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Evaluating Recovery Time from Long-term Projections Including Uncertainties: an Example for Cod on Southern Grand Banks (NAFO Divisions 3NO).

by

D. Rivard

Fisheries Research Branch, Fisheries and Oceans
200 Kent street, Ottawa, Ontario, Canada K1A 0E6

P. Shelton and D. Stansbury

Science Branch, Newfoundland Region, Fisheries and Oceans
P. O. 5667, St. John's, Newfoundland, Canada A1E 5X1

Abstract

Simulations are used to evaluate recovery time for cod on the southern Grand Banks (NAFO Divisions 3NO). These simulations take into account the precision of the stock size estimates currently available for this stock, as well as the observed variability in the stock-recruitment process. In this paper, we explore two interpretations of the stock-recruitment data: one assuming the recent low recruitment is the result of depensation at low spawning biomass level and another assuming that they are due to a low productivity regime. We conclude that changes in the productivity of the stock could have a major impact on the dynamics of the stock in future years and that recovery time will depend upon which recruitment process prevails in the future. Our results also suggest that fishing mortalities in excess of the by-catch levels observed in recent years could increase the recovery time considerably.

Introduction

Under the NAFO precautionary approach framework, biomass and fishing mortality limits are to be specified, together with a target for the recovery the biomass. For cod in NAFO Divisions 3NO, preliminary values of the stock spawning biomass (SSB) limit have been provided (Anon. 1999a; Anon. 1999b). As the current value of the stock spawning biomass is much below any reasonable candidate for the SSB limit, the immediate goal should be to bring the SSB above the limit. How many years will it take to reach the biomass limit? What is the probability that the SSB will still be below the limit in any given year in the future? What would be the yield potential at re-opening? These are questions that are currently asked for this stock. This paper uses simulations to address these questions. These simulations take into account the precision of the stock size estimates currently available for this stock, as well as the observed variability in the stock-recruitment process.

Materials and Methods

Notation and simulation parameters

The population of cod in NAFO Divisions 3NO is simulated by combining 1) a simple catch equation, 2) age-specific information on weight and 3) a discrete function representing age-specific allocation of fishing mortality (partial recruitment). The projections provide a description of population numbers and biomass, numbers and biomass of mature fish, catch numbers and biomass, as well as fishing mortalities. All quantities are age-specific and time-specific.

We use Greek letters to identify time-intervals. For example, if i is used to identify a given age and t a given time, then ι refers to age-interval i,i+1, while τ refers to the time-interval t,t+1. For this study, twenty-one age-groups were simulated and the youngest age-group included in the simulations was age 3. The initial year of the simulation was taken as 1999 and the last, as 2036.

Population dynamics

The input information required for the simulation consists of:

$N_{i,1999}$	population numbers at age i, at the beginning of the 1999. Estimates of population numbers and their variances, are typically obtained from age-structured analyses of historical data on catch age composition and survey indices.
$W_{i+0.5}$	Mid-year estimates of weight at age, in kilograms. These are obtained from the catch sampling information from 1972 to 1997. Beginning-of-year estimates were approximated as per the equations given in Rivard (1982).
d_i (i=3, …, 23) :	a value, between 0 and 1, indicating the proportion of fish in age-group i which are have attained maturity. The 1975-1997 average was used for the simulation and these values are assumed to be constant for all years of the projection.

The instantaneous rate of natural mortality, M, was assumed to be constant (0.2) for all ages and all years included in the simulations.

Fishing strategies. The evaluation of harvest control laws requires the application of a target fishing mortality for each year considered in the projection, say F . This stock has been under moratorium since 1994. There have been some catches, however, due to the by-catch in fisheries for other species. This level of catches has been related to a fishing mortality level of the order of 0.04 (1995-1998 average). Simulations are used to estimate the impact of such levels on the time of rebuilding to B_{lim} and, in that context, four options will be explored: 1) no fishing; 2) a level of fishing mortality corresponding to the recent by-catch level (F = 0.04); 3) a level of fishing mortality corresponding to twice the recent by-catch level (F = 0.08); and 4) fishing at $F_{0.1}$. The calculation of the instantaneous fishing mortalities at each age in each year-period τ are given by:

$$F_{,} \quad = \quad r \;\; F$$

where r are the "partial recruitment" coefficients. These are values, between 0 and 1, which indicate the proportion of fishing mortality which can be allocated to age-group i,i+1. In the simulations, the r are kept constant for all years and taken as the average from 1959 to 1997.

Population numbers. The number of fish at age i in year t is given by :

$$N_{i,t} \quad = \quad N_{i-1,t-1} \; \exp\,(\, -Z_{-1,\,-1} \quad)$$

$$\text{where} \qquad Z_{-1,\,-1} \quad = \quad F_{,} \; + M_{,}$$

Fish are assumed to leave the exploited stock at age 24. For each year of the projection, the numbers in the first age-group considered are set equal to the recruits R_t. The total number of fish is given by:

$$N_{\;,\,t} \quad = \quad \Sigma \;\; N_{i,t}$$

where the summation is for i=3, … 23 . Similarly, the total number of mature fish in year t is given by $\Sigma \; d_i \, N_{i,t}$, where the summation is over ages.

Population biomass. The age-specific biomass at the beginning of each year is given by:

$$B_{i,t} \quad = \quad W_{i,t}\ N_{i,t}$$

The total biomass is given by:

$$B_{\ ,t} \quad = \quad \Sigma\ B_{i,t}$$

where the summation is over ages i=3, … 23 . Similarly, the total biomass of mature fish at the beginning of each year is given by $\Sigma\ d_i\ B_{i,t}$. The average biomass (age-specific) for each year is given by:

$$\mathbf{B_{i,t}} \quad = \quad W_{i+0.5}\ N_{i,t}\ (1 - \exp(-Z_{,}\ ))\ /\ Z_{,}$$

Catch in numbers. The catch at age in each year is given by:

$$C_{,} \quad = \quad F_{,}\ \ N_{i,t}\ (1 - \exp(-Z_{,}\ ))\ /\ Z_{,}$$

The total number of fish in the catch in any given year is given by:

$$C_{\ ,t} \quad = \quad \Sigma\ C_{,}$$

Yield. The age-specific yield is calculated in any given year as:

$$Y_{,} \quad = \quad W_{i+0.5}\ C_{,}$$

The total yield in any given year is given by:

$$Y_{\ ,t} \quad = \quad \Sigma\ Y_{,}$$

Simulating process error and estimation uncertainties

Monte-Carlo simulations are used to capture the uncertainties in our estimation of stock abundance and the dynamics of the recruitment process. Each scenario is investigated by simulations using 2000 replicates resampling the assumed distribution of initial population size and resampling the observed recruitment within pre-determined ranges of SSB.

Precision of initial population size estimates.

Estimates of population numbers and their variances were obtained from an ADAPT analysis (Stansbury et al., 1999) using historical catch-at-age and independent indices of abundance for 3NO cod (Table 1). For the simulation, the initial population size for each age ($N_{i,1999}$) was sampled from a log-normal distribution with mean and variance provided by the ADAPT estimate expressed on the arithmetic scale. In one simulation used as a sensitivity test, the $\ln(N_{i,1999})$ were sampled from a normal distribution with mean and variance provided by the ADAPT log-estimate and its standard error.

Modeling recruitment process and variability.

