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A preliminary study regarding a Management Strategy Evaluation for 3LNO American plaice

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Abstract:

A Management Strategy Evaluation for 3LNO American plaice is proposed using a Bayesian surplus production model as an operating model. Four potential management procedures are carried over a 20 years period (2011 to 2030) and compared through various performance statistics such as annual average variation in catch (AAV), cumulated catches over 10 and 20 years or annual probabilities of being above Blim or BMSY. When considering the probabilities of being above Blim and BMSY, the management procedure that increases or decreases the TAC by 10% or 20% respectively depending on the an the average surveys index over the last 5 years, gives the best results.

Key words: Bayesian surplus production model, Div. 3LNO American plaice, Management Strategy Evaluation

Introduction

The Management Strategy Evaluation (MSE) conceptual framework involves two main components: an operating model (OM) and a management strategy or procedure (Fig. 1).

The operating model is used to simulate the stock's dynamics and is calibrated on the available information (data and expert knowledge) to be a realistic representation of the stock. In this study, the operating model is the (slightly modified) Bayesian surplus production model developed by Morgan (2012).

There are five key elements in the MSE approach (Smith et al., 1999):

1. Management objectives
2. Performance statistics
3. Alternative management strategies
4. Simulation evaluation of alternative management strategy performance and,
5. Presenting the results to decision makers.

It is important to note that elements 1 to 3 should be discussed and decided with managers, the public and industry. In this study, it has not been possible yet to meet with the different partners and agree on these aspects. It is anticipated that the new SC-FC WG on risk-based strategies will provide a platform for discussion of these aspects. In the meantime, a set of basic performance statistics was retained (annual average variation in catch, total catch after 10/20 years, annual probability of being above Blim and BMSY, Bratio: the ratio of biomass to BMSY). Management strategies developed to achieve satisfactory outcomes in regard to these performance statistics is based in part on previous work carried by NAFO on Greenland halibut (Miller et al., 2008) although new strategies are alos suggested. These strategies can easily be changed if required and new candidate strategies can be considered. The core of any strategy is the harvest control rule (HCR) which is tuned to achieve the desired performance. Previous experience has shown that simple HCRs based directly on survey observations can perform as well or better than more complex rules that incorporate biological reference points and model estimates of stock biomass (Shelton and Miller 2009).

The American Plaice stock in NAFO (Northwest Atlantic Fisheries Organisation) Divisions 3LNO (Fig. 2) is managed by an RFMO (Regional Fisheries Management Organisation). After observing a severe decline in landings and survey index as a result of overfishing, there has been no directed fisheries since 1993 (Fig. 3a). However there is still a significant by-catch (about 3000 tons a year) as a result of skate, redfish, Greenland halibut and yellowtail flounder fisheries. Additionally, a number of annual trawl surveys provide catch-independent biomass indices (Fig. 3b). Rebuilding strategies that are being developed by NAFO for this stock need to take into account ways of controlling the bycatch so the stock can recover to the PA Safe Zone.

The last paper presented to the scientific council about Div 3LNO American plaice (Morgan, 2012) focused on providing some information on the reliability of the MSY reference points estimated by Shelton and Morgan (2011). In this paper, we briefly describe the results regarding the historical part of the time-series (1959-2010) and then run simulations for the next 20 years (2011-2030) implementing several management procedures and comparing their performance.

surveys carried out in Div. 3LNO.

Material & Methods

1. Operating Model: Bayesian surplus model

    a. Data available

For this study we used the Bayesian version of the Schaefer surplus production model developed by Morgan (2012) with slight adjustments of the prior distributions. The dataset available for this study are as follow (see Table 1 and Fig. 2):

1. 3LNO commercial catches C_t (from 1960 to 2010)
2. 3LNO Research Surveys
    a. Canadian RV spring survey index: Engels Trawl $I_t^{Ca\_E}$ (from 1975 to 1984)
    b. Canadian RV spring survey index: Campelen Trawl or equivalent $I_t^{Ca\_s}$ (from 1985 to 2010)
    c. Canadian RV fall survey index: Campelen Trawl or equivalent $I_t^{Ca\_f}$ (from 1990 to 2010)
    d. EU RV survey index I_t^{EU} (from 1997 to 2009).

