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A biomass Limit Reference Point for the NAFO 4T American plaice (*Hippoglossoides platessoides*) fishery

Un point de référence limite de la biomasse pour la pêche de la plie canadienne (*Hippoglossoides platessoides*) dans la zone 4T de l'OPANO

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ABSTRACT

Several indicators of the status of NAFO 4T American plaice suggest that the stock is presently at an all-time low abundance level. The spawning stock biomass (SSB), estimated using an age-structured population model, underwent a major decline from the late 1970s to the early 2000s. SSB was at its lowest level in 2009 at less than 31,000 tonnes and the latest estimate (2012) was 41,676 tonnes. Age-4 recruits peaked in abundance in the late 1970s, reaching levels that up to 13 times their average abundance over the past five years. The dynamics of the 4T plaice stock are dominated by a pattern of high natural mortality on adults, combined with chronic poor recruitment. Several models of stock-recruit relationships were examined, but Bayesian formulations of the Beverton-Holt and Ricker models formed the basis for determining the median SSB that produced 50% of maximum recruitment (B_{lim}). B_{lim} was estimated at 68,000 tonnes from the Beverton-Holt model and 60,000 tonnes from the Ricker model. An intermediate level of the two estimates, 64,000 tonnes, was proposed as B_{lim} for 4T American plaice. The SSB for the 4T plaice stock has met or exceeded B_{lim} only once since 1996. The recent low stock performance was observed during a period of low fishing mortality. Fishing mortality (F) was negligible on 4 to 9-year-old plaice throughout the time series, but for older plaice, estimated F varied between 0.1 and 0.2 from the mid-1970s to the early 1990s, dropping to below 0.1 and reaching less than 0.01 in recent years.

RÉSUMÉ

Plusieurs indicateurs de l'état de la plie canadienne dans la zone 4T de l'OPANO semblent montrer que l'abondance du stock est actuellement au niveau le plus bas jamais atteint. La biomasse du stock reproducteur (BSR), estimée à l'aide d'un modèle de population structuré selon l'âge, a connu un grand déclin entre la fin des années 1970 et le début des années 2000. Le niveau de la BSR était à son plus bas en 2009, soit moins de 31 000 tonnes. L'estimation la plus récente (2012) fixait le niveau à 41 676 tonnes. L'abondance des recrues d'âge 4 a connu un pic à la fin des années 1970, atteignant des niveaux jusqu'à 13 fois plus élevés que ceux des 5 dernières années. La dynamique du stock de plie de la zone 4T est dominée par une tendance de mortalité naturelle élevée chez les adultes, en plus d'un recrutement chroniquement faible. Plusieurs modèles de relations stock-recrutement ont été examinés, mais les formules bayésiennes des modèles Beverton-Holt et Ricker ont servi de base à la détermination de la BSR médiane ayant produit 50 % du recrutement maximum (B_{lim}). Le B_{lim} a été estimé à 68 000 tonnes par le modèle Beverton-Holt et à 60 000 tonnes par le modèle Ricker. On a proposé un compromis entre les deux estimations, soit 64 000 tonnes, en tant que B_{lim} pour la plie canadienne dans la zone 4T. La BSR de la plie canadienne dans la zone 4T n'a atteint ou dépassé le B_{lim} qu'une seule fois depuis 1996. La mortalité par pêche (F) était négligeable pour ce qui est de la plie d'âge 4 à 9 dans toute la série chronologique. Cependant, dans le cas de la plie plus âgée, F se situait entre environ 0,1 et 0,2 du milieu des années 1970 jusqu'au début des années 1990. La mortalité par pêche a chuté en dessous de 0,1 pour atteindre moins de 0,01 au cours des dernières années.

INTRODUCTION

In April 2009, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recommended that the Maritime population of American plaice be considered as “threatened” (COSEWIC 2009). COSEWIC identified the southern Gulf of St. Lawrence (NAFO 4T) stock as a component of the Maritime population of American plaice. The COSEWIC recommendation on the threatened status of American plaice led to a peer reviewed assessment of the NAFO 4T American plaice in December 2010 (Morin and LeBlanc 2012) and to a Recovery Potential Assessment (RPA) in March 2011 (DFO 2011). The 2010 assessment of 4T plaice and analyses conducted for the 2011 RPA established that 4T plaice were at a low level of stock abundance and showed no signs of recovery, despite recent low harvests. Major contributing factors to the lack of recovery were persistent low recruitment and a high level of natural mortality acting on all ages.

The development of a structured population model for 4T American plaice has been important for deriving a comprehensive view of stock dynamics, including trends in the abundance of recruits and the parent stock, as well as estimates of mortality. A Virtual Population Analysis (VPA), using the adaptive framework (Gavaris 1988) was applied successfully to 4T plaice in a 2008 assessment (Morin et al. 2008). That assessment was based on data since 1993 when the commercial catch-at-age was considered to be more accurate. Uncertainties in the catch-at-age prior to 1993 were attributed to the high level of discarding that was reported from mobile gear fisheries in the southern Gulf. The 2008 VPA model also broke with the practice of fixing natural mortality (M). M was estimated across all ages and years. For the 2010 VPA, the commercial catch-at-age was extended back to 1976 and included estimates of discarded plaice. M was estimated in 5-year time blocks and two age groupings at the beginning of the time series.

This study was undertaken to establish the limit reference point for the 4T American plaice fishery, an issue that was not addressed in the 2008 and 2010 assessments. The VPA model is updated by including 2010 and 2011 data on the commercial catch-at-age and corresponding results from research surveys. In addition to annual ecosystem survey data that have been conducted since 1971, a second index, derived from the Sentinel program beginning in 2003, was added to the VPA.

FISHERY DATA

The NAFO 4T American plaice fishery continues a trend of low catch and diminished fishing effort. Preliminary landing statistics for the 2011 fishery estimate the total landed catch at approximately 90 tonnes, the lowest level on record. Recent landing declines have been attributed to decreasing effort brought on by a combination of poor market conditions, low quota, weak demand for the product, high cost associated with exploitation (mainly fuel), and low catch of large, higher quality plaice.

This resource was exploited with landed catches ranging between 6,000 and 12,000 tonnes from 1965 to the late 1980s (Table 1). A 10,000 tonne quota was imposed in 1977 and maintained at that level until 1993. It was reduced to 5,000 tonnes in 1993 as a measure to avoid redirecting fishing effort from vessels affected by the moratorium on cod fishing. Assessments of 4T plaice signaled a declining trend in abundance before 1993; however, discarding was widespread in the fishery and it was thought that reductions to the TAC could result in an increase in misreported or discarded catch. With the closure of the 4T cod fishery in 1993 and in years following, several management measures were introduced to prevent discarding and misreporting. It became mandatory to land all catches, mesh sizes were increased, and there was increased surveillance through at-sea observers and dockside monitoring. Several changes to the plaice TAC have been made since 1993 and the current level of 500 tonnes has been in effect since 2008.

The commercial catch-at-age is obtained by sampling catches in landing ports and at sea by observers. The sampling program for this fishery began in 1976. The sampling consists of obtaining sexed length frequencies from random samples. Otoliths are removed from one fish per 1-cm length and sex category in each sample. Ages are determined from otolith interpretation. Semi-annual age-length keys are made when possible and are applied to catch estimates by major gear types in two annual time periods: January-July and August-December. When landed catches decline to low levels, it is difficult to obtain representative samples from all gears in the time periods established earlier. In some cases, as in the seine fishery in 2011, insufficient sampling resulted in a grouping of samples from all months to obtain a single catch-at-age for seine catches.

Table 2 presents the total catch-at-age of American plaice. The maximum age recorded from the commercial fishery was 30, last observed in 1988. The oldest plaice found in the 2010 and 2011 fisheries were 22 years of age. In Table 2, catches are aggregated for plaice 20 years of age and over.

RESEARCH DATA

SEPTEMBER ECOSYSTEM SURVEY

The longest index of 4T American plaice population abundance, biomass and population structure is from the annual bottom trawl survey, conducted every September since 1971. The survey area is divided into 24 depth strata within which trawling locations are chosen randomly. Three inshore strata were added to the survey in 1984; however, these represent marginal habitat for American plaice and are excluded from plaice analyses. A full description of the survey methodology may be found in Hurlbut and Clay (1990).

Four vessels and two trawls have been used in this survey since 1971. The vessel E.E. Prince with the Yankee 36 trawl were used to 1985, replaced by the Lady Hammond with the Western IIa trawl. This same model of survey trawl has been used in each survey since 1985. The Lady Hammond was replaced by the CCGS Alfred Needler in 1990, then by the CCGS Teleost in 2004. Fishing experiments were conducted in 1984, 1992, 2004 and 2005 to compare the relative fishing efficiency of each vessel. Adjustments have been made to survey catches to standardize to a common vessel. These data were reanalyzed by Benoît and Swain (2003), resulting in a change in the factor relating E.E. Prince to Lady Hammond and Alfred Needler plaice abundance from 1.75 (Nielsen 1994) to 1.426. In this assessment, the 4T plaice survey index was revised to include the inter-vessel conversion factors established by Benoît and Swain (2003).

The survey abundance indices, including the revised vessel coefficients, are presented in Figure 1. These indices are expressed as the stratified mean catch per tow, adjusted to be equivalent to catches of the Alfred Needler with the Western IIa trawl. The stock was at a low level of abundance in 1971, but increased rapidly through the mid-1970s to attain a maximum of 917 fish per tow in 1977 (formerly estimated at 1,126 fish per tow). The stock declined in abundance after 1977 and, by 1984, the index of plaice abundance was well below the long-term average of 266 fish per tow (mean of values for 1971–2011). The survey index increased to values above the long-term average in 1990 and 1991 due to a moderate improvement in recruitment during the mid-1980s, and then continued to decline. The survey index reached its lowest point during the 2002 and 2004 surveys at 104 and 109 fish per tow, respectively. The 2009 survey index, at 115 fish per tow, was the next lowest level recorded in the time series.

Although the survey index remains at a low level, it has fluctuated in the last four years. The survey index rose to 178 fish per tow in 2008, partly due to two large catches of more than 1,000 American plaice. The index declined to one of its lowest points in 2009, at 115 fish per tow. However, in 2010 the index increased to 192 fish per tow, due to two exceptional catches in strata 416 and 426 in the northwestern part of 4T (catches of 5,900 and 4,008 fish per standard tow, respectively). Catches of more than 4,007 fish per standard tow have only occurred nine times in previous surveys, the last time in 1991 and seven times between 1976 and 1980. When the two large catches in the 2010 survey were removed, the abundance index dropped to 130 fish per tow. The abundance index in the 2011 survey was 152 fish per tow.

The stratified mean number at age of plaice is presented in Table 3, with all sets included from the 2010 survey. The population-at-age used in the assessment model was calculated by multiplying the mean catches by the number of standard tows required to cover the survey area. The effect of including the two large tows from that survey was spread across ages 5 to 11, not restricted to a single cohort. This survey catch-at-age tracks cohorts over several years (Morin et al. 2008). Recent surveys indicate a strong 2006 cohort, as well as larger catches of age-0 and age-1 plaice than in surveys before the 2000s.

Total mortality (Z) was estimated from the survey catch-at-age by a catch curve analysis described by Sinclair (2001). This method estimates Z as the slope of log-transformed catch in short time periods, accounting for variation in year-class abundance. The analytical model includes terms for age (a continuous variable) and year-class. The slope of catch relative to age represents Z standardized for year-class abundance. We calculated Z in 5-year time periods, beginning with 1971-1975 and ending with 2007–2011, and over ages that are well recruited to the survey trawl, 8 to 20 years of age. Total mortality has cycled from less than 0.3 in the early 1970s to 0.58 in 1978–1982, to a low of 0.24 in 1982–1986, followed by a high of 0.83 in 1991–1995 (Fig. 2). The trend in Z appears to have leveled since the late 1990s near the average of all 37 estimates of Z (0.52), despite harvest reductions. Z was estimated at 0.46 in the last two 5-year periods.

Previous assessments have shown that the survey length frequencies for 4T plaice have shifted over time to smaller sizes, with a more rapid decline in the upper quantiles of fish length (Morin et al. 2008). This pattern suggests a loss of larger plaice from the population, a result that is consistent with estimates of total mortality based on the survey catch-at-age.

SENTINEL SURVEY

The sentinel survey program was initiated in 1994 following the closure of the commercial fishery to provide an industry based abundance index for Atlantic cod (Savoie 2011). In 2003, the mobile gear sentinel program was revised. The survey began to use trawlers with a 300 Star Balloon otter trawl with a 40-mm liner in the codend. The revised program, conducted in August, adopted the same stratified random sampling design that is used in the annual September ecosystem survey. Tow speed and duration were standardized to 2.5 knots and 30 minutes. All catches were sorted to species, then weighed and counted. Sexed length frequencies were obtained for American plaice on either the whole catch or a subsample of 250 fish. Otoliths were not collected from plaice sampled in the sentinel program, so age-length keys from the

September ecosystem survey of the same year were used. No plaice sampled in the 2003 September survey were aged, so the age composition of the 2003 sentinel program was estimated by combining age-length keys from 2002 and 2004 surveys. We estimated the age composition of plaice at lengths that were not sampled in the September survey from age-length keys based on sampling since 1993 (i.e. drawing on age sampling up to 10 years before the sentinel survey began).

Seven trawlers have participated in the mobile gear sentinel program since 2003. Four vessels conduct the survey each year, overlapping in their coverage to allow for a comparison of their relative fishing efficiency. Following each survey, coefficients of relative fishing efficiency are computed (Savoie 2011; Savoie and Surette 2010). The sentinel survey catch index, adjusted for vessel effects, shows a declining trend since 2004 with an increase occurring in 2011 (Fig. 3). The sentinel survey population-at-age is presented in Table 4.