Long-term simulations must make assumptions on the dynamics linking recruitment to the stock spawning biomass. Long-term simulations are very sensitive to the characteristics of the spawner-recruit description. Figure 1 shows that recruitment and spawning stock size, as determined by Stansbury et al. (1999) are only weakly related for cod in NAFO Divisions 3NO.

Many authors have suggested various ways to capture both the dynamics and the uncertainties of the recruitment process by resampling the recruit-SSB scatter points. For instance, Getz and Schwartzmann (1981) used a transition matrix approach whereby the stock and recruit axes are partitioned into intervals based on historical stock and recruitment observations. Using a similar approach, Overholtz *et al* (1986) assume that, for a given stock interval, the recruitment comes from a uniform distribution on the interval. In our simulations, we opted to split the observed range of SSB into quartiles and to resample the observed recruitment within these quartiles. Since this approach is based on resampling observations, it does not require making assumptions about the recruitment probability density function (pdf). The re-sampling was done from the ADAPT bias-corrected recruitment/SSB pairs estimated by Stansbury et al. (1999) corresponding to the 1959-1996 year-classes, as provided in Table 2.

The benefit of non-parametric descriptions of stock-recruitment relationships is that they are able to capture the dynamics of the recruitment process without requiring explicit assumptions about the shape of the relationship. Depensation at lower levels of SSB, varying degrees of compensation and large degree of variation on the response of recruitment to SSB levels make it particularly difficult to derive functional relationships that are convincing. The two approaches described above allow both the shape of the relationship and the variation around it to be captured if these are apparent in the range of observed pairs. Both approaches have been used in the simulations, without resorting to a prescribed form of a relationship.

Low and high productivity periods

The stock-recruitment scatter-plot suggests that there are two distinct time periods of productivity in this stock: a period of high productivity from 1959 to 1981 with mean recruitment at age 3 of 72 million and a period of extremely low productivity from 1982 to 1996 with a mean recruitment of 7 million. Changes in the productivity of the stock could have a major impact on the dynamics of the stock in future years and, for that reason, simulations are used here to evaluate the impact of a persistence of the current productivity regime on future stock trends. It should be noted that for the period of low productivity, resampling of the recruitment-SSB pairs was not from quartiles but from the two ranges separated by the median (50,000 t SSB); the low number of observations prevents splitting the SSB range in quartiles for re-sampling. We also tested the sensitivity of the technique on the results by using a different break point for re-sampling recruitment and the 35,000 t threshold was used for that purpose SSB.

Modeling tools

A spreadsheet model was developed using the above description of the stock dynamics to provide some flexibility in simulating harvest control rules (HCR) and stock trajectories under PA-frameworks based on biomass targets and limits, as well as F targets and limits. In particular, the spreadsheet can be used to mimic HCRs under the ICES and NAFO PA frameworks, or simply to evaluate constant F-scenarios. It also permits to account for fishing mortality resulting from by-catch in periods of moratorium and allows options for specifying the HCRs. Risk analyses are performed using an Add-in to Excel called @Risk (Anon. 1997).

This approach allows the user to specify uncertainty in: a) population dynamic parameters; b) in initial conditions of the state variables; and c) in the stock-recruit relationship. It also provides tools to calculate the probability of achieving limits or targets in the simulation years, to calculate the time it takes to reach these targets and to evaluate other elements of interest to managers (e.g. number of closures after re-opening, recovery time).

As an alternative to the method described above, projections were carried which were identical except for (i) realizations of the ADAPT estimates of survivors at the beginning of 1999 were generated by resampling from the uncertainty in the logged survivors defined by the variance-covariance matrix and then back-transforming the values; (ii) recruitment values were randomly selected in each year with probabilities defined by a Cauchy kernel fitted to the stock-recruit estimates from ADAPT. With regard to (ii), the shape parameter for the kernel was estimated by minimizing the cross-validated prediction sums of squares (see Shelton and Morgan 1993, 1994) in which and applications of the Evans and Rice (1988) are explained in some detail.

PA Framework

A PA-framework similar to the one illustrated in Figure 2 provides some flexibility in specifying HCRs. In particular, fishing levels resulting from precautionary monitoring (e.g. through surveys) or bycatch in fisheries directed at other species could be simulated. The framework will be used here to explore re-opening criteria.

SSB Limit. The SSB and recruitment data over the 1959-95 period indicate a sharp decrease in the likelihood of obtaining high recruitment at SSBs below 60 000 tons. In April 1999, the Scientific Council concluded that 60 000 tons is the current best estimate of B_{lim} (Anon., 1999a). They also concluded that in the recent period of low productivity, there is an indication of even further reduction in recruitment at about half the B_{lim} level (35,000 t).

SSB Buffer. It has been recognized that it's the role of scientists to calculate the biomass levels B_{buf} which correspond to various probabilities of being below B_{lim} but that it is the role of managers to determine the level of risk (or probability level) applicable to a given stock. The buffer limit corresponding to various probability levels can be determined from the stochastic simulations but we have not evaluated recovery time to SSB buffers in these simulations. However, such calculations have been provided by Anon. (1999a).

SSB Target. While the NAFO PA framework include a target recovery level for the spawning biomass, such a level has not been determined yet for cod in 3NO. We use the simulations here to gain insight on the B_{MSY} level corresponding to various productivity regimes.

Harvest control rules. Limits and buffers on fishing mortality are also part of the NAFO PA framework but these will not be discussed here as the immediate goal is to determine the strategy to reach B_{lim} as soon as possible. Only a fishing mortality corresponding to the current by-catch (F=0.04) will be used, together with lower F-values simulating improved by-catch control.

Results and Discussion

Time trajectories (Figure 3)

For illustrative purposes, an example of the time trajectory of various population metrics and fishery characteristics is provide in Figure 3. The Monte-Carlo simulations are based on 2000 replicates and an example of the scatter resulting from these replicates is shown in Figure 4.

Simulation results

The results of the simulations are presented in Table 3, which provides the median of the distribution of SSB and yield expected in any given year under various recruitment and F scenarios. The trajectories of the median SSB are illustrated in Figure 5. Four F-scenarios were considered: 1) No fishing (perfect control of by-catch); 2) F=0.04, which is equivalent to the level of by-catch observed since 1995; 3) F=0.08, or twice the by-catch fishing level; and 4) F=0.2, i.e. $F_{0.1}$. Each scenario was evaluated under two recruitment hypothesis: i.e. future recruitment will respond to biomass changes in a manner similar to that observed 1) since 1959 [labeled "re-sampling full range of recruitment in the Table] or 2) since 1982, which is believed to correspond to a period of low productivity. The level of B_{lim} was taken as 60000t for the "full" scenario and as 35,000 t for the low recruitment scenario.

Time to reach B_{lim}

The results indicate that the recovery of cod in 3NO will largely depend upon the dynamics of the recruitment process. If the first year of recovery is defined as the year when the probability that the SSB in a given year has reached B_{lim} is 50%, then the first year when the biomass will be considered as recovered would be 2012 in the low recruitment regime and 2008 under the full regime under no by-catch scenario. The recovery time increases as F increases (see table 3). There is also a major difference between the level of biomass and the level of yield under each of the assumed productivity regimes. Both the projected biomass and yield under the low recruitment regime are of the order of one tenth the projected levels under the normal regime.

The fishing intensity also have an effect on the recovery time. For instance, taking the full recruitment regime into account, fishing at $F_{0.1}$ (F=0.2) indicates the first year of recovery at 2016, compared to 2008 under no fishing.

