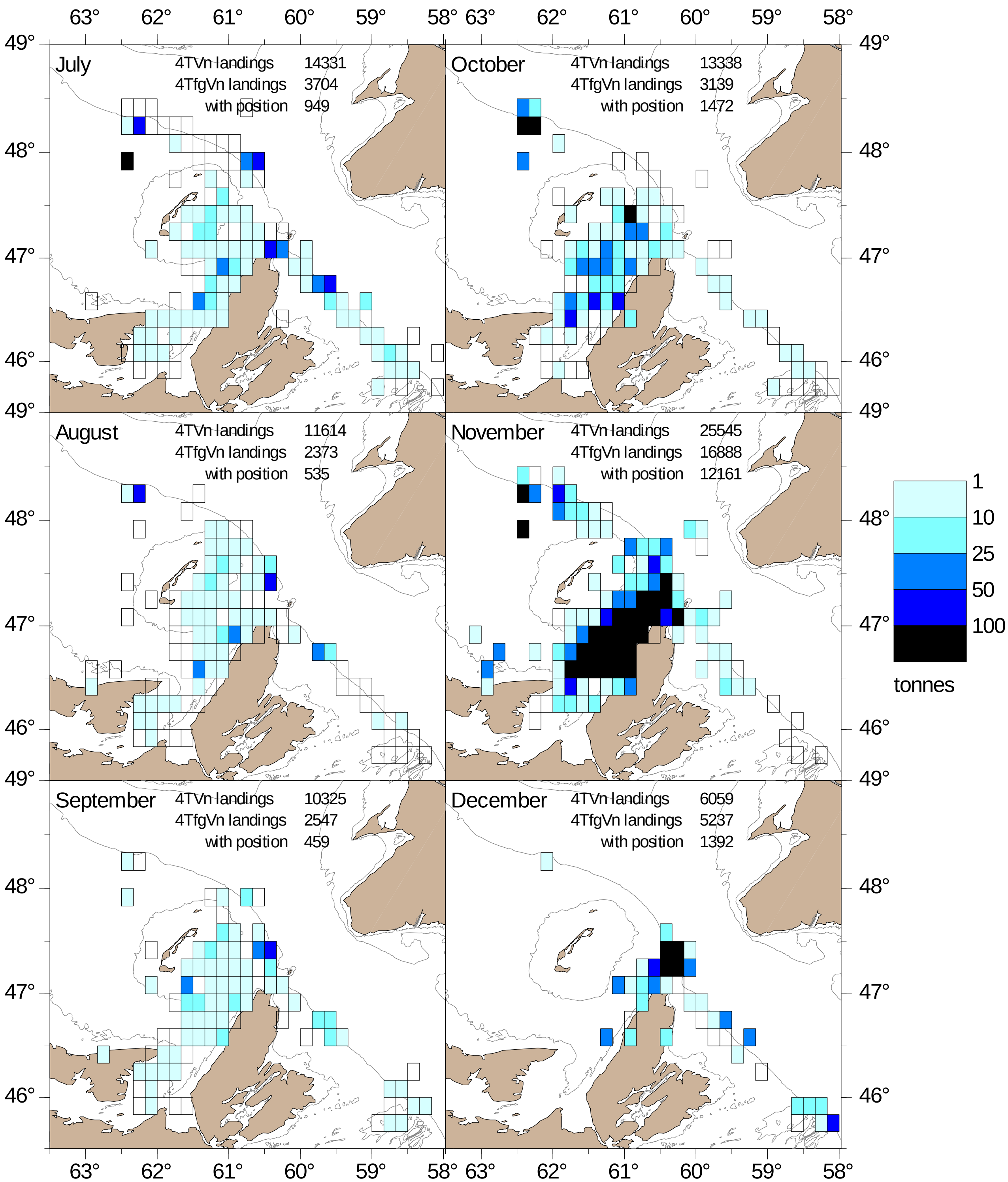


Figure 32 (continued).