POPULATION MODEL

Methods

The most recent assessment of this population (Morin and LeBlanc 2012) was based on a VPA implemented in ADAPT (Gavaris 1988). Inputs were the commercial catch at ages 4–20+ years in 1976–2009 revised to include estimates of discarded plaice, and abundance indices at ages 4–20+ years in 1976–2002 and 2004–2009 from the annual September Research Vessel (RV) survey. Abundance indices were not available for 2003 because the survey was incomplete and conducted by an uncalibrated vessel. Abundance indices were at the scale of “trawlable abundance”, i.e. stratified mean catch per standard tow expanded to the survey area. Catchability was set to 1 for ages 10–15 and estimated for other ages. The instantaneous rate of natural mortality M was estimated in blocks of years: 1976–1980, 1981–1985, 1986–1990, 1991–2000, 2001–2005 and 2006–2009. Estimates of M were obtained separately for ages 4–9 and 10–20+ in the first two time periods and aggregated over all ages (4–20+) for the remaining time periods.

This updated analysis is based on VPA implemented in AD Model Builder (Fournier et al. 2011). The model used here is similar to the previous assessment model, except that annual variation in M was modelled as random walks, with separate trends for ages 4–9 and 10+ years. These time trends in M were modelled as follows:

$M_{j,y} = Minit_j$ if y=1976

$M_{j,y} = M_{j,y-1} * \exp(Mdev_{j,y})$ if y>1976

where y indexes year and j indexes age class (4–9 or 10+), Mdev is normally distributed with mean 0 and standard deviation sdev, and Minitj is a parameter for M of age-class j in 1976. The value of sdev 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. Based on previous experience (Swain 2012), sdev was set at 0.075. Results with sdev set at 0.1 were similar to those presented here. Simulation studies indicate that time trends in M are well estimated by this model (Swain 2011), given the characteristics of the 4T plaice data (i.e., a sharp drop in fishing effort and substantial variation in year-class strength).

Model inputs were the commercial catch at ages 4–20+ years in 1976–2011 revised to include estimates of discarded plaice, the RV abundance indices at ages 4–18 years in 1976–2002 and

2004–2011, and abundance indices for ages 4–18 years from the 2003 to 2011 sentinel bottom-trawl survey. As in the previous model, abundance indices were at the scale of “trawlable abundance”. Catchability was set to 1 for ages 10–15 from the RV survey and estimated for other ages for the RV survey and all ages for the sentinel survey. Additional parameters to be estimated were beginning-of-year abundances at ages 5–20+ in 2012. The model included a 20+ group and was fit using the F-ratio method, as described by Gavaris (1988). The F-ratio (the ratio between F’s of 20+ and 19-year-old plaice in year t) was set to 1 in all years.

Parameters were estimated by minimizing an objective function with the following components:

1. residuals between observed and predicted abundance indices:

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

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 index. cv was set to a constant value of 0.3, and thus had no effect on the minimization (except for its effect on the weight attributed to this component of the objective function).

2. random-walk deviates

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

3. prior value for initial *M*

$$\mathrm{f}_3 = 0.5 \left(\frac{M\mathrm{init}_\mathrm{j} - M\mathrm{prior}_\mathrm{j}}{0.05} \right)^2 + \log(0.05)$$

where the prior for *M* in 1976 was set at 0.6 for ages 4–9 and 0.3 for ages 10+.

Results

Residuals between the abundance indices and model predictions showed reverse patterns between the RV and sentinel indices during the 2003–2011 period (Fig. 4). This reflected contrasting trends between the two surveys, with the RV indices generally stable and the sentinel indices generally declining over this period (Fig. 5). The residuals also indicated a number of year-effects and cohort-effects, in particular a tendency for the model to under-estimate the strength of the 1991 year-class compared to its relative abundance in the survey. Nonetheless, estimates of abundance from the model corresponded well with the trends in the abundance indices (Fig. 6). Retrospective analyses did not reveal any tendency for the model to over- or under-estimate abundance or spawning stock biomass (Fig. 7).

Estimated catchability curves were moderately dome-shaped for both the RV and sentinel surveys (Fig. 8). Catchability appeared to be higher to the RV survey than to the sentinel survey.

Estimated spawning stock biomass (SSB) generally declined from the late 1970s to the early 2000s (Fig. 9). Recruit abundance in the mid to late 1970s was estimated to be about 13 times the average value over the last five years (Fig. 9). Estimated abundance of plaice aged 4–9 years declined sharply in the late 1970s and early 1980s and gradually thereafter (Fig. 10). Estimated abundances of this age-group over the last five years are the lowest in the time series. Estimated abundance of older (10+) plaice declined sharply between the mid-1980s and the mid-2000s, with estimated abundance in the mid-2000s about 25% of the 1976–1985 level (Fig 10). Estimated abundance of this age group increased slightly in recent years.

Estimated M of pre-commercial sizes of plaice (ages 4–9 years) was highest in the late 1970s, declining to a level between 0.45 and 0.6 throughout the 1990s and 2000s (Fig. 11). The high level estimated for the late 1970s may partly reflect an underestimate of the level of discarding during this period (Morin and LeBlanc 2012). For older plaice, estimated M was between about 0.2 and 0.25 in the late 1970s and early 1980s, increasing to a peak near 0.6 in the early to mid-1990s and then decreasing to 0.4–0.45 throughout the 2000s (Fig. 11). Estimated fishing mortality F on pre-commercial sizes (ages 4–9) was negligible throughout the time series, at a level near 0.01 from the mid-1970s to the early 1990s, declining to a level <0.001 in the 2000s (Fig. 12). For older plaice, estimated F varied between about 0.1 and 0.2 from the mid 1970s to the early 1990s and then declined, falling to a level below 0.01 in recent years.

STOCK-RECRUIT RELATIONSHIP

The model estimates of SSB and the number of age-4 plaice recruits produced by that SSB are shown in Table 5. Since the most recent survey was in 2011, the last estimate of SSB for which we have corresponding recruits four years later is 2007. SSB in 2007 was estimated as slightly less than 59,000 tonnes. However, SSB has continued to decline, reaching its lowest point in 2009, at less than 31,000 tonnes (Table 5). The latest estimate of the SSB, for 2012, was 41,676 tonnes.

Recruitment reached a peak early in the time series, in the 1970s (Figs. 9 and 13A). Recruitment was highest for the 1972–1974 year-classes, but estimates of the SSB producing these year-classes are not available. The highest level of recruitment for which we have the SSB that produced it, occurred in 1976 with SSB at approximately 388 kt. That level of SSB was exceeded only the following year, but failed to produce the same level of recruitment as the 1976 SSB (Fig. 13B). Recruitment rate, shown in Figure 13C as the number of recruits divided by the number of spawners that produced them (SSN), provides an index of the survival of recruits (in this case, up to age-4). The recruitment rate has cycled through high and low periods, year classes of 1985–1989 and 1999–2002 appearing to have been abundant relative to the spawning stocks that produced them. This may be indicative of favourable conditions for the survival of recruiting plaice in those periods.

DFO applies the Precautionary Approach (PA) to harvest strategies in a framework that defines three stock status zones (DFO 2006, 2009), referred to as critical, cautious and healthy zones. The Critical Zone is defined in relation to the Limit Reference Point (LRP), a stock level below which productivity is sufficiently impaired to cause serious harm. The Upper Reference Point (URP) is the stock level below which the maximum removal rate is reduced and any stock at a level exceeding the URP is considered to be in a Healthy Zone. The Cautious Zone lies between the LRP and the URP and requires fisheries management measures to promote stock rebuilding to the Healthy Zone. A stock in the Critical Zone, below the LRP, requires management that promotes stock growth, including actions to reduce removals to the lowest possible level.

We estimated the LRP for 4T American plaice using eight modelling approaches to the stock-recruit relationship. We adopted the same models proposed by Duplisea and Fréchet (2009), which comprised methods that could be separated into three groups: parametric models (Beverton-Holt, Ricker, Hockey Stick); non-parametric models (NP50, Serebryakov, Binfl, P0.1); and one empirical approach based on observed properties of the time series (Bloss), the lowest observed level of SSB from which recovery was observed in the past.

The Beverton-Holt (BH) model is of the form:

(1)
$$R_t \sim Lognormal(\mu_t, \varepsilon)$$
$$\mu_t = \log\left(\frac{aS_t}{b + S_t}\right)$$
$$\varepsilon \sim Normal(0, \sigma^2)$$

where R is the number of recruits in a given year class, S is the spawning stock biomass that produced that year class, a is the maximum number of recruits produced, and b is the spawning stock biomass needed to produce, on average, recruitment equal to half of maximum R. The recruitment is assumed to be lognormally distributed. The parameter b, also referred to as BH50, is recommended as the LRP, where the model is appropriate (Myers et al. 1994; Duplisea and Fréchet 2009).

The Ricker model is of the form:

(2)
$$R_t \sim Lognormal(\mu_t, \varepsilon)$$
$$\mu_t = \log\left(\alpha S e^{-\beta S}\right)$$
$$\varepsilon \sim Normal(0, \sigma^2)$$

where α is the recruits per unit of spawner biomass at low stock levels and β relates to the rate of decline in the recruits per unit of spawner biomass as S increases. The recruitment is assumed to be lognornally distributed. The LRP, RK50, is the SSB at 50% of the maximum recruitment, similar to BH50 above. It is estimated by iteration.

The Hockey Stick regression method (also referred to as change-point or segmented regressions) models the relation in two segments, one being a flat line at maximum recruitment and the other a straight line from the origin to a point intersecting the flat segment. The intersection of the two lines is determined by a numerical optimization approach outlined by Julious (2001).

The non-parametric approach includes a cubic spline fitted to the data (NP50 method, Duplisea and Fréchet 2009) and defines the reference level as SSB at 50% of the estimated maximum recruitment. Binfl and P0.1 are two approaches proposed by Duplisea and Fréchet (2009). Based on the same smoother fit used for NP50, Binfl defines the LRP as the SSB level corresponding to the maximum change in recruitment. P0.1 defines poor recruitment as the 10th percentile of cumulated R. They propose the SSB level associated with the 10th percentile as the LRP.

The Serebryakov approach sets the LRP at the SSB corresponding to the intercept of a percentile of observed recruitment and a percentile of the recruit to spawner biomass ratio. This was initially proposed to be the 50th percentile of recruitment and the 90th percentile of the R/SSB ratio (DFO 2002). In simulation studies on cod, this formulation of the LRP tends to be risk-prone (Shelton 2005). Duplisea and Fréchet (2009) adopted the Serebryakov model based on 90%R and 90% R/SSB as a more conservative reference level.

Applied to 4T American plaice data, the three parametric models gave the lowest estimates of the LRP, ranging between 43,000 and 81,000 tonnes (Fig. 14). The BH and Ricker models produced similar estimates of the LRP (81,000 and 77,000 tonnes, respectively). The BH model gave a somewhat lower residual mean square than the Ricker (299,000 versus 318,700 on 30 degrees of freedom); however, the parameter b on the BH model was not significant (P=0.078). The Hockey-Stick model estimated the lowest estimate of the LRP (43,000 tonnes) of all eight models examined; the estimate from this model was outside of the range of the data and was felt not to be credible.

The four non-parametric methods estimated SSB at the LRP ranging between 87,000 and 361,000 tonnes (Figs. 15 and 16). The non-parametric smoother (a cubic spline used here) failed to identify a clear recruitment plateau from which a reference point could be defined. The spline fit to observations is shown in the upper graph in Figure 15, resulting in a LRP of 91,000 tonnes, based on SSB corresponding to 50% of maximum recruitment. The SSB at maximum change in recruitment (Binfl) was based on the same non-parametric smoother. Since the maximum change in recruitment occurred at extreme levels of the SSB, the LRP from this method was correspondingly extreme (361,000 tonnes) and not credible (Fig. 15). The P0.1 method referenced cumulative recruitment at the lower end of the relationship, defining a poor level of recruitment. This appears to have resulted in an estimate of the LRP that was similar (87,000 tonnes, Fig. 15) to values obtained by the BH and Ricker models. The Serebryakov model (Fig. 16) gave a conservative estimate of the LRP (106,000 tonnes), but with 32 years of stock-recruit observations, the Serebryakov model draws on only three observations that are in the upper 10th percentile of recruitment, a point that was also made by Duplisea and Fréchet (2009). The Serebryakov model was rerun with the 50th and 75th quantiles of recruits and 90th percentile of R/SSB. The model results were sensitive to the model assumptions. Ser9090 estimated the LRP at 106,000 tonnes; Ser7590: 77,000 tonnes; and Ser5090: 50,000 tonnes.

Bloss was implemented as the SSB associated with recovery, defined here as 30% of the maximum recruitment. This method yielded the third highest estimate of all the methods that we applied to 4T plaice data (104,000 tonnes). This level of recovery was obtained from a low level of SSB observed in 1985 (Fig. 16). The model was rerun with recovery defined as 20% of maximum recruitment. This resulted in LRP at approximately 81,000 tonnes, but with the model unable to associate a year in which that recovery occurred.

BAYESIAN APPROACH TO S-R RELATIONSHIP

The Beverton-Holt and Ricker models provided similar estimates of the lower reference point, at an intermediate level amongst the more credible results of the eight S-R models that were explored. The properties of the BH and Ricker models were examined further in a Bayesian framework. The data inputs were the mean estimated stock and recruitment (divided by 1,000) (Table 5) for 1976–2007. The BH model was specified in its alternative form from equation 1:

$$R_t \sim Lognormal(\mu_t, \varepsilon)$$

(3) $$\mu_t = \log\left(\frac{aS_t}{1+\frac{\alpha S_t}{K}}\right)$$

$$\varepsilon \sim Normal(0, \sigma^2)$$

where R is the number of recruits in a given year, S is the spawning stock biomass that produced them, α is the slope at the origin, and K is the maximum number of recruits at large stock size. Under this formulation, BH50 is calculated as:

(4) $$BH50 = \frac{K}{\alpha}$$

The Ricker model was parameterized as in equation 2.

The Bayesian models were specified with vague priors on parameters. In the following table, the parameters of the normal and lognormal distributions indicate the specified mean and precision (variance^{-1}). The process error (ε), formulated as precision, was given a prior gamma distribution with shape and inverse scale parameters of 0.1 and 0.01, respectively. The prior distribution on the parameter K was chosen as a uniform distribution, equivalent to between 10 thousand and 10 million recruits.