The Bayesian model fit could have been extended by two years (2011 and 2012) but the catch data are not available yet.

    b. Model description

Henceforth, the notation a|b ~ f(b) means the random variable a (whether unobservable or observable) is distributed according to the probability distribution function (PDF) f conditionally on b.

Population abundance P_t (as a proportion of carrying capacity K) in a given year is modelled as follows:

$$Eq.\ 1 \quad Log(P_t) = \mu_t^P + \eta_t$$

Where μ_t^P is the average relative abundance calculated as a surplus model with a Shaefer (1954) functional form:

$$Eq.\ 2 \quad \mu_t^P = Log\left(P_{t-1} + r \cdot P_{t-1} \cdot (1 - P_{t-1}) - \frac{C_{t-1}}{K}\right)$$

Where P_{t-1} and C_{t-1} denote exploitable biomass (as a proportion of carrying capacity K) and catch respectively, for year *t-1*. Carrying capacity, K, is the level of stock biomass at equilibrium prior to commencement of a fishery, r is the intrinsic rate of population growth.

The process errors η_t are drawn independently from a Normal distribution centered on 0 with a random residual variation σ^η as follow:

$Eq.\ 3 \quad \eta_t|\sigma^{\eta} \sim Normal(0, \sigma^{\eta})$

The estimated biomass P_t is related to each survey index as follow:

$Eq.\ 4a\ I_t^{Ca\_E} = Log(q^{Ca\_E} \cdot P_t) + \varepsilon^{Ca\_E}$ and $Eq.\ 5a \quad \varepsilon^{Ca\_E}|\sigma^{Ca\_E} \sim Normal(0, \sigma^{Ca\_E})$
$Eq.\ 4b\ I_t^{Ca\_s} = Log(q^{Ca\_s} \cdot P_t) + \varepsilon^{Ca\_s}$ and $Eq.\ 5b \quad \varepsilon^{Ca\_s}|\sigma^{Ca\_s} \sim Normal(0, \sigma^{Ca\_s})$
$Eq.\ 4c\ I_t^{Ca\_f} = Log(q^{Ca\_f} \cdot P_t) + \varepsilon^{Ca\_f}$ and $Eq.\ 5c \quad \varepsilon^{Ca\_f}|\sigma^{Ca\_f} \sim Normal(0, \sigma^{Ca\_f})$
$Eq.\ 4d\ I_t^{EU} = Log(q^{EU} \cdot P_t) + \varepsilon^{EU}$ and $Eq.\ 5d \quad \varepsilon^{EU}|\sigma^{EU} \sim Normal(0, \sigma^{EU})$

Where q are the catchabilities associated with each survey index and ε the associated observation error.

c. Bayesian inference

Weakly informative and independent prior probability distributions were assigned to model parameters (Table 2) to make sure the posterior inferences primarily reflect the information brought by the observed data. The joint posterior distribution of all the model variables was approximated using MCMC sampling (Gelman et al. 2003). All computations were carried out with the OpenBUGS software (version 3.2.1; Thomas et al. 2006; Spiegelhalter et al. 2007) and R (version 2.14.0, www.r-project.com).

The Gelman–Rubin (Brooks and Gelman 1998) diagnostic was used as implemented by OpenBUGS. This diagnostic indicated that good mixing of the MCMC chains was obtained after 5×10^5 iterations. One in every 50 iterations was retained to obtain a sample of 10,000 values. The first 5000 were discarded to remove the influence of the MCMC starting values. The 5000 values left were then used to approximate posterior distributions of all the model unknowns.

d. Posterior checking

Posterior checking was carried out by means of checking the posterior distributions of all variables estimated and looking for systematic structure of residuals. Additionally the influence of expert based priors (for r and K , Table 2) was examined.