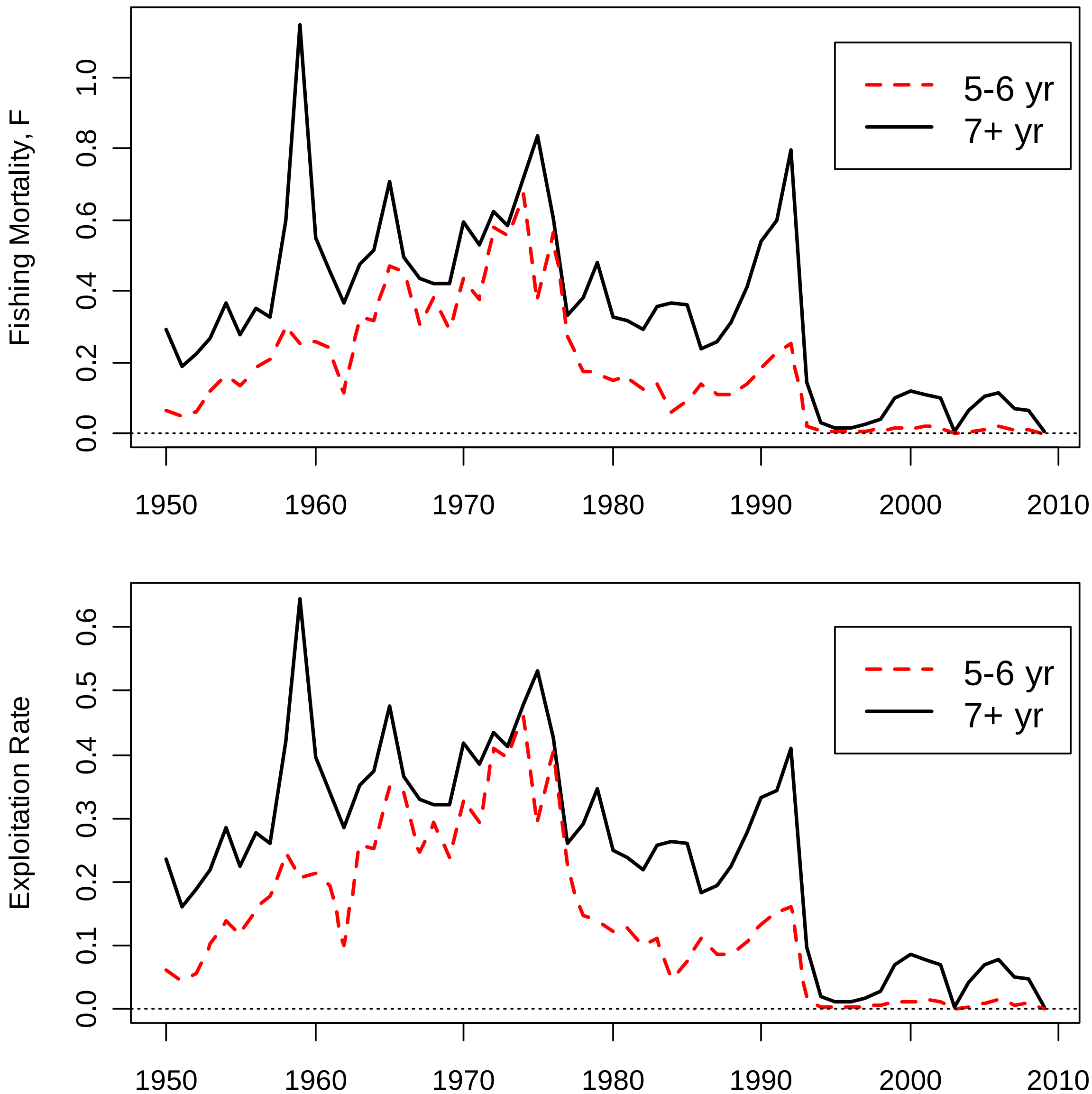


Figure 33. Estimated fishing mortality and exploitation rate of southern Gulf cod.

Appendix I. Comparison of biomass estimates from the M-walk and M-block models. Heavy lines show median estimates and light lines the 2.5th and 97.5th percentiles.