Model	Parameter	Prior distribution
Ricker	Log(α)	Normal (0, 0.01)
	β	Normal (0, 0.01)
	ε	Gamma (0.1, 0.01)
Beverton-Holt	α	Lognormal (0, 0.1)
	K	Uniform (10, 10000)
	ε	Gamma (0.1, 0.01)

The Bayesian models were fitted using Monte Carlo Markov Chain with Gibbs sampling in "Winbugs" (Lunn et al. 2000). Posterior estimates were summarized from 10,000 samples, following the discarding of the first 10,000 observations.

Prior distributions were significantly updated by the stock-recruit data (Fig.17). Substantial amounts of precision were obtained for all parameters, though posterior distributions of the Beverton-Holt parameters were somewhat skewed with long upper tails. Recruitment was predicted from the two models for SSB ranging from 2,000 to 500,000 tonnes in steps of 2,000. Table 6 presents the model estimates (mean and median) with their Bayesian 95% credible interval (95% BCI, represented by the 2.5 and 97.5 percentiles of the posterior distributions).

Figure 18 presents the VPA-estimated age-4 recruits and their parent SSB with the corresponding median predictions of recruitment from the two Bayesian SR models. The 95% BCI for both models were large, encompassing all data points. The SSB at 50% maximum recruitment from the BH model was approximately 68,000 tonnes (95% BCI range 13,000 to 221,000 t) (Table 6, Fig. 18). For the Ricker model, we estimated to the nearest 1,000 tonnes, the SSB that produced 50% of Rmax and the median of the posterior distribution was approximately 60,000 t (95% BCI range 42,000 to 105,000 t).

The BH and Ricker models provided similar estimates of the LRP, differing by about 8,000 tonnes. Both models have fairly wide credible intervals about their estimates of the LRP.

The recommended LRP for 4T American plaice is an intermediate level between the two estimates, i.e. 64,000 tonnes. The history of stock performance relative to this reference point is shown in Figure 19. The 4T plaice stock has failed to reach the LRP in 15 of the past 16 years, last attaining it in 2004 when the SSB was estimated at over 67,000 t. This low stock performance was observed during a period of low fishing mortality. Current trends in stock performance may make it difficult to achieve sustained recovery above the recommended LRP.

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There are uncertainties in the identification of maturity stages for 4T American plaice prior to 1997. As a result, annual maturity ogives were used since 1997, whereas a constant maturity ogive was applied to the 1976–1996 period. This may affect the estimation of the SSB that resulted from the population analysis. There is evidence from other 4T groundfish species that maturation changed over the 1976–1996 period and a decline in the size and age at maturity was found for 3LNO plaice. However, the 4T plaice population model accounts for other changes that have occurred, such as changes in the size and age composition of the SSB, as well as mortality effects on the SSB. The residual pattern of the stock-recruit relationship indicates that the time series has been stationary.

As with most Atlantic groundfish stocks, 4T American plaice were exploited for many decades before the assessment data series began. The 4T plaice commercial catch-at-age began in 1976. The first observed cohorts were the most abundant; however, survey data indicate that cohorts originating from spawning before 1976 were considerably stronger. The lack of data from this period may affect the definition of the Healthy zone for this stock. It may also imply that the defined stock-recruitment relationship does not adequately describe the dynamics of the 4T plaice stock in a more productive period prior to 1976.

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Table 1. Landings of American plaice in NAFO Division 4T by major gear type. Gear codes: OTB= otter trawls, SNU=seines, PTB=pair trawls, GNS=gillnets, LLS= longlines, LH=handlines, TAC= total allowable catch.

YEAR	OTB	SNU	PTB	GNS	LLS	LH	OTHER	TOTAL	TAC
1965	7782	1854	0	388	212	0	149	10385	
1966	8647	2322	0	375	2	0	434	11780	
1967	7448	1151	0	326	117	50	259	9351	
1968	8137	911	0	298	4	36	182	9568	
1969	6034	1418	0	421	58	17	244	8192	
1970	6299	2241	0	439	79	7	136	9201	
1971	5405	2884	0	876	21	9	318	9513	
1972	5149	2576	0	286	73	11	199	8294	
1973	3578	2743	0	241	73	1	269	6905	
1974	4141	3719	0	250	6	5	364	8485	
1975	4003	3897	0	217	14	0	312	8443	
1976	7003	3395	0	225	2	6	562	11193	
1977	4671	4013	0	242	16	17	271	9230	10000
1978	4598	3495	0	379	42	38	479	9031	10000
1979	4459	3719	0	721	9	17	1071	9996	10000
1980	3852	3500	0	717	62	5	156	8292	10000
1981	2623	3570	0	1084	98	2	457	7834	10000
1982	1459	4124	0	805	94	5	55	6542	10000
1983	1402	4095	0	494	76	10	17	6094	10000
1984	3418	3702	0	1905	386	25	163	9599	10000
1985	4016	3870	83	997	404	29	91	9490	10000
1986	2967	3289	105	657	318	44	28	7408	10000
1987	3226	3140	123	831	664	67	13	8064	10000
1988	2557	2842	0	957	484	33	116	6989	10000
1989	2111	2489	0	501	212	386	18	5717	10000
1990	1891	2259	4	474	240	26	13	4907	10000
1991	1400	3057	94	525	102	22	22	5222	10000
1992	1599	2793	174	537	70	14	11	5198	10000
1993	226	928	63	592	28	1	15	1853	5000
1994	278	1761	90	243	13	0	35	2420	5000
1995	348	1752	123	136	2	0	33	2394	5000
1996	234	1019	99	42	1	0	11	1406	2000
1997	259	1282	124	49	2	0	1	1718	2500
1998	144	898	70	43	12	1	0	1168	1500
1999	254	1047	127	109	3	0	1	1540	2000
2000	205	1041	121	49	2	0	0	1417	2000
2001	147	869	139	32	3	0	0	1190	2000
2002	82	516	55	23	1	1	0	678	1000
2003	25	248	94	23	1	0	0	390	750
2004	52	298	11	38	1	0	0	400	750
2005	51	155	84	48	1	0	0	339	750
2006	102	233	92	35	1	0	11	474	750
2007	64	170	79	20	0	0	39	372	750
2008	42	66	0	40	0	0	23	171	500
2009	37	42	2	31	0	0	15	127	500
2010	32	84	0	30	0	0	0	146	500
2011	26	50	0	14	0	0	0	90	500
Mean	2606	2032	42	378	85	19	140	5302	

Table 2. Estimated annual catch-at-age (thousands), including discards, of NAFO 4T American plaice.

	AGE																		
Year	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1976	0	48	1418	9985	19232	13687	7846	6583	5023	3096	3298	1523	813	498	534	295	249	285	463
1977	0	21	805	5121	11416	17458	10189	5077	3206	2073	2192	763	659	225	293	177	248	81	279
1978	0	7	435	2312	5365	10328	9658	3864	3285	2576	1403	1329	863	538	233	137	75	40	220
1979	0	3	169	1293	3802	8043	11048	8310	4720	2687	1670	1101	1143	354	244	154	50	89	234
1980	1	61	650	1990	4425	6890	7890	5922	3372	2334	2403	1812	1332	778	450	207	91	145	174
1981	6	36	254	527	1326	2206	2871	2789	2236	1857	1383	948	779	1225	533	693	341	87	622
1982	2	15	65	460	699	1539	3199	3247	3320	1950	1479	1059	810	423	403	292	245	39	192
1983	11	12	97	430	795	915	1435	1922	2122	2057	2001	1587	829	592	601	530	316	353	355
1984	1	28	251	638	1127	1823	1970	2386	3572	2671	2136	1166	1206	868	388	403	389	378	327
1985	2	58	204	811	985	1323	1939	1837	2424	3217	3438	2293	1793	1106	780	531	262	269	287
1986	3	29	243	442	1334	1582	1975	1814	1651	1844	2115	1900	1319	907	658	342	167	167	380
1987	2	27	306	1154	2293	3553	3508	2899	2994	2452	2602	1962	1946	1042	625	500	249	290	695
1988	1	14	134	572	1698	1617	2409	2251	1325	1295	1427	1307	1116	756	660	402	355	211	334
1989	1	46	242	948	1686	3358	3054	3133	2222	1429	1159	910	728	519	437	313	239	104	234
1990	7	34	373	1356	2168	2352	3529	2231	1874	1331	851	780	445	421	280	201	162	130	122
1991	14	158	1046	3051	5156	6352	5321	6516	3903	3044	2242	1255	977	694	505	585	281	222	410
1992	3	94	450	1604	3521	4412	4494	2884	3391	1942	1359	663	544	368	306	125	155	104	205
1993	1	18	305	1324	2150	2625	2719	1816	1052	1149	603	292	139	80	83	46	36	28	45
1994	0	0	29	326	1051	1208	1066	855	722	449	423	222	130	81	49	23	57	26	43
1995	0	5	9	55	347	874	980	964	917	713	488	438	208	179	73	66	42	56	64
1996	1	12	30	78	238	599	584	482	536	393	261	190	170	63	61	18	20	5	18
1997	1	9	15	43	201	383	772	896	851	590	480	258	167	118	64	24	7	6	8
1998	0	8	19	82	137	444	456	528	570	271	285	181	90	83	34	25	12	7	6
1999	3	14	43	79	330	365	894	758	761	497	355	153	76	37	15	6	3	1	1
2000	1	15	32	91	155	327	284	634	500	511	449	296	151	127	34	20	17	7	8
2001	2	4	50	70	246	352	441	322	576	342	390	265	143	96	31	27	9	4	5
2002	0	11	15	78	136	216	248	211	205	226	161	121	83	53	35	12	7	3	3
2003	0	1	5	11	119	130	154	135	137	77	76	61	22	21	6	3	2	1	3
2004	1	0	11	28	39	123	120	153	137	106	101	112	73	48	41	13	14	8	2
2005	0	11	13	35	76	55	134	152	112	101	104	71	46	21	35	20	7	2	3
2006	0	0	7	4	55	135	93	200	170	164	177	124	62	60	44	31	24	16	14
2007	0	0	3	13	51	79	113	109	140	134	106	73	94	59	13	37	6	3	4
2008	0	0	0	1	5	11	39	60	41	40	25	33	38	18	7	4	4	8	5
2009	0	0	0	15	14	39	56	64	41	32	35	26	7	10	1	2	2	0	0
2010	0	0	1	18	10	30	35	37	62	89	25	34	25	18	20	19	6	1	10
2011	0	0	0	16	11	26	42	79	44	47	23	11	7	3	2	0	2	1	1

Table 3. Stratified mean catch (number) per standard tow of American plaice in the annual southern Gulf trawl survey.

	AGE																				
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1971	0.0	1.5	5.7	17.6	28.3	28.4	31.1	35.9	23.5	7.7	5.1	4.6	2.9	2.0	1.7	1.0	1.0	0.8	0.4	0.1	0.2
1972	0.0	1.0	6.7	12.6	27.9	27.9	31.5	36.0	25.5	11.7	6.6	3.2	3.1	1.6	1.1	0.5	0.7	0.2	0.2	0.1	0.0
1973	0.0	0.8	5.6	18.7	25.5	29.3	22.7	19.0	22.8	18.1	8.3	4.1	3.0	2.3	2.9	1.4	1.1	1.3	0.5	1.3	1.3
1974	0.0	0.6	11.9	41.3	85.9	73.2	59.4	39.6	32.7	39.0	22.0	10.3	3.7	3.1	3.3	2.4	1.1	0.5	0.4	0.2	0.4
1975	0.0	0.7	3.0	18.0	64.7	113.0	59.8	49.3	30.8	24.9	15.9	12.3	3.3	2.0	1.6	0.9	1.0	0.1	0.9	0.4	0.8
1976	0.0	0.0	2.9	35.3	123.8	193.2	157.4	74.3	34.9	31.9	21.6	15.1	9.6	5.7	3.0	1.4	1.1	1.1	0.5	0.2	0.6
1977	0.0	0.6	4.8	65.1	190.2	266.6	166.9	115.4	51.8	21.0	13.1	8.1	5.3	3.5	1.7	1.2	0.2	0.6	0.5	0.4	0.1
1978	0.0	0.0	0.6	6.7	64.1	86.3	94.8	95.3	58.7	20.5	14.1	7.5	4.1	4.6	1.9	1.2	0.4	0.4	0.4	0.5	0.4
1979	0.0	0.1	1.3	5.5	50.5	134.7	125.7	146.3	111.7	52.0	27.6	15.4	8.4	5.3	4.9	2.8	1.9	0.4	0.6	0.3	0.9
1980	0.0	2.1	6.7	31.3	68.4	79.5	99.0	71.2	57.2	30.5	16.3	10.6	6.3	4.6	2.4	1.0	0.6	0.4	0.1	0.1	0.1
1981	0.0	3.0	10.5	23.4	54.3	71.7	89.6	94.8	55.2	36.9	19.4	9.3	4.3	2.5	1.5	1.1	0.9	0.3	0.2	0.2	0.3
1982	0.0	0.3	7.0	12.5	15.5	31.1	29.3	44.3	59.0	29.3	18.8	7.4	3.3	1.6	1.7	1.0	1.0	0.7	0.3	0.4	0.3
1983	0.2	2.2	8.8	22.0	26.0	32.0	31.3	23.7	38.4	37.3	21.6	21.4	11.2	4.5	2.2	1.7	1.0	0.9	0.7	0.2	0.4
1984	0.0	0.2	2.3	4.1	17.6	23.4	21.8	19.5	18.1	16.5	19.7	7.2	6.2	2.8	1.1	1.1	0.5	0.4	0.4	0.3	0.5
1985	0.0	1.6	5.5	18.7	17.4	31.0	23.5	13.7	15.6	11.8	13.1	14.0	10.6	6.6	4.5	2.5	1.2	1.0	0.7	0.6	1.1
1986	0.0	4.1	7.0	13.9	30.6	30.2	38.3	27.0	12.0	14.3	5.9	7.6	14.0	8.4	8.3	5.2	3.5	1.0	1.0	0.6	1.2
1987	0.0	0.6	8.0	15.3	30.5	43.5	36.3	36.7	21.3	17.5	10.8	8.0	6.9	2.7	2.8	1.4	0.7	0.6	0.4	0.4	0.5
1988	0.0	0.6	4.5	15.8	26.2	31.8	49.7	31.8	30.6	18.6	9.3	6.7	5.6	5.1	4.3	2.3	1.0	0.9	0.3	0.3	0.4
1989	0.0	0.7	4.3	12.1	27.3	38.0	28.8	31.7	20.9	13.0	9.0	4.6	4.3	3.2	2.3	1.4	0.8	0.6	0.2	0.2	0.3
1990	0.0	0.8	14.6	34.4	56.6	78.5	59.4	30.7	29.0	16.3	10.5	7.4	3.4	2.7	1.2	1.3	0.6	0.2	0.2	0.1	0.2
1991	0.0	1.9	16.7	27.4	51.2	63.8	65.0	45.1	27.0	25.6	12.5	8.4	5.9	2.7	2.6	1.9	1.1	1.0	0.5	0.3	0.4
1992	0.0	2.2	7.1	27.6	40.6	46.2	45.1	29.8	20.9	10.4	8.4	4.6	3.2	1.9	1.1	0.7	0.6	0.2	0.2	0.1	0.1
1993	0.0	2.1	11.0	13.0	39.1	39.0	34.5	26.5	18.6	10.6	5.0	4.7	2.3	1.4	0.5	0.2	0.3	0.2	0.1	0.1	0.2
1994	0.0	1.3	2.5	19.3	25.8	43.1	38.3	30.5	19.1	12.1	8.1	3.7	3.5	1.3	0.6	0.3	0.2	0.2	0.1	0.1	0.1
1995	0.0	2.7	5.6	8.5	29.2	23.3	32.4	22.8	19.8	12.5	8.6	4.8	2.9	1.6	0.6	0.4	0.1	0.0	0.0	0.1	0.0
1996	0.0	1.8	7.2	13.8	18.6	33.8	22.9	22.4	16.7	12.3	9.5	4.5	3.4	1.5	1.0	0.5	0.2	0.1	0.0	0.0	0.0
1997	0.0	2.8	6.4	16.0	19.5	11.4	25.6	11.8	14.3	8.0	6.1	3.6	2.9	1.7	0.4	0.7	0.1	0.2	0.0	0.0	0.1
1998	0.0	4.5	6.7	17.0	22.7	23.3	12.3	18.3	12.8	11.4	9.2	4.1	3.7	1.6	0.7	0.5	0.1	0.0	0.0	0.0	0.0
1999	0.0	1.1	15.6	16.3	23.3	16.9	15.3	8.4	13.5	6.5	6.8	3.0	2.0	0.8	0.4	0.2	0.2	0.0	0.0	0.0	0.0
2000	0.0	7.2	3.2	19.3	17.7	19.0	14.2	8.6	7.5	8.2	5.3	4.9	2.5	1.8	0.6	0.2	0.1	0.1	0.1	0.0	0.0