Comparison with results from the alternative variance-covariance-kernel approach

In general terms, the results from the alternative approach applied to the recruitment data for 1959 to 1996, using the variance-covariance matrix to describe the uncertainty in survivors and generating recruitment values from a Cauchy kernel (Figure 8), were similar (Table. 4). For zero catch, there are higher probabilities of being below the 60,000 t spawner biomass limit over the period 2007 to 2012 and for median SSB to be lower, but thereafter the outcome is similar. For the low by-catch level (F=0.04), there is a similar difference but, at the high by-catch level (F=0.08) and at the $F_{0.1}$, the results from the two approaches are very similar.

Under the low recruitment regime, the variance-covariance-kernel approach suggests a much lower probability of recovery than the re-sampling approach for comparable time periods under each of the fishing mortality levels. The explanation for these differences would appear to be that the stock has greater difficulty escaping the low recruitment values below 35,000 t SSB limit because of the low probabilities assigned to the recruitment values by the fitted kernel (Fig. 8). When the re-sampling approach was used with a break point of 35,000 t SSB for re-sampling recruitment (the sensitivity run referred to above), both approaches gave very similar results. They suggest that recovery to the 35,000 t threshold is unlikely under a "low recruitment" regime in the timeframe shown in Tables 3 and 4 even with no removals (F=0).

B_{MSY} *and* F_{MSY} *estimates*

An approximation to the age-structured stock production model was obtained by using the average of the last five years of the long-term projection as a proxy to equilibrium biomass and equilibrium yield under various "constant F" scenarios. Results are presented in Figure 6 for the full range of recruitment and in Figure 7 for the low recruitment regime since 1982.

These results indicate that the maximum equilibrium yield under the low recruitment regime is about one-tenth the equilibrium yield inferred from re-sampling the full recruitment range. It should also be noted that these equilibrium curves were obtained by using constant vectors for mean weights-at-age and maturity-at-age. These approximations could be refined by using a re-sampling scheme similar to that used for the recruitment to capture the dynamics of these variables as a function of total biomass. Also, as all observations of the total biomass are below the estimate of B_{MSY}, the estimate of B_{MSY} is not well specified and cannot be obtained until the biomass wanders beyond the current range of observations.

Uncertainty in other variables

The simulations performed in this study took into account only the uncertainty in the estimation of the initial stock size and in the stock-recruitment process. The uncertainty and stochastic processes associated with fish growth, as reflected in mean weight at age, in fishery selection patterns (partial recruitment factors) or in maturity have not been included in these simulations. However, the analytical framework and software tools used in this study would allow taking these sources of uncertainty into account.

It should also be noted that these simulations were done without a plus-group (fish were assumed to leave the stock at age 24). Consequently, the estimates of long-term yield and stock size could be underestimated by this approach. However, as there is little information on the growth of fish older than 24, little can be done at present to improve our knowledge of growth for older ages. In addition, the dynamics of the stock at high levels (i.e. beyond the historical high observed) is largely unknown. Density-dependent mechanisms are expected to enter into action beyond B_{MSY} and mean weights-at-age are expected to decline as the stock is approaching its carrying capacity.

Conclusions

The results of the simulations provided insight on the time it will take for the cod stock on the southern Grand Banks to recover from its current low level. These simulations take into account the precision of the stock size estimates currently available for this stock, as well as the observed variability in the stock-recruitment process. These results suggest that changes in the productivity of the stock could have a major impact on the dynamics of the stock in future years and that recovery time will depend upon which recruitment process prevails in the future. They also suggest that annual fishing mortality rates in excess of those observed in recent years (which were associated with by-catch in fisheries for other species) could increase considerably the recovery time in a low recruitment regime.

Mid-term

For the purpose of this study, the spawning biomass was considered "recovered" when B_{lim} (60,000 t) had been reached for 50% of the replicates (i.e. the median). The recovery to B_{lim} was achieved by year 2012 in the low recruitment regime, and 2008 under the full regime under the "no by-catch" scenario. The fishing intensity had a noticeable impact on recovery time. For instance, taking the full recruitment regime into account, fishing at $F_{0.1}$ (F=0.2) means that B_{lim} would be reached by year 2016, compared to 2008 under no fishing. Under the low recruitment regime, recovery to the milestone of 35,000 t was achieved by year 2017 at the current by-catch mortality; however, it was not achieved by year 2020 with by-catch levels in excess of those observed in recent years. There is also a major difference between the level of biomass and the level of yield under each of the assumed recruitment regimes: both the projected biomass and yield under the low recruitment regime are of the order of one tenth the projected levels under the full regime.

In order to evaluate the impact of the assumptions made in describing the recruitment dynamics under a low recruitment regime, the above results were compared to those obtained from an analysis using a different method for describing recruitment. The second method suggests that recovery to the 35,000 t threshold is unlikely by year 2020 under a low recruitment regime, even with no removals. For the "full" recruitment regime, no major differences were identified between the two approaches to modeling recruitment dynamics.

While these simulations allow estimates of the probability distributions for recovery time to specific targets or for other parameter of interests, the results have been described here solely in terms of the median to simplify their description. The probability distribution of the time to reach given milestones or of any other quantity of interest to the managers can also be provided and should be focused on once such quantities have been determined or agreed upon. Examples of such calculations for cod in 3NO are provided in Anon. 1999a.

Long term

The results of a production analysis indicate that the maximum equilibrium yield under the low recruitment regime is about one-tenth the maximum inferred from re-sampling the full recruitment range.

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Table 1. Age-specific estimates of population abundance at the beginning of 1999 from an ADAPT analysis (Stansbury, 1999), relative error of stock size estimates, partial recruitment, mean weight at age (mid-year) and maturity at age used in the simulations.

Age	Stock Numbers for 1999 (x1000)	Relative Error of stock numbers (%)	Partial recruitment	Mean Weight mid-year (kg)	Maturity %
3	113	66	0.20	0.55	0.003
4	113	48	0.64	0.92	0.019
5	437	40	0.97	1.42	0.128
6	297	36	1.00	2.15	0.461
7	136	32	1.00	3.12	0.827
8	64	35	1.00	4.45	0.967
9	394	33	1.00	6.42	0.996
10	568	32	1.00	8.00	1.000
11	61.5	33	1.00	8.99	1.000
12	43.9	40	1.00	10.90	1.000
13			1.00	10.53	1.000
14			1.00	10.89	1.000
15			1.00	11.28	1.000
16			1.00	11.67	1.000
17			1.00	12.08	1.000
18			1.00	12.50	1.000
19			1.00	12.94	1.000
20			1.00	13.39	1.000
21			1.00	13.86	1.000
22			1.00	14.35	1.000
23			1.00	14.85	1.000

Table 2. Recruitment at age 3 and Stock Spawning Biomass for cod in NAFO Divisions 3NO, as calculated from ADAPT (Stansbury, 1999).