2. Management procedures

Using the fitted model parameter estimates for the OM, simulations were carried out for 20 years (2011-2030) with a number of candidate survey based feedback harvest control rules (as well as one constant TAC rule for comparison). Note that in our simulations we assume that all the TAC is taken and no more. This could be modified and we could modify the model so the number of fish caught is the TAC with a certain error (implementation error).

i. *Cst*: Constant TAC (value fixed as the average catch during the last 5 years in the real fishery)
ii. *AvgI*: Modification of the TAC according to the perceived status of the stock from research surveys (20% decrease of the TAC if at least one of the 3 surveys for a given year is less than the 5 year running average of surveys, 10% increase of the TAC if all the surveys for a given year are above the 5 year running average of surveys)

iii. *SlpI*: Modification of the TAC according to the perceived status of the stock from research surveys with the following rule:

$$TAC_{y+1} = TAC_y \times (1 + \lambda \times slope)$$

Where $slope$ is the unweighted average slope of log-linear regressions fit to the last five years of the Canadian fall and spring and European survey (mean weight per tow) and λ a tuning parameter which allows reducing or increasing the annual TAC variation. In this study λ was set at 1.

iv. *SlpIcap*: is the same rule as iii but a cap is incorporated so the TAC can't vary by more than 5% from one year to another.

The performance statistics chosen to assess the management procedure are:

- Annual average variation in catch (AAV)

$$AAV_t = 100 \times \frac{\sum_{i=t'}^{t} \left|1 - \frac{L_i}{L_{i-1}}\right|}{t - (t' - 1)}$$

  Where L_i is the landings in year t and $t'$is the first year when the catch was determined by the management strategy (2012)
- Total catch after 10 and 20 years of a given management strategy
- Annual probability of being above BMSY
- Annual probability of being above Blim (30% of BMSY)
- Bratio, the annual ratio of biomass to BMSY (when Bratio is greater than one, the MSY will be produced).

<u>Results</u>

1. Historical analysis

The parameters of the model are estimated with various levels of uncertainty (see Table 2). Overall parameters are estimated with reasonable coefficients of variation (CVs). The observation error for the Engels trawl surveys σ^{Ca_E} is fairly uncertain (CV = 0.71) but these surveys are not carried out anymore and are therefore not used in the management procedures. The intrinsic growth r rate is on average 0.16 with a carrying capacity K of 880 thousand tons. Both seem reasonable for this stock given what is known about its biology and historic biomass. The process error is estimated at around 0.13 while the observation errors for the various surveys range from 0.10 to 0.47 (the highest being found for the EU Spain surveys).

Over the time-series, the total biomass has been on an overall declining trend due to overfishing. There is large uncertainty in the earliest part of the series due to the lack of surveys. As survey data becomes more available in the late 1980s the uncertainty reduces. In the last decade, there has been a slow and small increase in B (difficult to visualize because of the scale). Following the moratorium in 1995, the total catch declined substantially leading to a reduction of the fishing mortality from about 0.3 to 0.03. F then peaked around 0.23 (in 2003) and is now around 0.05.

The probability of being above BMSY started decreasing in the mid 60's, at the beginning of the 70's, the probability of B > BMSY was already under 0.5. For the last 20 years this probability has been null. This translates in a slowly declining Bratio over the years to reach a current value of around 0.05. The probability of being above Blim was high (> 0.9) until the beginning of the 90's when it dropped severely within a few years to reach probabilities close to 0.

2. MSEs : True vs Perceived

For each management procedure it is possible to compare the "true" population in the simulation to the population as it is perceived by the 3 type surveys ($I_t^{Ca\_s}$, $I_t^{Ca\_f}$, I_t^{EU}). For illustrative purpose 6 typical "true" vs. perceived population simulations outputs are represented in Fig. 5. There is no systematic trend as a result of a given survey always over- or under-estimating the "true" population. However, the EU surveys are more prone to larger displacement from the "true" population which can potentially impact the management procedure.