Table 3 continued.

AGE	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
2001	0.0	5.5	9.6	5.9	17.5	15.6	17.5	12.8	9.3	4.7	7.0	4.4	4.7	2.3	0.9	0.5	0.2	0.1	0.1	0.0	0.0
2002	0.0	1.1	9.0	17.1	10.5	17.3	13.3	9.3	9.5	5.9	3.4	2.9	2.3	1.3	0.6	0.5	0.2	0.1	0.0	0.0	0.0
2003																					
2004	0.0	1.3	5.6	8.0	25.7	23.5	7.5	10.9	7.2	7.0	4.6	2.7	1.7	1.2	0.9	0.7	0.1	0.1	0.0	0.0	0.0
2005	0.0	2.0	3.4	10.7	19.1	30.6	23.3	10.5	11.1	5.3	5.3	2.8	2.1	1.0	0.7	0.4	0.2	0.2	0.0	0.0	0.1
2006	1.0	1.3	6.6	8.2	19.9	16.2	26.6	17.8	7.2	6.1	4.2	3.4	2.9	1.2	0.6	0.4	0.1	0.1	0.1	0.0	0.0
2007	0.5	14.4	4.4	12.6	14.2	19.0	19.5	17.5	11.1	5.1	5.2	3.3	1.9	1.2	0.6	0.6	0.3	0.1	0.1	0.0	0.0
2008	0.0	8.6	22.7	11.5	17.9	13.8	23.5	17.7	29.4	14.6	6.3	5.3	2.3	1.7	0.7	0.4	0.4	0.4	0.2	0.1	0.1
2009	0.4	5.2	11.2	25.4	8.4	12.2	8.3	12.6	8.7	10.8	5.6	1.8	1.8	1.1	0.6	0.3	0.1	0.1	0.1	0.0	0.0
2010	0.7	14.2	10.8	16.0	41.5	16.9	20.6	12.3	18.6	9.7	15.6	7.1	2.9	2.2	1.0	0.7	0.6	0.2	0.1	0.1	0.0
2011	3.1	4.5	16.9	15.1	19.6	30.0	13.2	11.6	7.7	9.5	6.7	7.6	2.8	1.4	0.8	0.6	0.3	0.1	0.1	0.1	0.0

Table 4. Survey population-at-age (thousands), based on the mobile gear Sentinel Program with vessels adjusted to a common efficiency.

	AGE																
Year	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
2003	6539	15020	9731	13377	11222	9956	6622	4658	3283	2292	1557	1214	283	210	58	39	16
2004	11572	19690	8740	15088	10745	10986	7490	4545	2932	2341	1868	1455	334	190	100	6	4
2005	7136	14149	13619	7253	8499	4396	4400	2659	2097	1118	752	467	413	268	24	18	45
2006	4583	5860	12096	10254	5021	4648	3438	2995	2563	1222	676	413	198	154	56	11	51
2007	2468	5594	8091	8181	5988	3135	3360	2356	1394	957	501	458	254	97	54	0	14
2008	2563	2897	6375	5625	10672	6252	2781	2608	1327	957	519	264	293	243	138	49	8
2009	1221	3924	3669	6968	5349	7689	4653	1599	1576	1014	640	255	156	85	72	12	0
2010	3803	2131	4042	2758	4904	3006	5115	2775	1260	1127	537	410	331	132	55	119	11
2011	2808	8567	5776	6519	4971	6493	4774	5468	2060	1062	626	404	215	81	57	57	1

Table 5. Estimates of spawning stock biomass (SSB, tonnes) and the number of recruits (R, in thousands) that they produced at age-4.

Year	SSB	R
1976	388346	1881000
1977	405083	1062790
1978	350624	754225
1979	267945	635257
1980	239850	681958
1981	206628	606070
1982	165823	721865
1983	126201	646591
1984	105363	586194
1985	103889	1205070
1986	105835	901765
1987	110623	1044730
1988	105265	818273
1989	118094	1177570
1990	136641	724281
1991	150097	324565
1992	142814	469860
1993	127320	458525
1994	113807	490266
1995	95504	519153
1996	80046	463680
1997	55195	516632
1998	55730	416563
1999	56478	729936
2000	52571	932899
2001	38895	516449
2002	38921	503115
2003	50541	265704
2004	67737	321157
2005	52926	220309
2006	57822	603558
2007	58929	383965
2008	38309	
2009	30777	
2010	43967	
2011	35214	
2012	41676	

Table 6. Parameter estimates from Bayesian analysis of the Beverton-Holt and Ricker stock-recruit models applied to 4T American plaice. The parameters include the spawning stock biomass at 50% of maximum recruitment (BH50) for the B-H model and maximum recruitment (K, Rmax) and spawning stock biomass at maximum recruitment (Smax) for the Ricker model. All stock and recruitment estimates are in thousands. Other model parameters are explained in the text. Posterior distribution summaries include the mean and standard deviation (sd), Monte Carlo standard error (MC error) and percentiles from 10,000 MCMC draws.

Beverton-Holt model						
Parameter	Mean	sd	MC error	2.5%	Median	97.5%
K	1119	357.5	10.04	680.4	1050	2000
BH50	79.47	56.87	1.633	12.66	67.56	220.8
alpha	21.45	60.6	1.127	8.78	15.57	56.33
sigma	0.426	0.058	6.39E-04	0.332	0.419	0.558
Ricker model						
Rmax	942.3	161.4	2.249	729.8	915.2	1315
Smax	272.4	77.75	1.485	179.3	257.8	452.6
Log(alpha)	2.26	0.139	0.002993	1.982	2.26	2.539
beta	0.003883	8.46E-04	1.81E-05	0.00221	0.003879	0.005578
sigma	0.456	0.062	6.29E-04	0.354	0.449	0.593

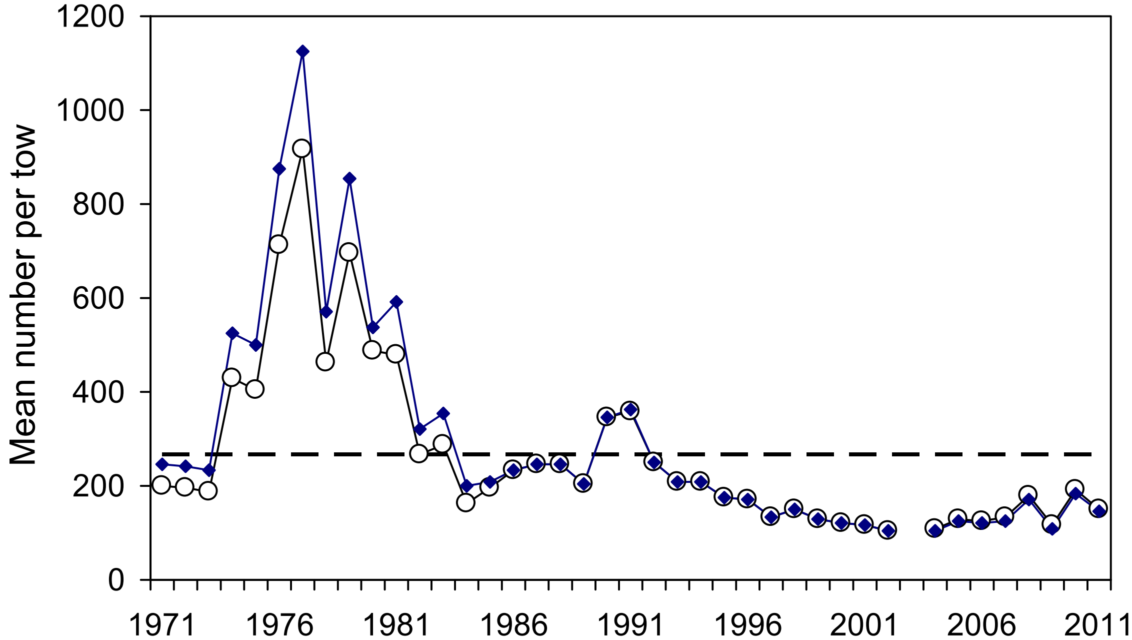


Figure 1. Research vessel trawl survey index for 4T American plaice showing revised index (open circles) and previous estimates (closed symbols). The horizontal dashed line indicates the mean annual catch (266 plaice per tow).

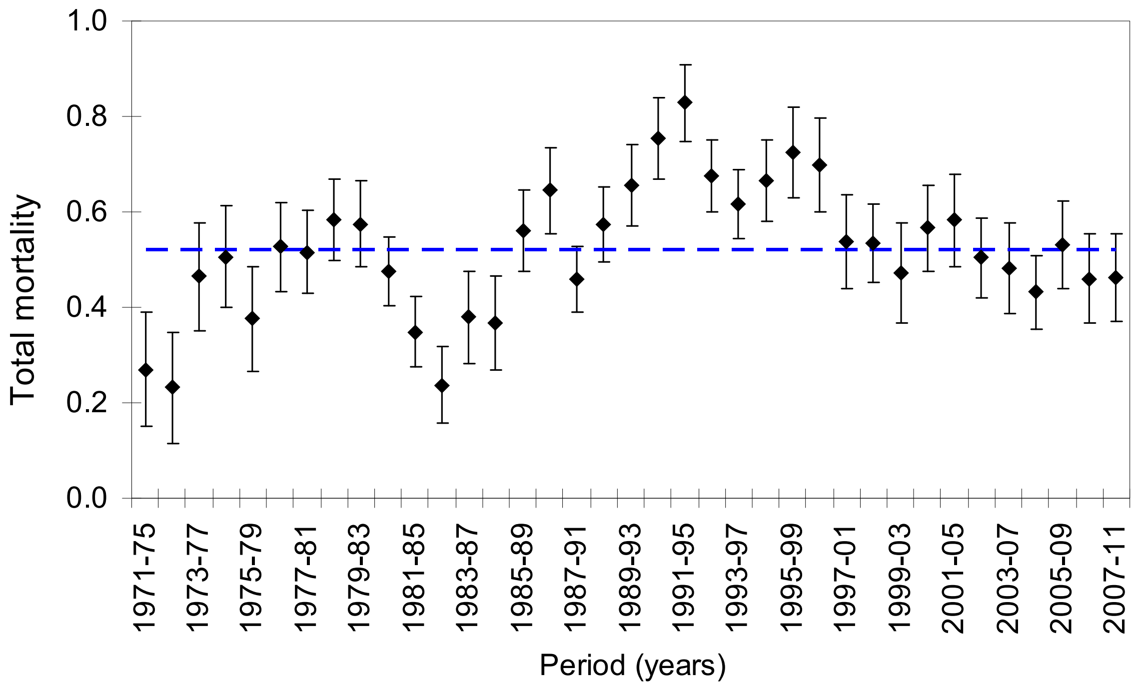


Figure 2. Estimates of total mortality of 4T plaice between 8 and 20 years of age, based on multiplicative models of survey catch data in 5-year periods with 95% confidence limits as vertical bars. The horizontal broken line is the mean of all estimates since 1971 (0.52).