Year-class	Numbers at age 3 (x 1000)	SSB (t)		Year-class	Numbers at age 3 (x 1000)	SSB (t)
1959	106515	87921		1979	21326	23678
1960	77456	74628		1980	34672	37512
1961	110562	73170		1981	40710	69035
1962	160052	70048		1982	31807	82581
1963	207114	77503		1983	8613	84671
1964	181079	84493		1984	6332	87284
1965	99509	110168		1985	12464	82186
1966	126175	104120		1986	12326	77906
1967	79267	87556		1987	4902	80815
1968	83222	78821		1988	5180	51035
1969	61009	67143		1989	13646	49712
1970	34539	69411		1990	5984	36672
1971	36122	76002		1991	540	27742
1972	22725	73505		1992	331	11717
1973	26976	65822		1993	568	5222
1974	44648	62841		1994	641	2759
1975	40875	31367		1995	125	3204
1976	17069	10680		1996	87	4544
1977	19361	11278		1997		
1978	27015	14953		1998		

Table 3. Results of simulations done for cod in 3NO to evaluate the impact of various fishing mortality levels on stock recovery. Each simulation represents 2000 iterations.

	Re-sampling full range of recruitment											
	No catch			F = 0.04 (current bycatch level)			F= 0.08 (twice current bycatch)			F = 0.20 (F0.1)		
Year	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t
1999	7740	0	100%	7765	354	100%	7786	695	100%	7747	1636	100%
2000	8448	0	100%	8153	378	100%	7830	717	100%	6926	1536	100%
2001	8907	0	100%	8254	440	100%	7630	809	100%	6007	1621	100%
2002	9691	0	100%	8609	708	100%	7736	1313	100%	5608	2879	100%
2003	11072	0	100%	9487	1006	100%	8319	1874	100%	5851	3583	100%
2004	18906	0	100%	15936	1322	100%	14185	2511	100%	10821	4707	100%
2005	32670	0	93%	26185	1724	98%	23074	3190	100%	15150	5685	100%
2006	43503	0	72%	35355	2165	86%	31520	3851	93%	19949	6576	100%
2007	58773	0	51%	46737	2612	69%	40927	4565	81%	24561	7397	100%
2008	**72723**	**0**	**35%**	57303	3122	54%	48603	5250	69%	27494	7983	99%
2009	87159	0	24%	**66190**	**3722**	**42%**	55205	6090	57%	30476	8733	98%
2010	102381	0	16%	77710	4441	31%	**62893**	**7144**	**46%**	32830	9454	97%
2011	121228	0	10%	90009	5383	23%	70473	8400	36%	35009	10301	94%
2012	147526	0	7%	106368	6520	15%	81461	10102	27%	37565	11431	89%
2013	184057	0	3%	129237	7999	10%	96226	12122	19%	40886	13047	80%
2014	230393	0	2%	159381	9749	7%	116280	14576	13%	45840	14949	69%
2015	290398	0	1%	198912	11943	4%	143603	17320	10%	52128	17652	60%
2016	368172	0	1%	245171	14273	2%	174190	20426	7%	**60448**	**19848**	**50%**
2017	453774	0	0%	294934	16896	2%	207726	24394	5%	70659	22290	41%
2018	540360	0	0%	354261	19561	1%	241971	28723	3%	80929	24404	35%
2019	629882	0	0%	419071	22092	1%	285382	32477	2%	90196	26478	30%
2020	706820	0	0%	480448	24564	1%	334915	36099	2%	98820	29159	27%

	Re-sampling recruitment since 1982											
	No catch			F = 0.04 (current bycatch level)			F= 0.08 (twice current bycatch)			F = 0.20 (F0.1)		
Year	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t
1999	7797	0	100%	7783	354	100%	7761	693	100%	7786	1641	100%
2000	8503	0	100%	8153	354	100%	7824	671	100%	6960	1414	100%
2001	8879	0	100%	8190	375	100%	7544	683	100%	5963	1294	100%
2002	9043	0	100%	8033	383	100%	7161	687	100%	5046	1208	100%
2003	9170	0	100%	7903	445	100%	6797	798	100%	4342	1401	100%
2004	9627	0	100%	8049	525	100%	6795	913	100%	4099	1543	100%
2005	12197	0	98%	10081	645	100%	8678	1123	100%	5331	1890	100%
2006	15195	0	92%	12620	774	97%	10422	1340	99%	6096	2213	100%
2007	19407	0	84%	15951	891	91%	13255	1513	97%	7535	2289	100%
2008	24436	0	74%	19902	982	86%	16256	1637	94%	9031	2466	100%
2009	28893	0	65%	22369	1106	80%	17814	1779	91%	9526	2625	100%
2010	30998	0	58%	24115	1186	75%	19028	1892	89%	9962	2723	100%
2011	34134	0	52%	26263	1265	71%	20199	1984	86%	10387	2803	100%
2012	**36853**	**0**	**47%**	28113	1340	67%	21201	2095	84%	10722	2805	100%
2013	38810	0	44%	29052	1396	64%	21905	2152	84%	10804	2847	100%
2014	41537	0	40%	30532	1467	60%	22966	2211	82%	10866	2838	100%
2015	45548	0	34%	32214	1548	56%	23739	2269	79%	10901	2821	100%
2016	49785	0	30%	33734	1614	52%	24231	2321	75%	10931	2846	100%
2017	54560	0	26%	**36112**	**1711**	**48%**	24868	2372	73%	10853	2839	100%
2018	60850	0	23%	37692	1811	46%	25375	2450	70%	10842	2819	100%
2019	68784	0	21%	39523	1965	43%	26107	2534	68%	10854	2831	100%
2020	77984	0	18%	42196	2109	41%	27023	2619	66%	10798	2846	100%

Table 4. Results of simulations done to evaluate the impact of various fising mortality levels on stock recovery using the Cauchy smoother. Each simulation represents 1000 iterations.

	Re-sampling full range of recruitment											
	No catch			F = 0.04 (current bycatch level)			F= 0.08 (twice current bycatch level)			F = 0.20 (F0.1)		
Year	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<60000 t
1999	8151	0	100%	8162	372	100%	8241	734	100%	8132	1714	100%
2000	8861	0	100%	8565	362	100%	8296	686	100%	7259	1426	100%
2001	9238	0	100%	8580	339	100%	7991	621	100%	6211	1133	100%
2002	8901	0	100%	7926	334	100%	7109	596	100%	4889	1009	100%
2003	8155	0	100%	7024	326	100%	6078	566	100%	3742	1053	100%
2004	6142	0	100%	5098	669	100%	4370	1195	100%	2554	2467	100%
2005	6848	0	100%	6286	1093	100%	5189	1968	100%	3697	3784	100%
2006	17705	0	99%	16769	1578	100%	13984	2766	100%	10175	5257	100%
2007	31574	0	87%	28536	2076	91%	24394	3660	97%	16059	6425	100%
2008	47435	0	64%	43450	2633	72%	35691	4640	83%	23114	7651	98%
2009	67542	0	43%	57448	3294	53%	47680	5549	67%	28565	8806	96%
2010	87840	0	27%	72412	3933	38%	59122	6498	52%	32646	9718	92%
2011	106788	0	16%	86200	4756	26%	68159	7651	40%	36285	10812	88%
2012	126831	0	10%	99881	5693	18%	78448	8981	30%	39929	12208	84%
2013	148529	0	5%	117528	6616	13%	89348	10368	22%	43776	13145	78%
2014	167112	0	3%	133421	8256	9%	100774	12206	17%	47465	14698	72%
2015	202593	0	2%	157044	10316	6%	118064	14928	13%	52059	16371	61%
2016	258078	0	1%	196509	12895	4%	141213	18500	8%	58381	18460	52%
2017	343715	0	1%	256193	16141	3%	174166	22861	6%	65765	20899	43%
2018	454042	0	1%	329692	19667	1%	216118	28166	4%	74355	24584	34%
2019	575298	0	0%	404137	23376	1%	272596	33620	2%	85082	28601	27%
2020	709517	0	0%	496667	27379	1%	334285	39080	2%	100309	32947	22%