For each management procedure, a summary figure displaying the total biomass and some of the performance statistics was produced (Fig. 6 to 9). In all scenarios, the total biomass slowly increases over the 20 years of the simulation. The probabilities of reaching BMSY or Blim increase accordingly (Table 3). All management procedures provided similar probabilities of being above Blim after 10 or 20 years with *AvgI* having the highest probabilities after 20 years (a bit more than 80%), *cst* and *Slpcap* having probabilities around 70% and *SplI* generated the lowest probability (just above 60%). In all scenarios, the probability of being above BMSY after 10 years was very low (about 1%). After 20 years this probability increased to 18% for *SlpIcap* and around 25 % for *cst* and *AvgI* while this probability remained low for *SlpI* (8%). In order to compare the different strategies, the evolution of the probabilities of being above Blim (30% of BMSY) were plotted on the same graph (Fig. 10). Similar performance was obtained regarding the probability of being above BMSY except with probability much smaller in the short term: the probability of being above BMSY after 10 years for all management procedures is around 1%. After 20 years, *AvgI* had 30% chances to be above BMSY and *SlpI* only 8%.

Regarding the catches (Table 4 and Fig. 11), the *AvgI* management procedure provides the highest annual average variation (9.65 % on average) and also the smallest cumulated catch after 10 and 20 years.the SlpI and SlpIcap management procedures have lower AAVs (6.17% and 2.68% respectively) and much higher cumulated catches after 10 and 20 years. The *cst* management procedure obviously has a null AAV and shows cumulated catches a bit smaller than the *SlpIcap* management procedure.

Discussion

In this study, we implement a MSE where a Bayesian version of the Schaefer surplus production model (Morgan, 2012) is used as an operating model and the parameter estimations of this model, accounting for both process and observation errors, are used to run simulations within a MSE framework. Four preliminary candidate management procedures are implemented and their results are compared and discussed with regards to the performance statistics. Due to the nature of the model, and the value of the growth rate r and carrying capacity K estimated from the historical data as well as the level of catch simulated in the four different management procedures, the stock's biomass invariably increases over time. However all scenarios do not allow for the same speed of recovery. The management procedure *AvgI* leads to higher probabilities of reaching Blim or BMSY after 10 or 20 years but the cost for this is smaller and more variable catches over the time period of the simulation. Management procedures *cst* and *SlpIcap* have lower probabilities of reaching Blim and BMSY but higher cumulated catches. Finally, the management procedure *SlpI* has significantly smaller probabilities of being above the reference points Blim and BMSY by allowing higher cumulated catches. The next step regarding these management procedures will be to discuss with the different partners (i.e. managers, the public and industry) to define the actual objectives for this stock. It is anticipated that this can be carried out under the auspices of the new NAFO SC-FC WG on risk-based strategies in the near future.

Additionally to the work that has already been carried out, we are hoping to add another performance statistics: during the simulation process, there were some cases during which the TAC (and therefore the number of fish caught) could be higher than the population biomass. If this was to occur in the reality this would mean the collapse of the stock. In our simulations, when such a situation occurred the total biomass of the population was reduced to very low level (10^{-7}). After such an event the population remains at a low level as seen in the top panels of Fig. 5. One of the improvements that can be made to this study will be to track the number of occurrences of these situations (which can be seen as a stock depletion) as another performance statistics of a given management procedure.

In the future, we are hoping to use/build different OMs. A potential option is a Bayesian age-structured operating model for 3LNO American plaice similar to the ones developed in Millar and Meyer (2000) and Rivot et al. (2004). While this will provide a more realistic view of the population and allow using an additional large available dataset (age/length measurements, maturity estimates), it will also allow developing other types management procedures (i.e. scenarios involving age selectivity) and performance statistics (e.g. spawning-stock biomass).

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Table 1: Summary of the data available and used in the Bayesian surplus production model.