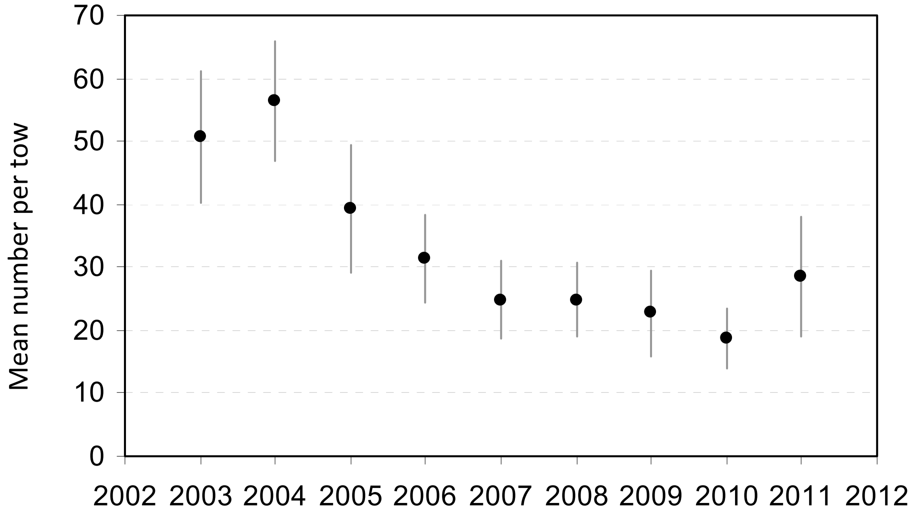


Figure 3. Sentinel mobile gear survey catch index for 4T American plaice. Error bars indicate approximate 95% confidence limits.

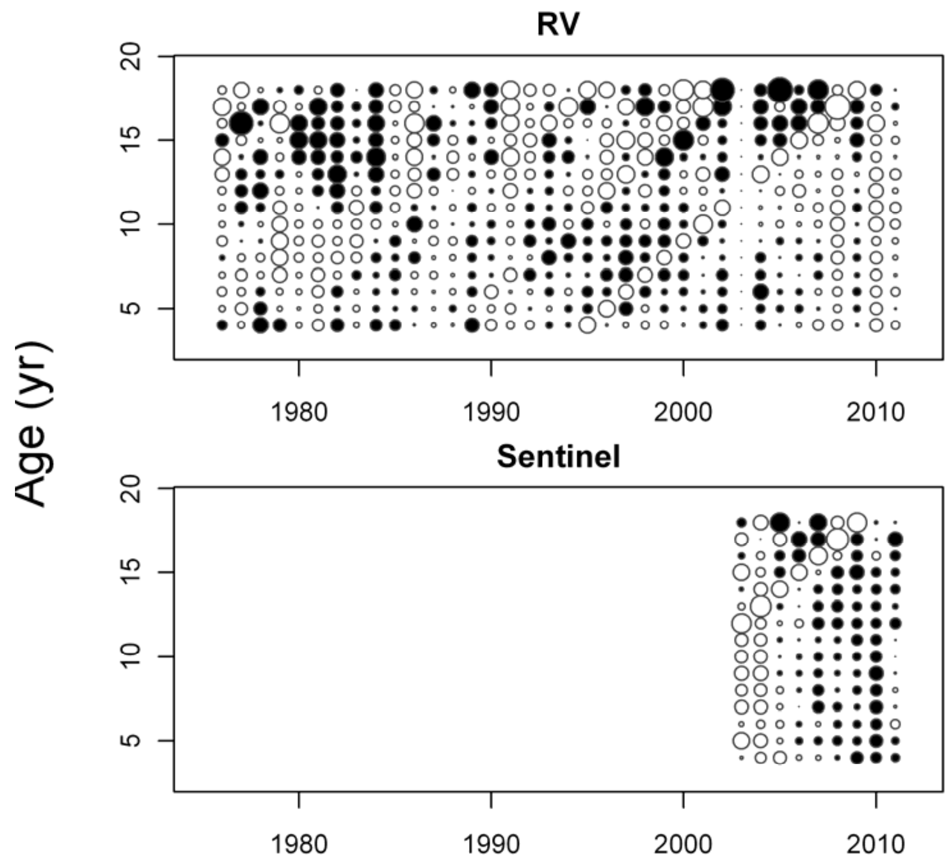


Figure 4. Residuals between the research vessel (RV) and sentinel mobile gear survey indices and their predicted values from the population model. Black circles indicate negative residuals (index less than the predicted value).

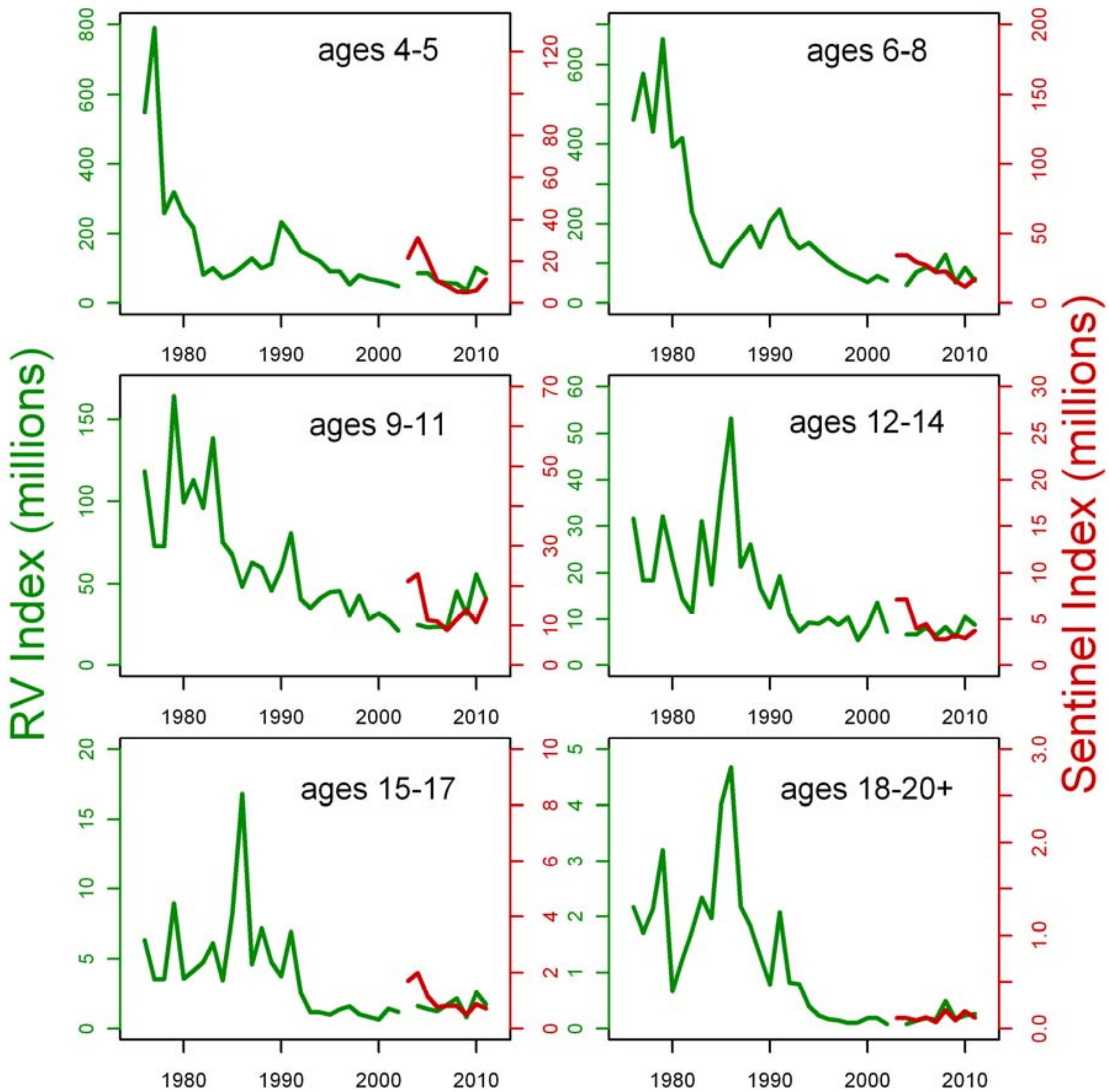


Figure 5. Comparison between research survey (RV) and mobile gear sentinel survey indices for 6 age groups.

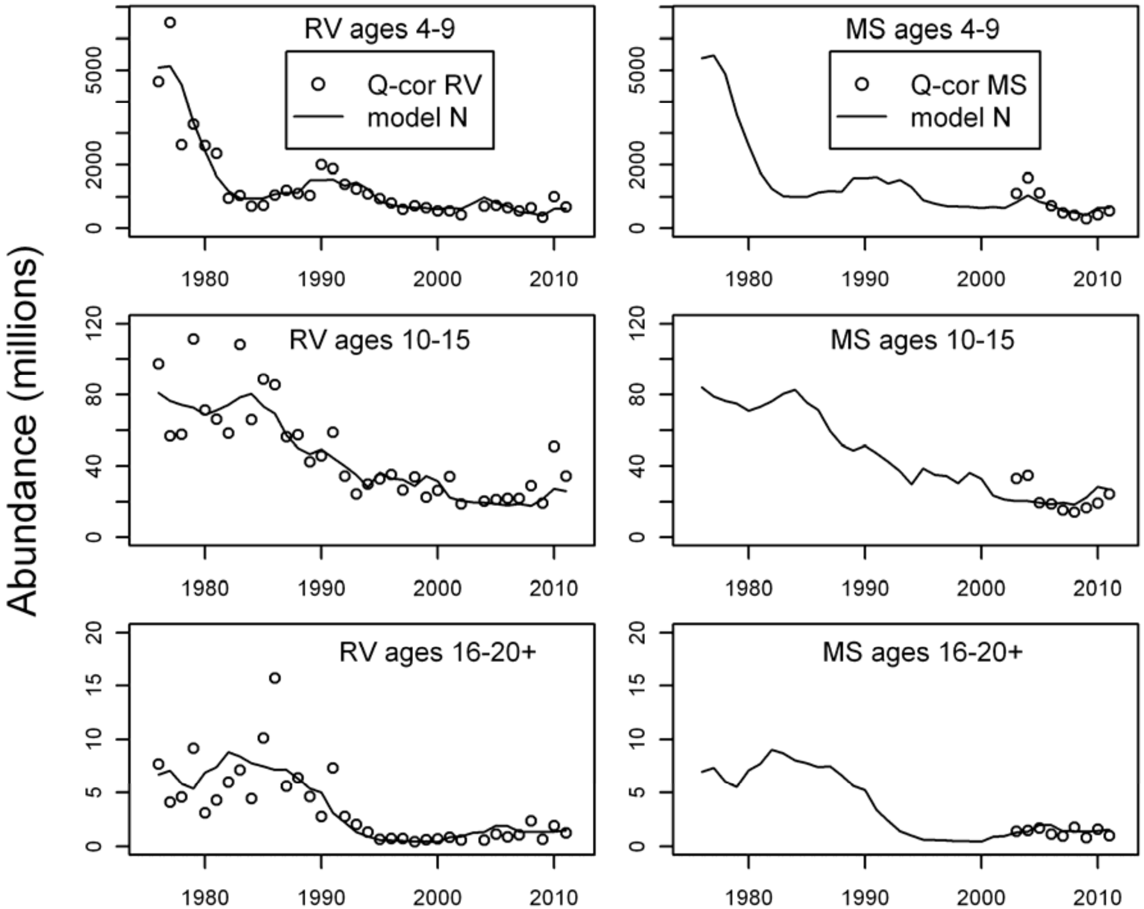


Figure 6. Comparison between q-corrected abundance indices and model estimates of abundance (adjusted to September or August for the research vessel (RV) and mobile gear sentinel (MS) comparisons, respectively). Catchability for ages 19 and 20+ was assumed to equal that for age 18.

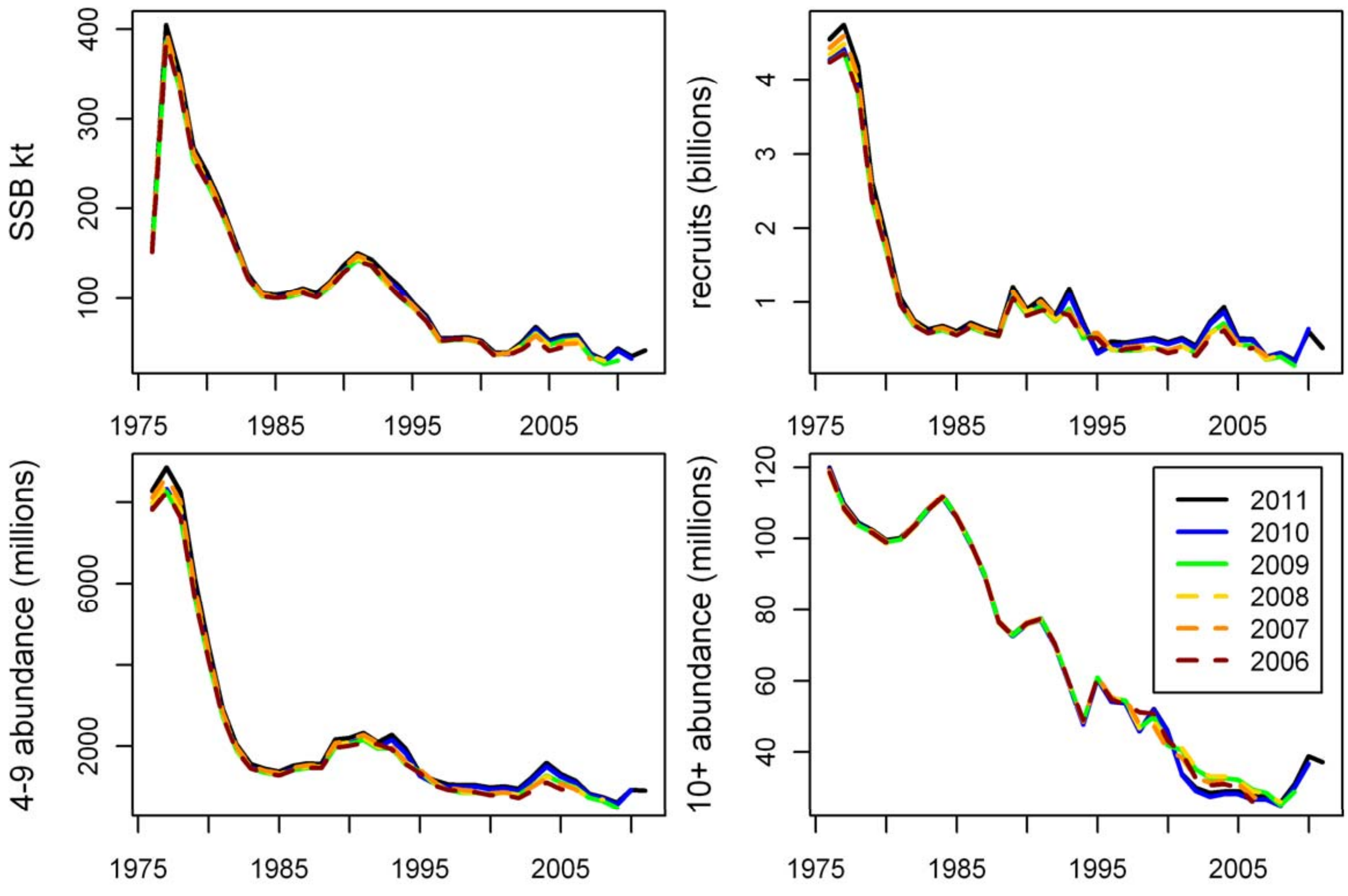


Figure 7. Retrospective analysis for spawning stock biomass (SSB) and abundances of age-4 recruits and age groups 4-9 and 10+ years. Legend indicates the last year included in the analysis.