	Re-sampling recruitment since 1982											
	No catch			F = 0.04 (current bycatch level)			F= 0.08 (twice current bycatch level)			F = 0.20 (F0.1)		
Year	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t	Median SSB (t)	Median Yield (t)	Prob. SSB<35000 t
1999	8270	0	100%	8295	375	100%	8073	721	100%	8126	1716	100%
2000	8960	0	100%	8643	366	100%	8157	675	100%	7274	1424	100%
2001	9354	0	100%	8702	344	100%	7836	608	100%	6209	1135	100%
2002	8982	0	100%	8031	302	100%	6951	518	100%	4902	870	100%
2003	8148	0	100%	6974	188	100%	5829	315	100%	3654	478	100%
2004	5168	0	100%	4232	139	100%	3438	229	100%	1930	339	100%
2005	3663	0	100%	2889	138	100%	2325	229	100%	1213	335	100%
2006	3687	0	100%	2880	140	100%	2288	226	100%	1181	339	100%
2007	3678	0	100%	2822	133	100%	2242	219	100%	1179	343	100%
2008	3512	0	99%	2755	132	100%	2199	220	100%	1242	361	100%
2009	3548	0	97%	2818	153	100%	2279	252	100%	1342	412	100%
2010	4344	0	94%	3310	174	99%	2665	299	100%	1523	454	100%
2011	6019	0	93%	3869	217	98%	3038	390	100%	1719	516	100%
2012	9910	0	92%	4393	285	98%	3624	523	100%	1875	555	100%
2013	11260	0	90%	5237	273	98%	4464	513	99%	2059	506	100%
2014	11102	0	90%	5034	254	98%	4374	487	100%	1907	509	100%
2015	10580	0	91%	4817	249	98%	4490	485	99%	1883	470	100%
2016	10654	0	91%	4740	269	98%	4110	470	99%	1809	479	100%
2017	10649	0	90%	4771	267	97%	3939	460	99%	1778	477	100%
2018	11011	0	89%	4772	315	95%	3901	481	99%	1783	475	100%
2019	11759	0	86%	5291	347	94%	4011	535	99%	1787	484	100%
2020	12466	0	84%	6032	366	94%	4675	541	98%	1828	480	100%

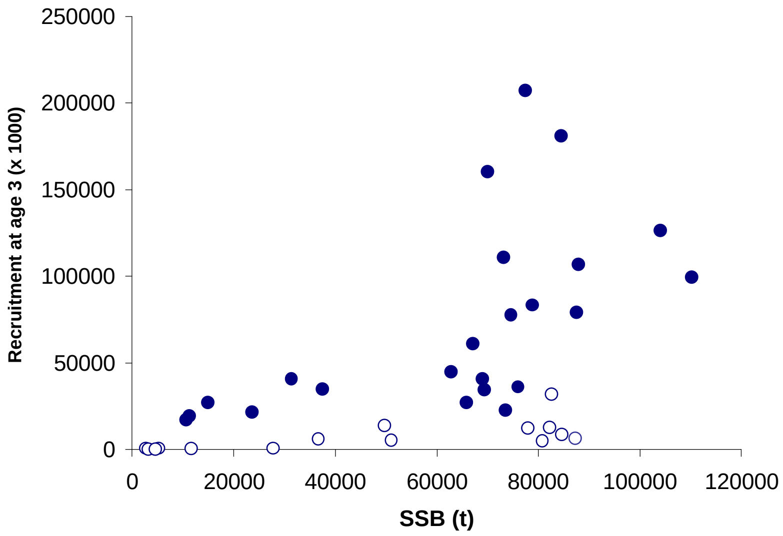


Fig. 1. Stock-recruit scatter-plot for cod in NAFO Divisions 3NO. Open circles represent the observations since 1982.

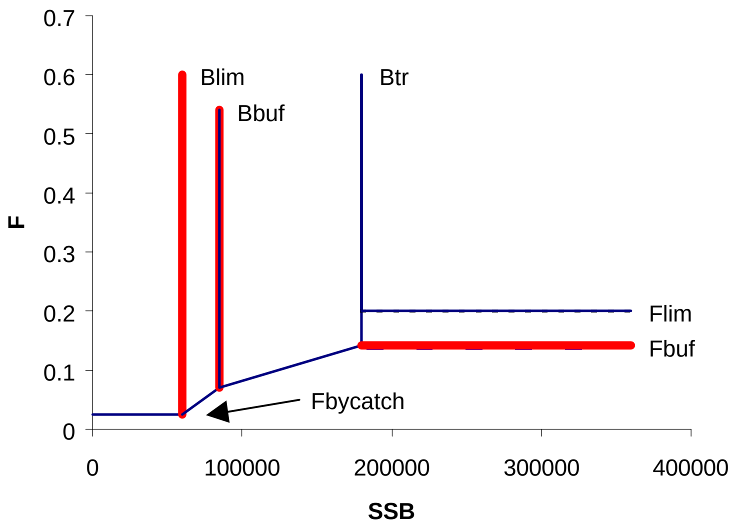
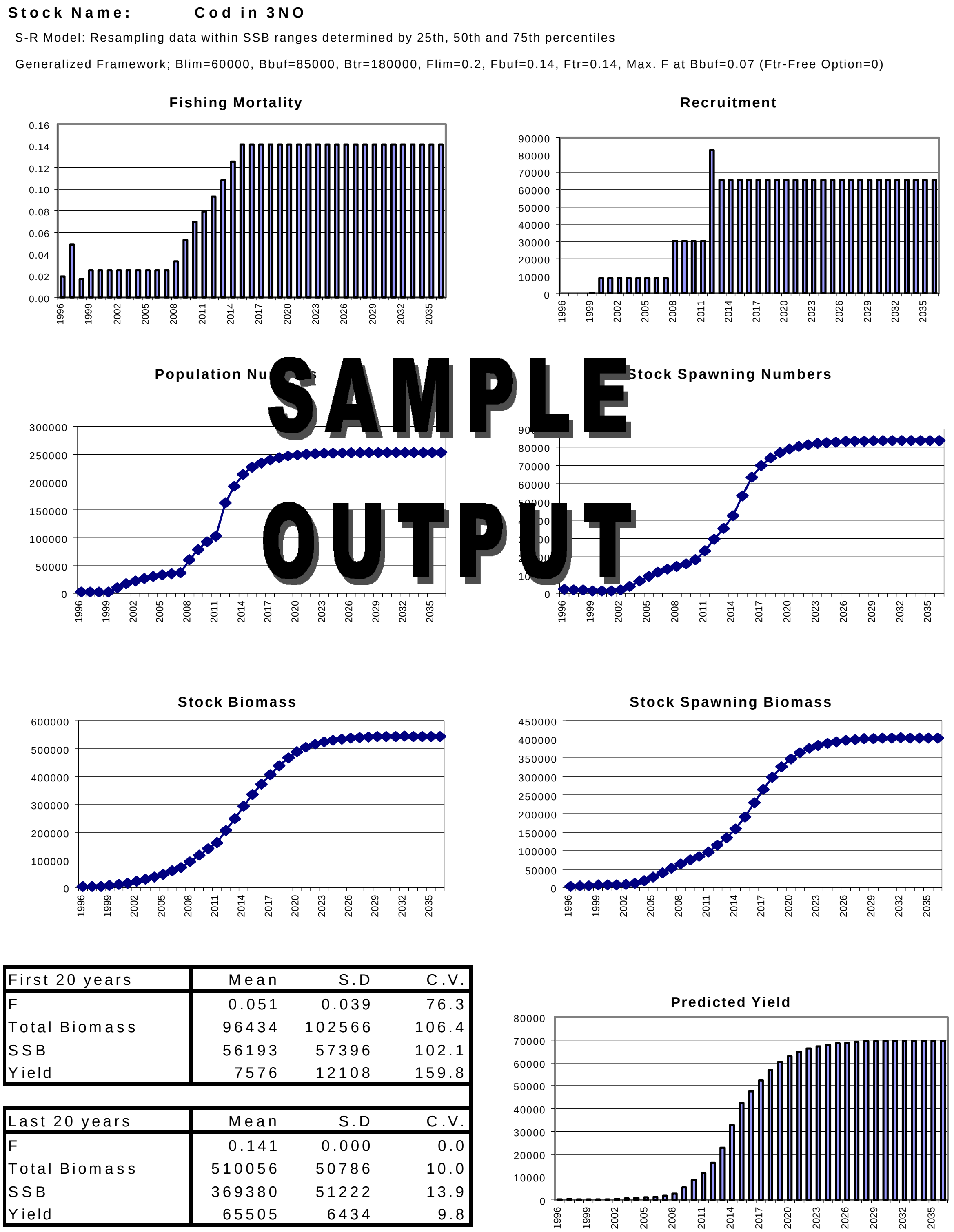