years	C_t	$I_t^{Ca\_f}$	$I_t^{Ca\_s}$	I_t^{EU}	$I_t^{Ca\_E}$
1960	21.373	NA	NA	NA	NA
1961	16.373	NA	NA	NA	NA
1962	16.192	NA	NA	NA	NA
1963	25.719	NA	NA	NA	NA
1964	38.567	NA	NA	NA	NA
1965	53.261	NA	NA	NA	NA
1966	65.011	NA	NA	NA	NA
1967	94.413	NA	NA	NA	NA
1968	73.167	NA	NA	NA	NA
1969	79.437	NA	NA	NA	NA
1970	66.653	NA	NA	NA	NA
1971	67.888	NA	NA	NA	NA
1972	59.361	NA	NA	NA	NA
1973	52.843	NA	NA	NA	NA
1974	46.297	NA	NA	NA	NA
1975	43.221	NA	NA	NA	196.5
1976	51.825	NA	NA	NA	274.6
1977	43.981	NA	NA	NA	395.0
1978	50.028	NA	NA	NA	330.6
1979	48.569	NA	NA	NA	336.5
1980	49.086	NA	NA	NA	352.9
1981	50.158	NA	NA	NA	368.6
1982	50.337	NA	NA	NA	324.3
1983	37.720	NA	NA	NA	NA
1984	36.063	NA	NA	NA	209.8
1985	54.212	NA	762.8	NA	NA
1986	64.570	NA	657.4	NA	NA
1987	55.012	NA	783.7	NA	NA
1988	40.835	NA	713.7	NA	NA
1989	43.369	NA	632.7	NA	NA
1990	32.501	641.0	476.7	NA	NA
1991	34.681	469.0	267.5	NA	NA
1992	13.350	299.0	136.0	NA	NA
1993	17.122	293.0	146.9	NA	NA
1994	7.378	154.0	83.5	NA	NA
1995	0.637	152.1	60.0	NA	NA
1996	0.913	153.6	106.1	NA	NA
1997	1.401	162.3	92.4	21.8	NA
1998	1.618	187.9	103.0	64.6	NA

1999	2.565	190.0	192.3	110.0	NA
2000	5.176	268.2	154.7	153.0	NA
2001	5.739	201.5	192.7	101.1	NA
2002	4.870	249.2	129.6	69.5	NA
2003	8.727	222.6	159.2	116.8	NA
2004	6.158	NA	142.9	129.4	NA
2005	4.110	223.4	214.7	123.2	NA
2006	2.828	232.9	NA	170.9	NA
2007	3.606	241.9	231.1	112.1	NA
2008	2.515	333.4	234.1	172.7	NA
2009	3.015	254.3	123.1	93.0	NA
2010	2.898	281.6	150.1	NA	NA

Table 2: Parameters summary (prior and posterior distributions) for the Bayesian surplus production model.

			Posterior							
parameter	description	Prior	mean	sd	CV	2.5th	25th	median	75th	97.5th
r	Intrinsic growth rate	$LogNormal(-3.81, 0.262)$	0.159	0.0519	0.38	0.0358	0.129	0.163	0.193	0.253
K	Carrying capacity	$LogNormal(6.80, 1.24)$	999.2	425.8	0.43	485.5	741.4	878.0	1119.0	2308.0
P^{init}	Average relative population abundance for the first year of the time series	$Uniform(10^{-4}, 1.5)$	0.870	0.368	0.42	0.206	0.572	0.879	1.182	1.465
σ^{η}	process error	$Uniform(0,10)$	0.128	0.058	0.45	0.020	0.086	0.129	0.170	0.243
q^{Ca_E}	Catchability for $I_t^{Ca\_E}$	$Uniform(0,10)$	0.945	0.260	0.27	0.454	0.773	0.9316	1.095	1.501
q^{Ca_s}	Catchability for $I_t^{Ca\_s}$	$Uniform(0,10)$	4.228	0.895	0.21	2.100	3.719	4.290	4.828	5.795
q^{Ca_f}	Catchability for $I_t^{Ca\_f}$	$Uniform(0,10)$	6.729	1.421	0.21	3.338	5.924	6.835	7.704	9.184
q^{EU}	Catchability for I_t^{EU}	$Uniform(0,10)$	2.992	0.7806	0.26	1.435	2.5	2.976	3.467	4.553
σ^{Ca_E}	Observation error for $I_t^{Ca\_E}$	$Uniform(10^{-4}, 10)$	0.182	0.130	0.710	0.0084	0.0812	0.165	0.257	0.482
σ^{Ca_s}	Observation error for $I_t^{Ca\_s}$	$Uniform(10^{-4}, 10)$	0.249	0.0441	0.18	0.176	0.218	0.245	0.274	0.349
σ^{Ca_f}	Observation error for $I_t^{Ca\_f}$	$Uniform(10^{-4}, 10)$	0.107	0.0321	0.300	0.0516	0.0863	0.104	0.125	0.181
σ^{EU}	Observation error for I_t^{EU}	$Uniform(10^{-4}, 10)$	0.491	0.120	0.240	0.316	0.406	0.470	0.554	0.779

Table 3: Evolution of the probability of being above BMSY and Blim for the 4 different management procedures tested.