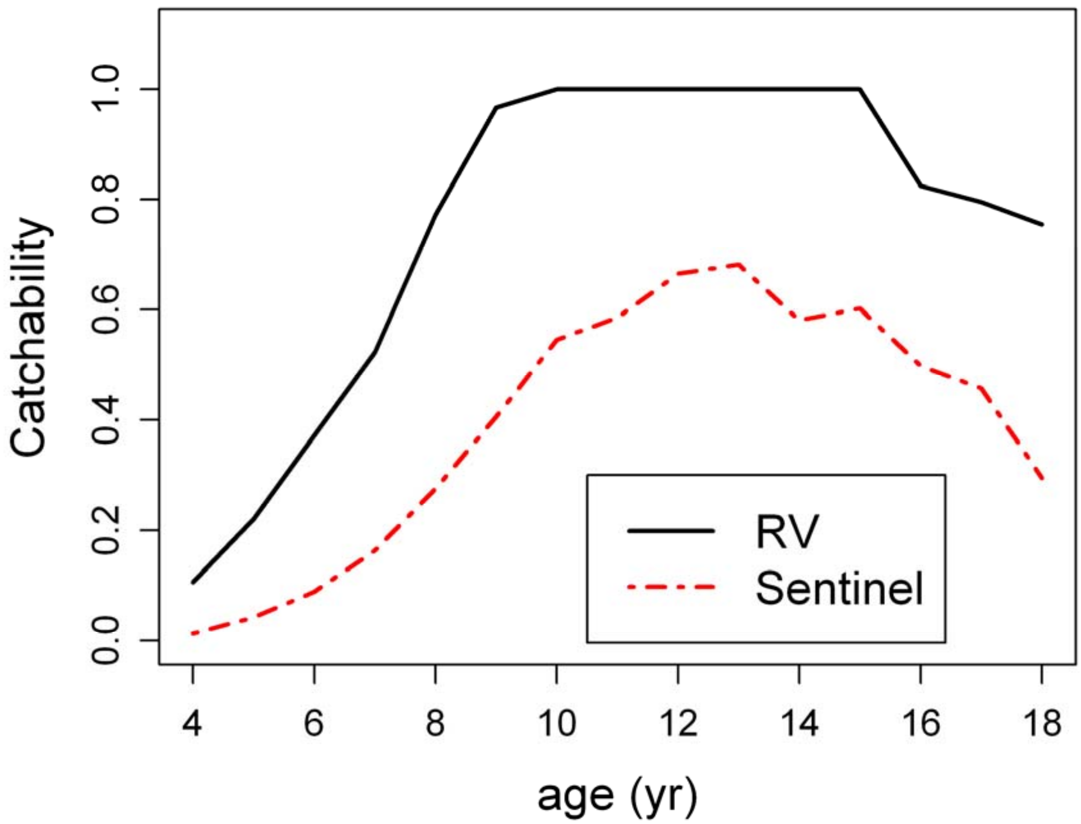


Figure 8. Estimated catchability of plaice to the research vessel (RV) and mobile gear sentinel surveys of the southern Gulf of St. Lawrence. Catchability to the RV survey was fixed at 1 for ages 10-15.

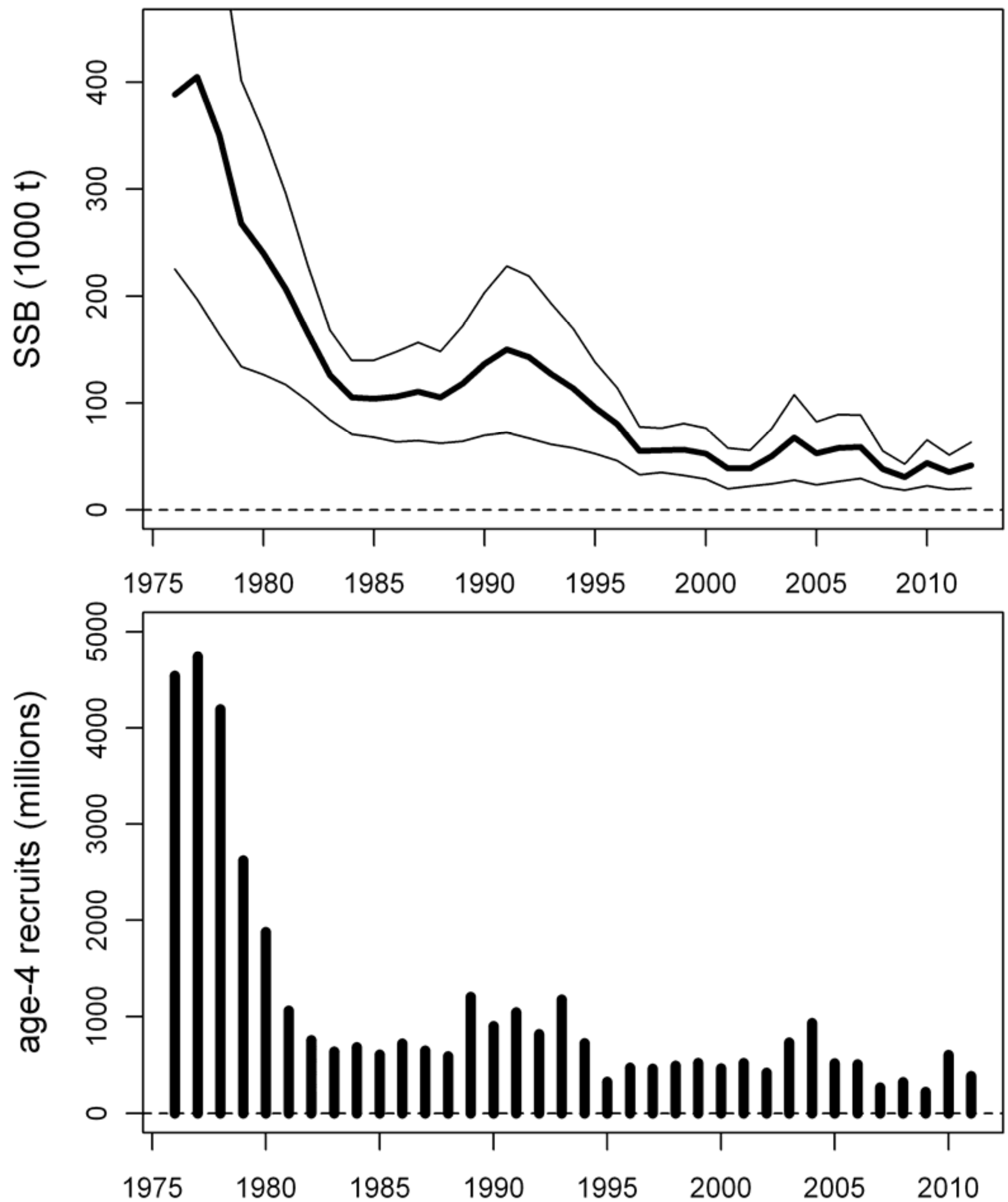


Figure 9. Estimated spawning stock biomass (SSB) and abundance of age-4 recruits for the 4T plaice population. Heavy line shows the parameter estimate of SSB and light lines represent the approximate 95% confidence limits (±2SD).

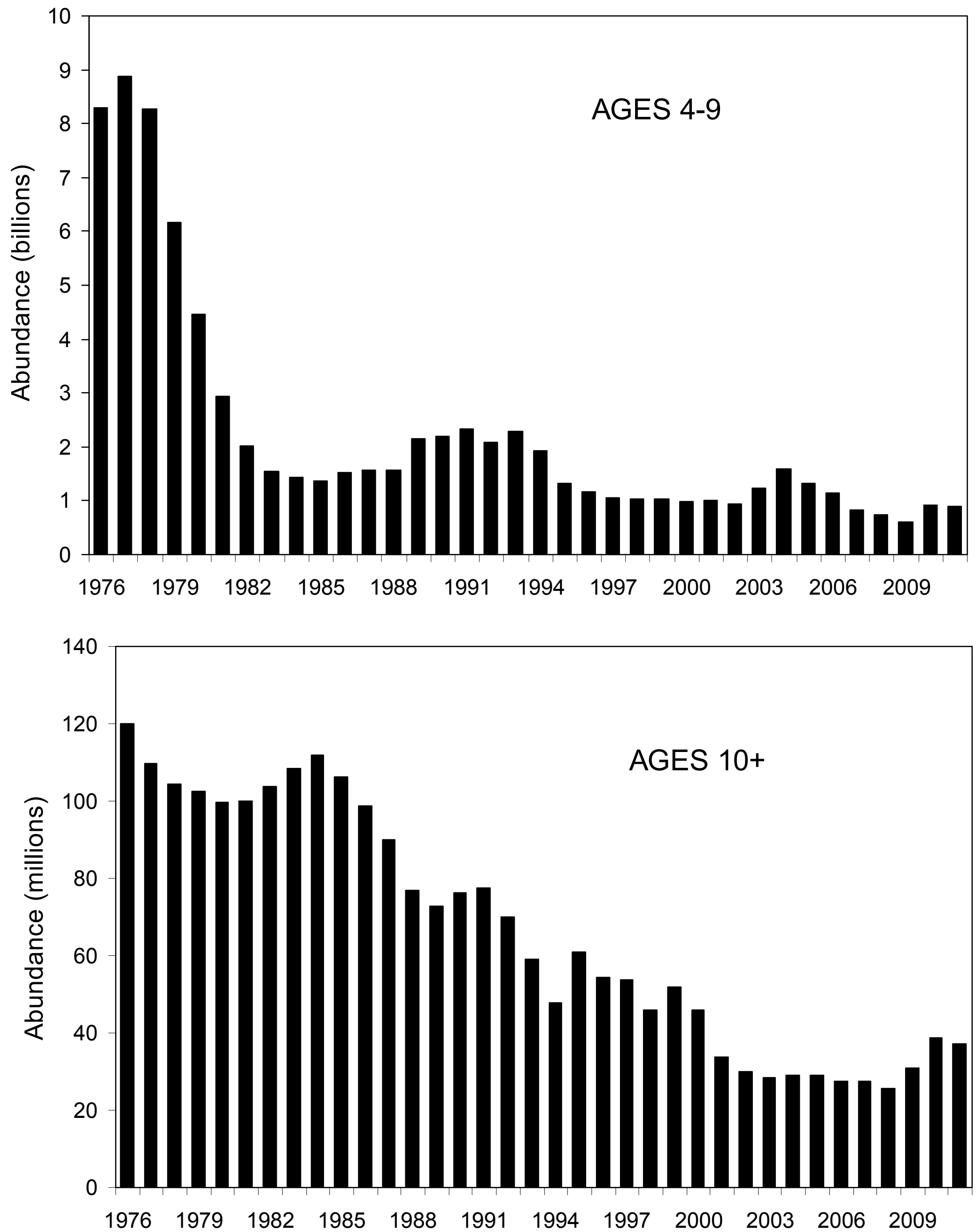


Figure 10. Estimated abundance of age groups 4-9 and 10+ years in the 4T American plaice population.