Fig. 2. PA framework acccounting for bycatch or precautionary monitoring below B_{lim}. While this feature is not used in these simulations, the framework also allows to specify an harvest control rule below B_{buf} .



Stock Name: Cod in 3NO

S-R Model: Resampling data within SSB ranges determined by 25th, 50th and 75th percentiles

Generalized Framework; Blim=60000, Bbuf=85000, Btr=180000, Flim=0.2, Fbuf=0.14, Ftr=0.14, Max. F at Bbuf=0.07 (Ftr-Free Option=0)

Fishing Mortality

Recruitment

Population Numbers

Stock Spawning Numbers

Stock Biomass

Stock Spawning Biomass

First 20 years	Mean	S.D	C.V.
F	0.051	0.039	76.3
Total Biomass	96434	102566	106.4
SSB	56193	57396	102.1
Yield	7576	12108	159.8

Last 20 years	Mean	S.D	C.V.
F	0.141	0.000	0.0
Total Biomass	510056	50786	10.0
SSB	369380	51222	13.9
Yield	65505	6434	9.8

Predicted Yield

Fig. 3. Example of the time trajectory of various population metrics and fishery characteristics calculated during the simulations.

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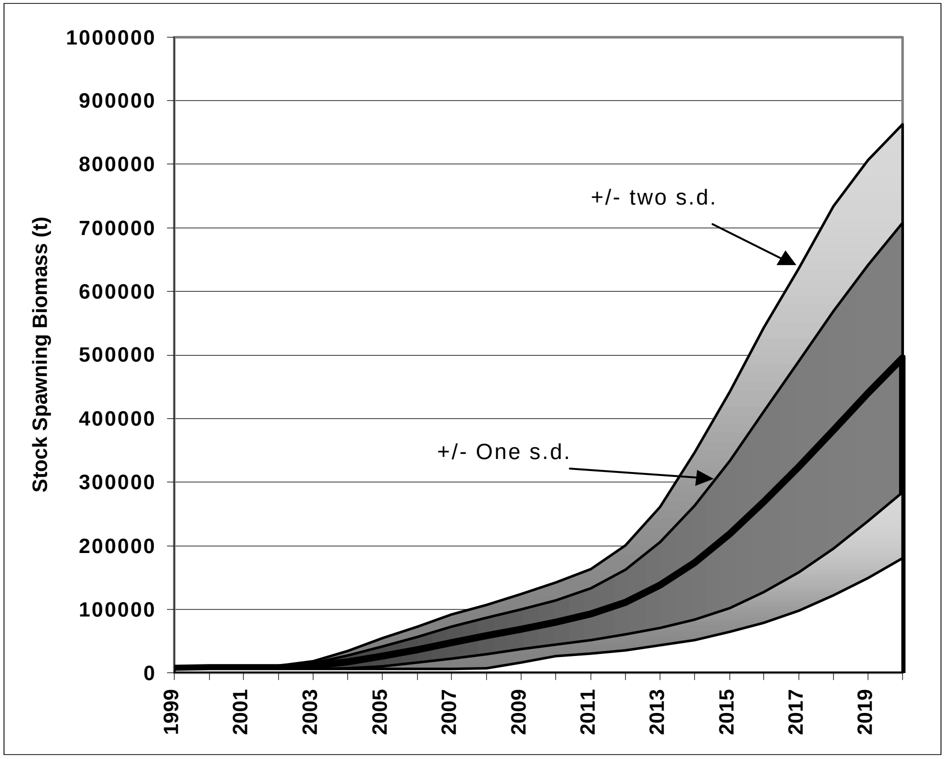
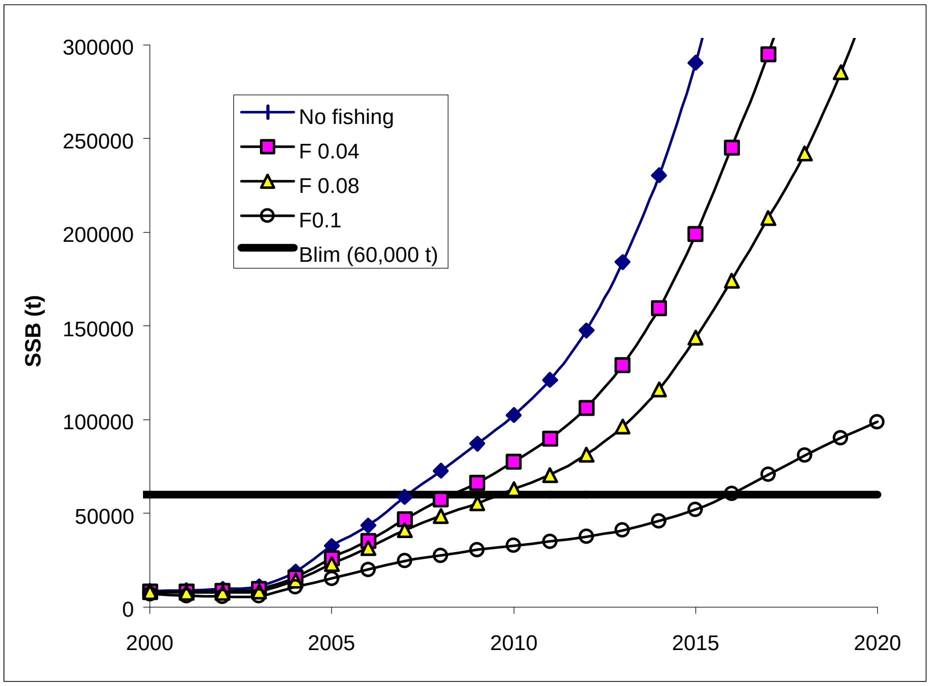


Fig. 4. Envelope of the SSB-trajectories resulting from 2000 replicate of the time trajectories (Assumes bycatch fishing mortality level of 0.04, re-sampling the full range of observed recruitment).



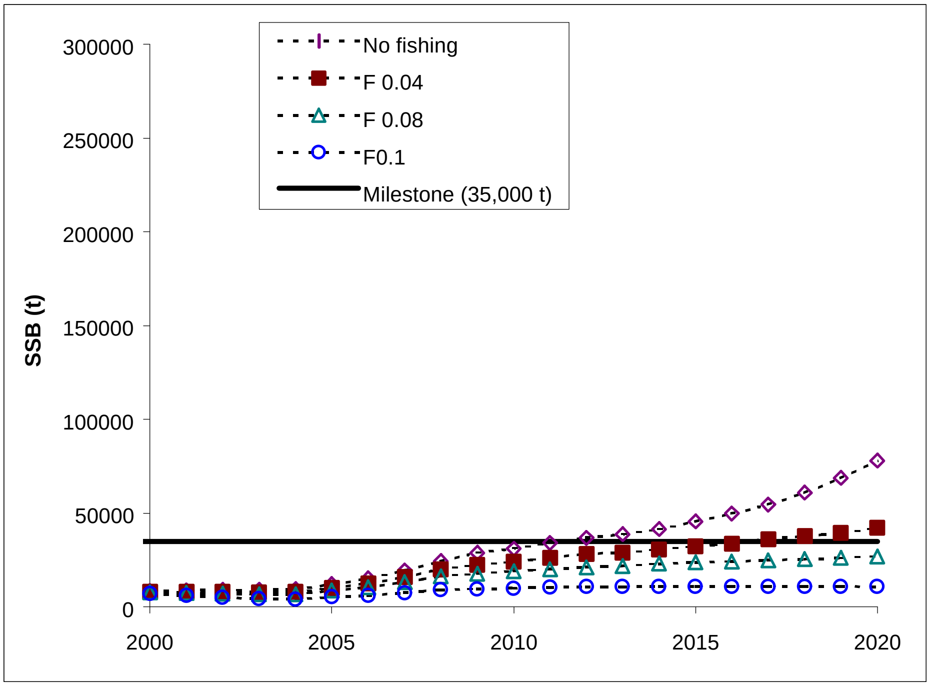


Figure 5. Trajectory of the median SSB for cod in 3NO, from the simulations assuming that recruitment relate to SSB in a manner similar to that observed since 1959 (top panel) or in a manner similar to that observed since 1982 (bottom panel).

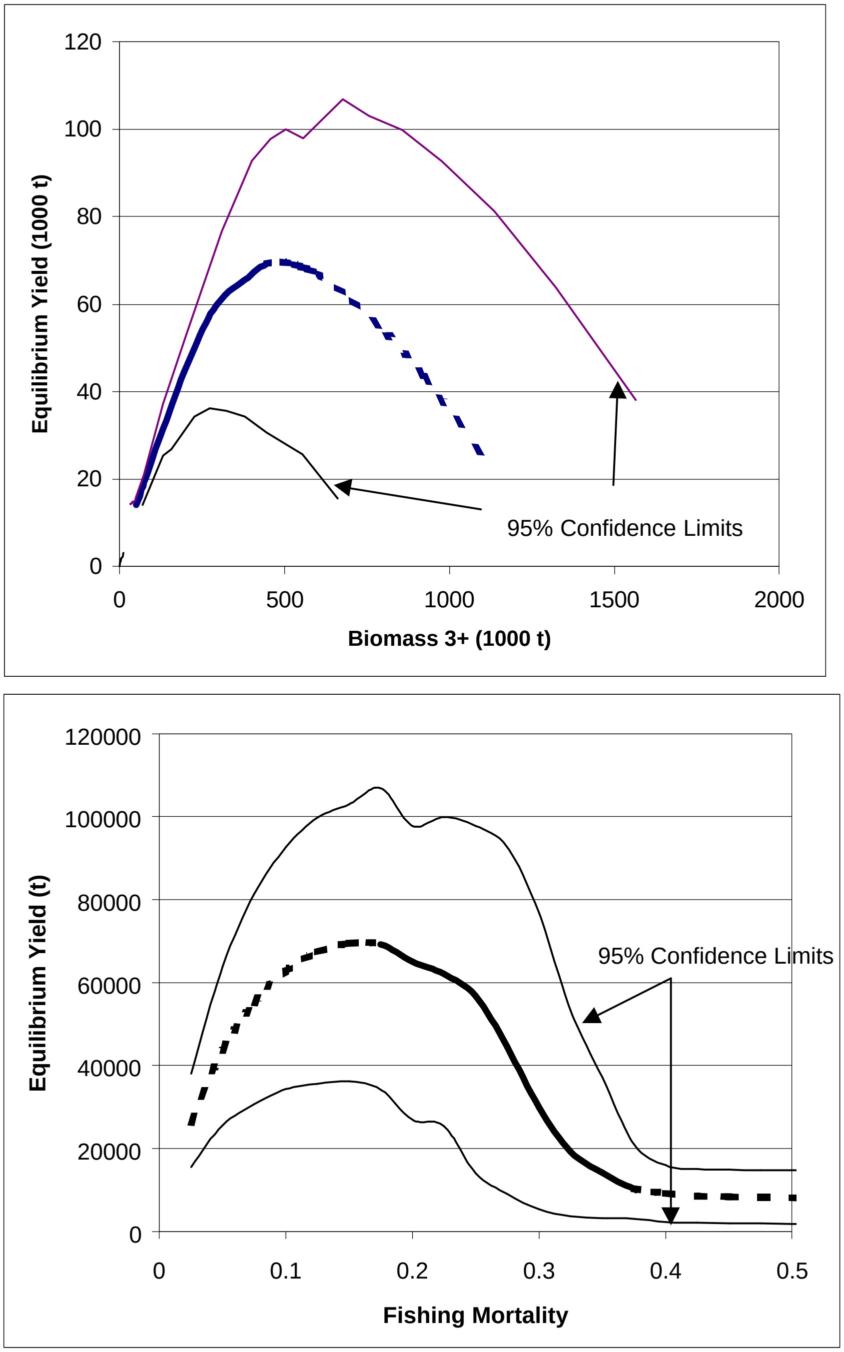


Fig. 6. Production model corresponding to the full recruitment dynamics: a) equilibrium yield against total biomass (3+) and b) equilibrium yield against F. These are based on 100 replicates for each constant-F scenario (F varied from 0 to 0.7 in 0.025 increments). The heavy solid line represents the points where the total biomass simulated was within the observed range of total biomass values.