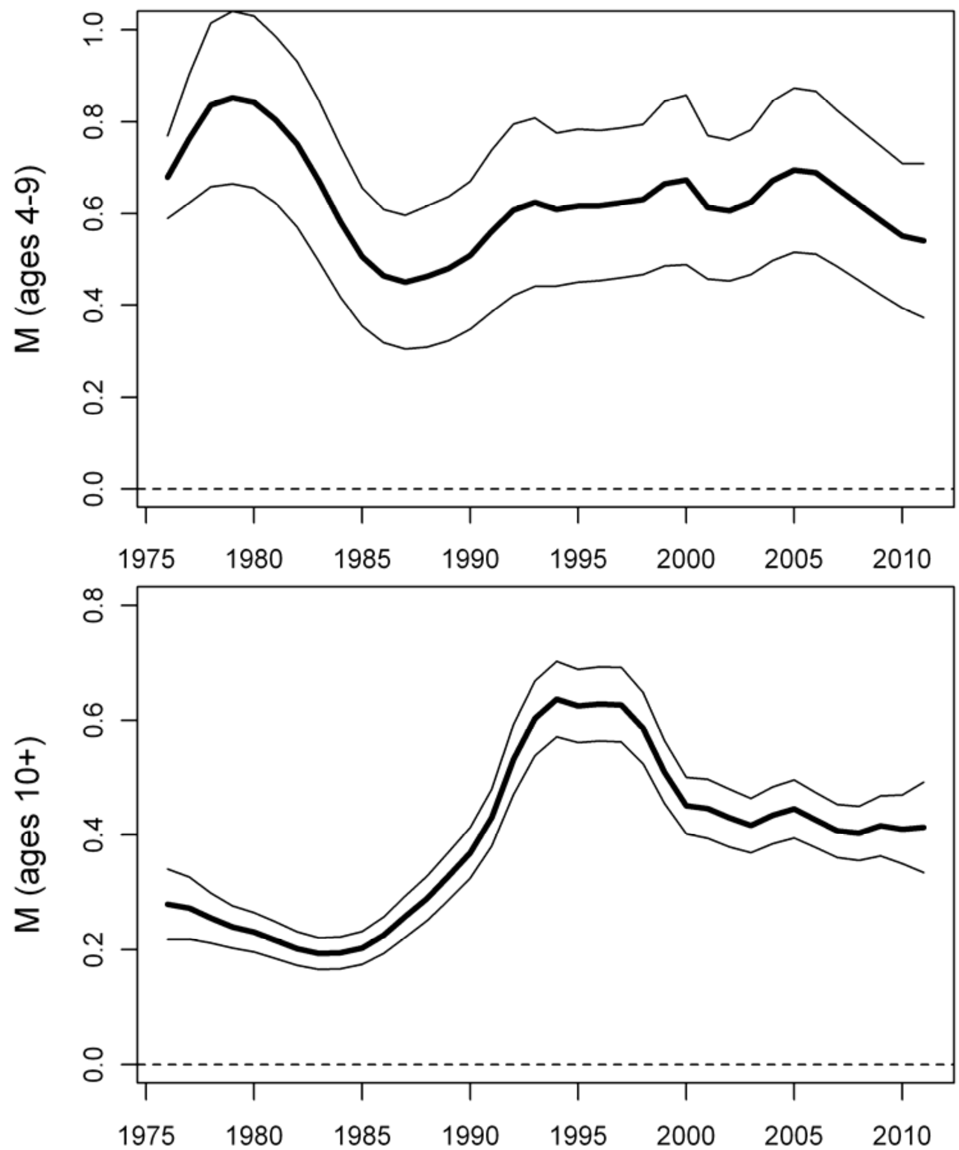


Figure 11. Estimated instantaneous rate of natural mortality M for age groups 4-9 and 10+ years in the 4T American plaice population. Heavy lines show the parameter estimates and light lines the approximate 95% confidence limits.

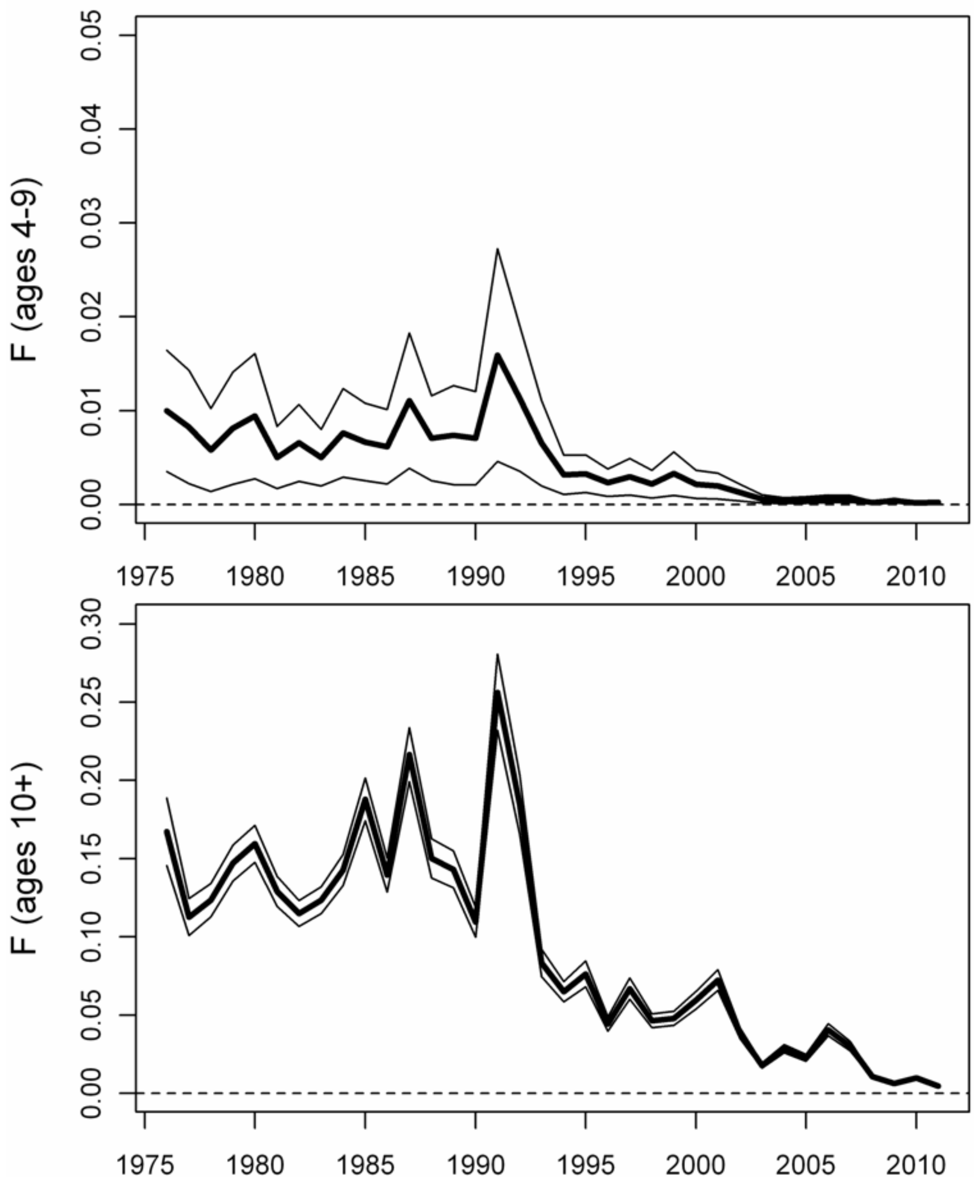


Figure 12. Estimated instantaneous rate of fishing mortality F for age groups 4-9 and 10+ years in the 4T American plaice population. Heavy lines show the parameter estimate and light lines the approximate 95% confidence limits.

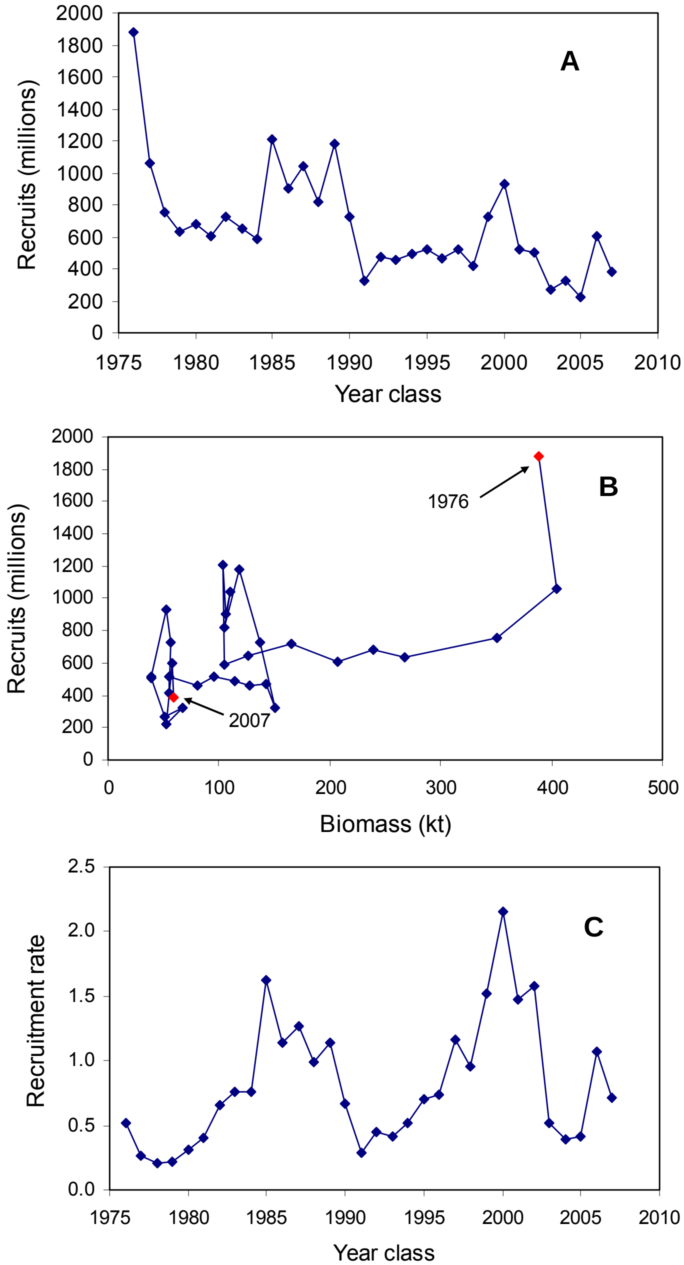


Figure 13. Stock-recruit relationships based on population model estimates. A: the abundance of age-4 recruits by year-class. B: the relationship between spawning stock biomass (SSB) and the number of recruits (age-4 plaice). C: the ratio of the abundance of age-4 plaice to the number of spawners that produced them (recruitment rate).

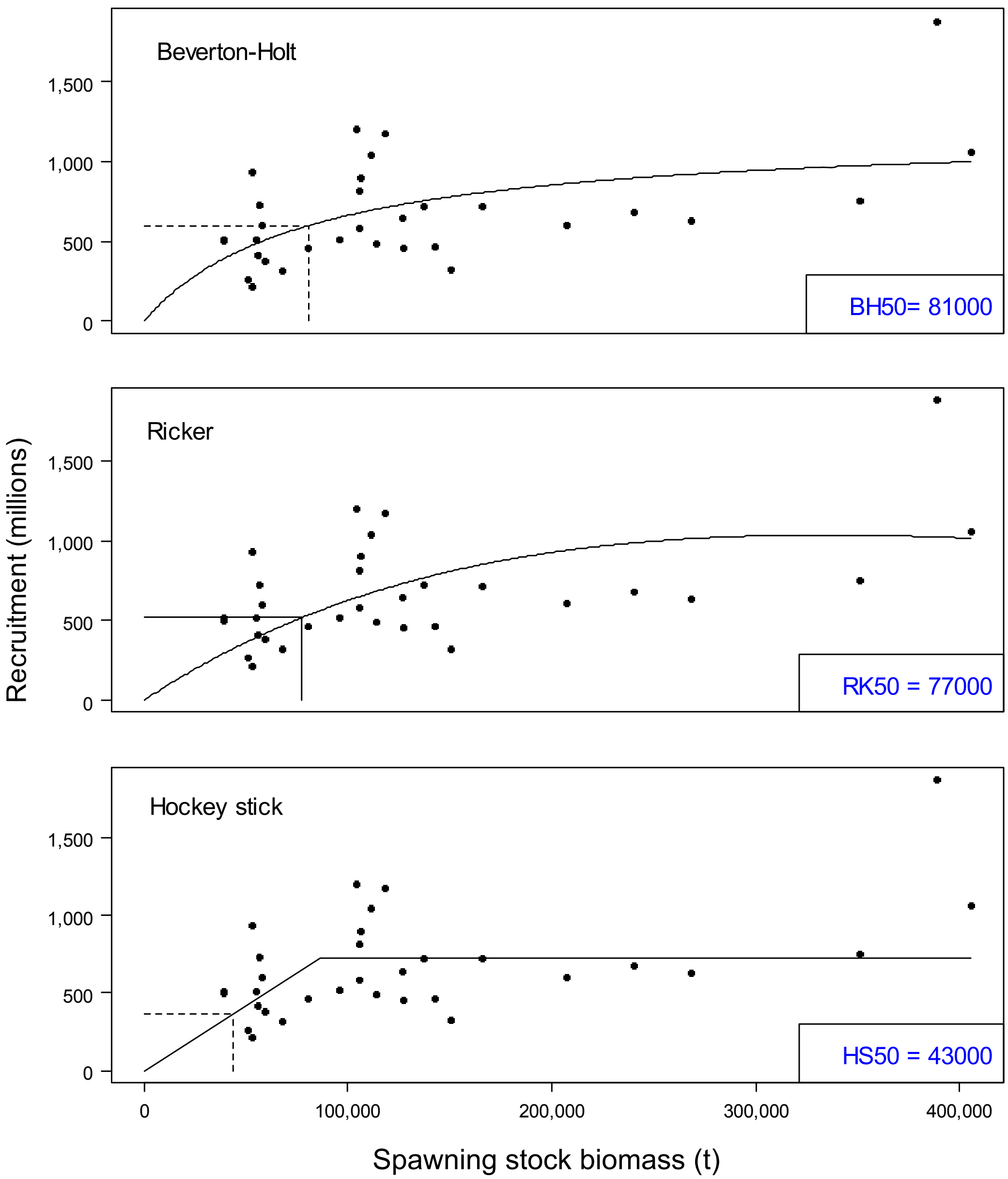


Figure 14. Three parametric models of the relationship between recruitment (numbers at age-4) and spawning stock biomass (SSB) applied to 4T American plaice data. Insets show model estimates of the Lower Reference Point in tonnes.