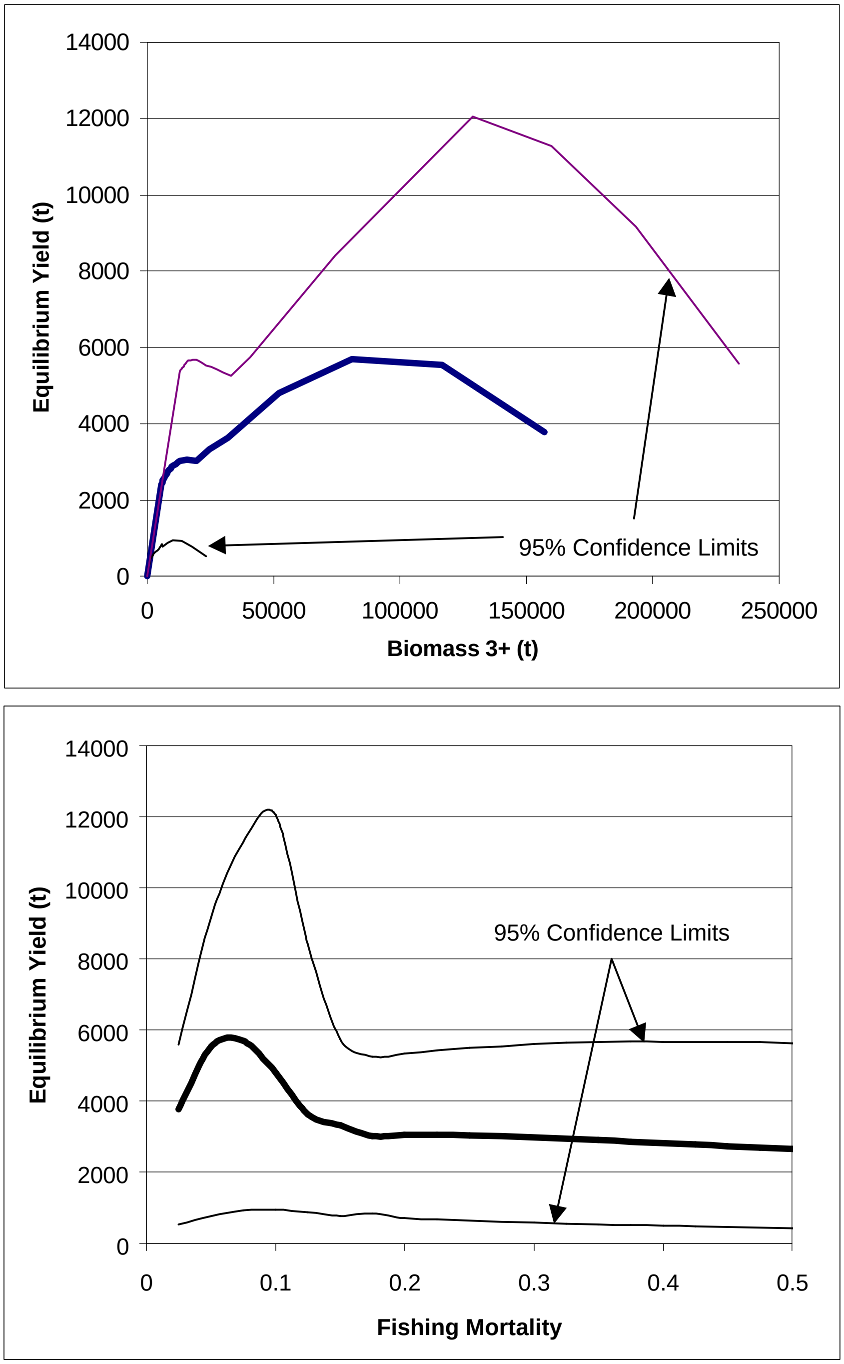


Fig. 7. Production model corresponding to the low recruitment period: a) equilibrium yield against total biomass (3+) and b) equilibrium yield against F. These are based on 100 replicates for each constant-F scenario (F varied from 0 to 0.7 in 0.025 increments).

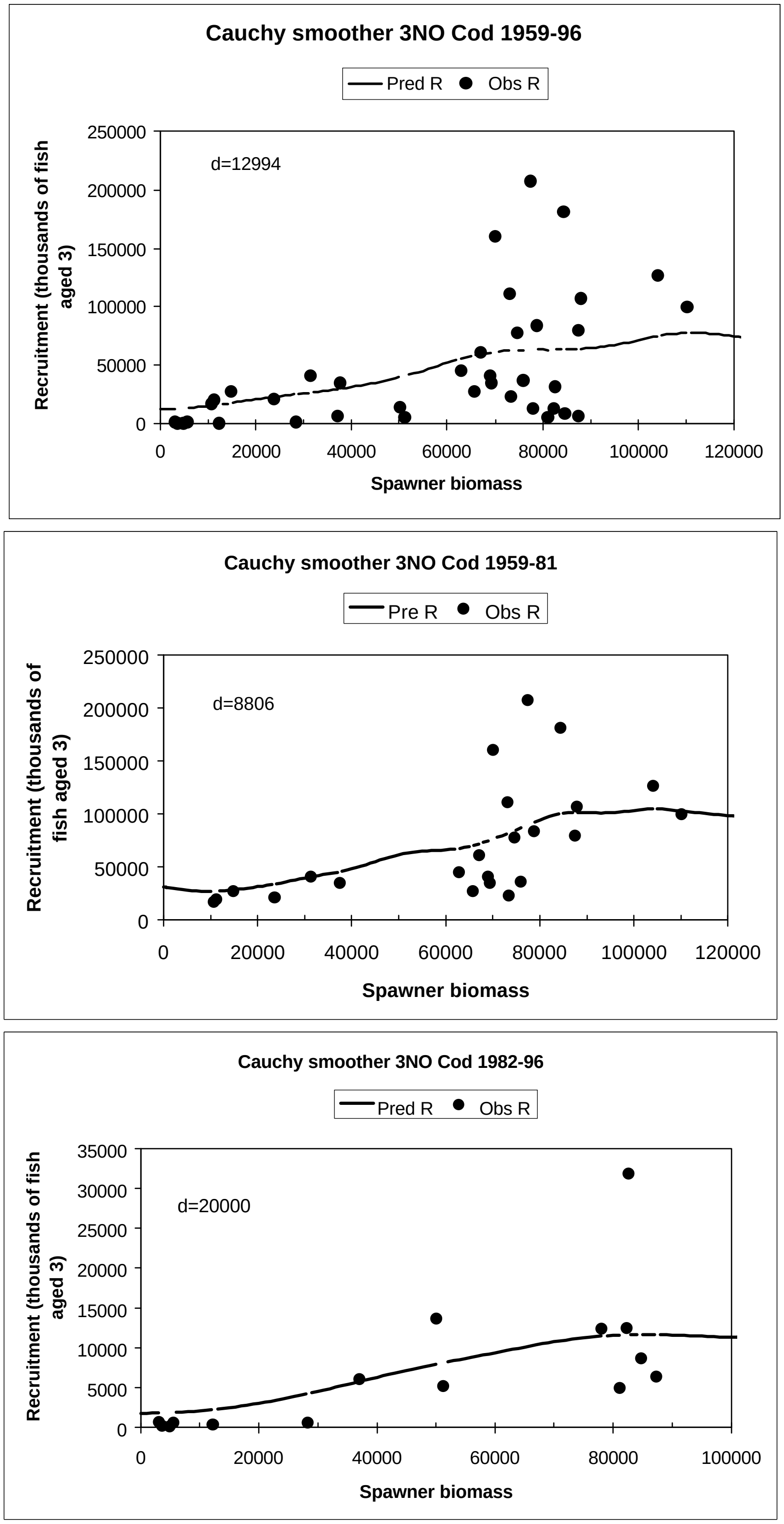


Fig. 8. Cauchy smoother applied to recruitment data for cod in NAFO Divisions 3NO for various time intervals.