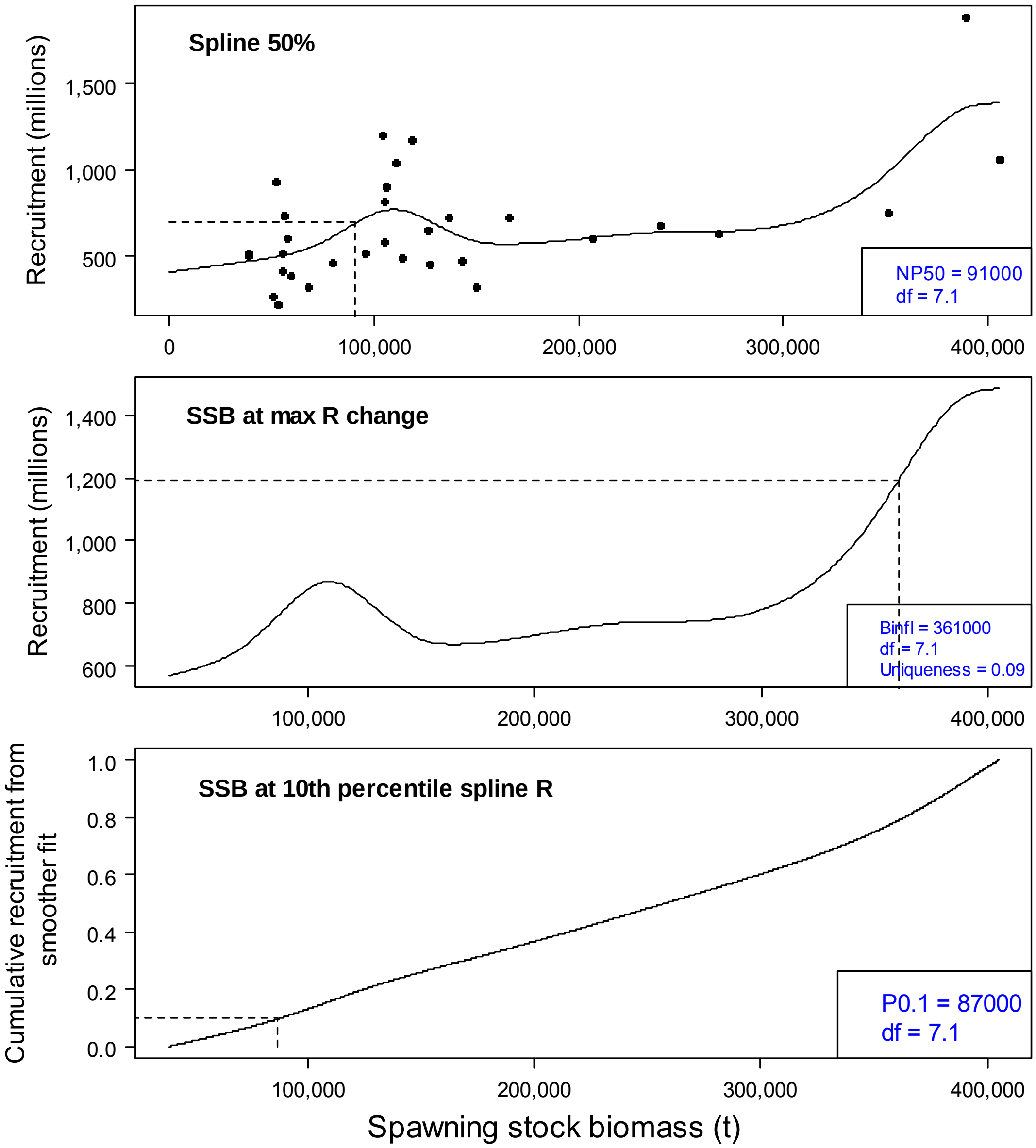
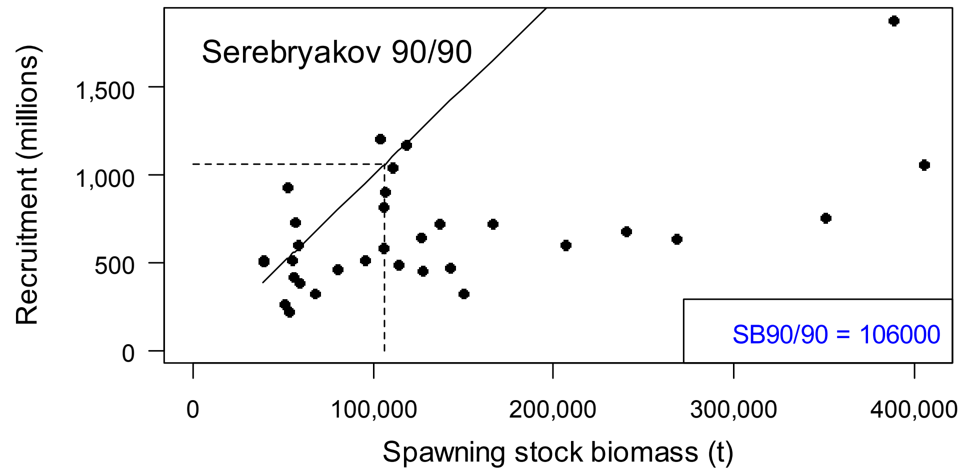


Figure 15. Three non-parametric models based on spline fits of the relationship between recruitment (numbers at age-4) and spawning stock biomass applied to 4T American plaice data. Insets show model estimates of the Lower Reference Point in tonnes.



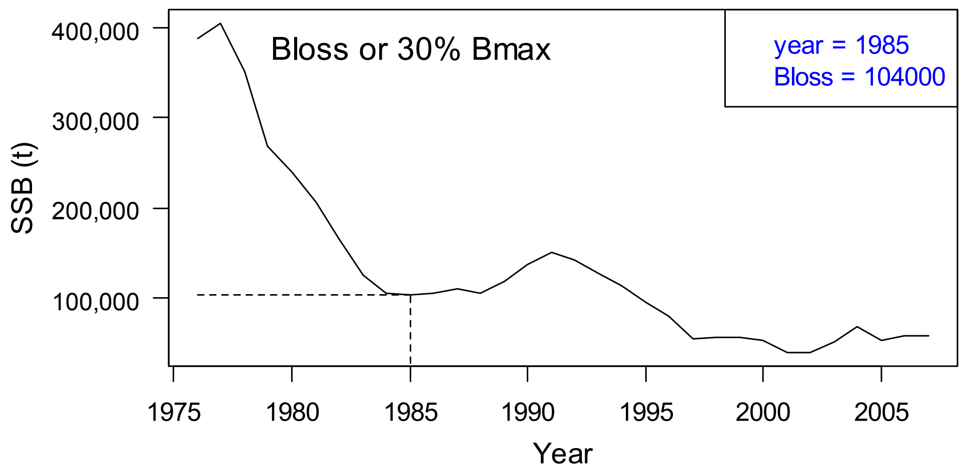


Figure 16. The Serebryakov model fit to age-4 4T plaice recruits and spawning stock biomass (upper graph). The inset shows the model estimate of the Lower Reference Point in tonnes. Lower graph shows Bloss or the lowest level of the spawning stock biomass (SSB) from which the stock recovered to 30% of its maximum observed SSB. The inset shows the level of Bloss in tonnes and the year in which this level of SSB occurred.

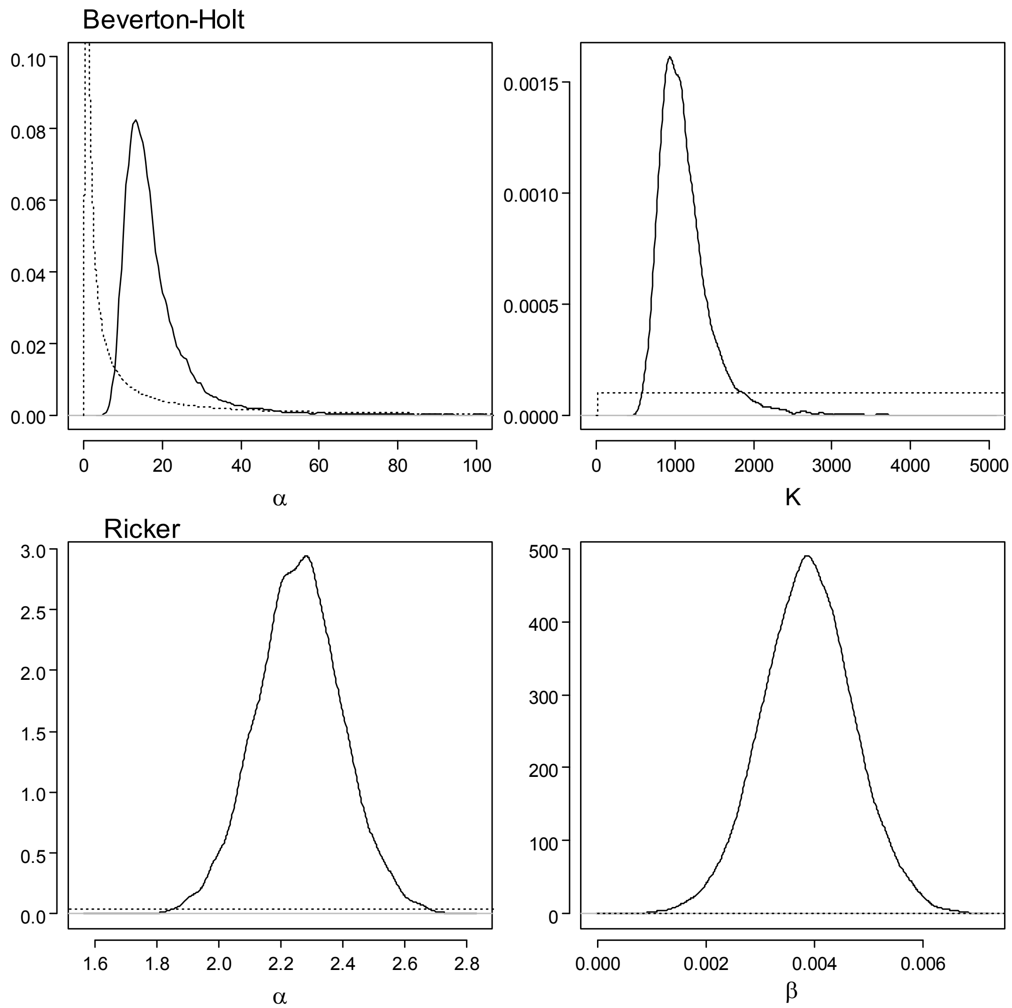


Figure 17. Density plots of prior (dotted lines) and posterior (solid lines) distributions on parameters of the Beverton-Holt and Ricker stock-recruit models.

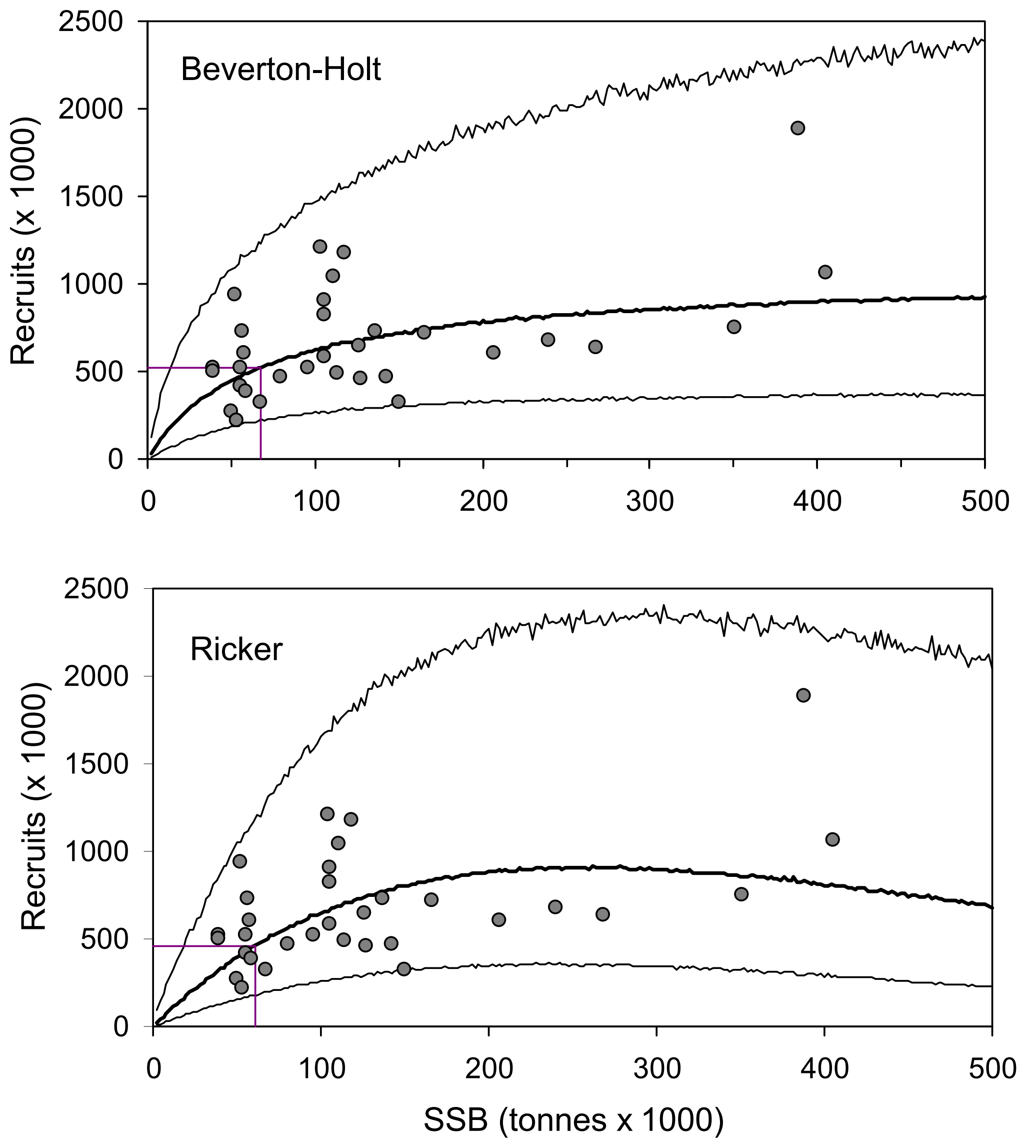


Figure 18. Stock-recruit relationship for 4T American plaice showing population model estimates of recruits and spawning stock biomass (SSB, data points) and median estimates of predicted recruits (dark lines) from Bayesian estimates of the Beverton-Holt and Ricker models. Also shown are the 95% credible intervals of the predicted recruits. Horizontal and vertical lines indicate the Lower Reference Point based on each model, for an SSB corresponding to 50% of maximum recruitment.

Figure 19. The estimated spawning stock biomass (SSB) of 4T American plaice, 1976-2012 (points), and the proposed biomass Lower Reference Point of 64,000 tonnes (horizontal line).