	Probability of being above BMSY				**Probability of being above Blim**			
Year	*cst*	*AvgI*	*SlpI*	*SlpIcap*	*cst*	*AvgI*	*SlpI*	*SlpIcap*
2011	0.0000	0.0000	0.0000	0.0000	0.0074	0.0094	0.0094	0.0094
2012	0.0000	0.0000	0.0000	0.0000	0.0124	0.0146	0.0146	0.0146
2013	0.0000	0.0000	0.0000	0.0000	0.0208	0.0238	0.0226	0.0226
2014	0.0002	0.0000	0.0000	0.0000	0.0376	0.0444	0.0404	0.0410
2015	0.0006	0.0002	0.0002	0.0002	0.0542	0.0668	0.0590	0.0620
2016	0.0010	0.0004	0.0004	0.0004	0.0874	0.1024	0.0788	0.0888
2017	0.0014	0.0020	0.0012	0.0018	0.1306	0.1510	0.1092	0.1238
2018	0.0034	0.0038	0.0022	0.0030	0.1832	0.2244	0.1446	0.1744
2019	0.0052	0.0068	0.0036	0.0058	0.2582	0.3128	0.1914	0.2384
2020	0.0110	0.0112	0.0064	0.0100	0.3210	0.3896	0.2428	0.3038
2021	0.0168	0.0178	0.0092	0.0156	0.3900	0.4634	0.2950	0.3606
2022	0.0240	0.0260	0.0138	0.0208	0.4478	0.5282	0.3476	0.4174
2023	0.0360	0.0394	0.0176	0.0288	0.5056	0.5836	0.3890	0.4646
2024	0.0516	0.0588	0.0234	0.0406	0.5484	0.6338	0.4342	0.5114
2025	0.0672	0.0792	0.0288	0.0562	0.5876	0.6808	0.4710	0.5498
2026	0.0920	0.1102	0.0376	0.0736	0.6208	0.7224	0.5012	0.5852
2027	0.1188	0.1424	0.0486	0.0948	0.6496	0.7544	0.5340	0.6156
2028	0.1490	0.1932	0.0562	0.1212	0.6818	0.7762	0.5622	0.6476
2029	0.1882	0.2482	0.0678	0.1436	0.7038	0.7994	0.5902	0.6726
2030	0.2418	0.3006	0.0792	0.1832	0.7252	0.8222	0.6124	0.6970

Table 4: summary statistics of the performance measures (AAV, total catch after 10 years and 20 years) for the 4 management procedures tested in this study.

AAV	mean	sd	2.5th	25th	Median	75th	97.5th
cst	0	0	0	0	0	0	0
AvgI	9.71	0.95	7.93	8.96	9.65	10.34	11.72
SlpI	6.17	1.7	3.34	4.98	5.99	7.16	10.07
SlpIcap	2.68	0.25	2.12	2.53	2.72	2.87	3.09
Total catch after 10 years	mean	sd	2.5th	25th	Median	75th	97.5th
cst	29.72	29.72	29.72	29.72	29.72	29.72	29.72
AvgI	20.97	5.62	13.26	16.70	20.15	24.29	34.48
SlpI	39.12	10.55	20.96	32.09	38.43	45.05	61.68
SlpIcap	32.36	3.17	25.12	30.43	32.66	34.80	37.31
Total catch after 20 years	mean	sd	2.5th	25th	Median	75th	97.5th
cst	59.44	59.44	59.44	59.44	59.44	59.44	59.44
AvgI	32.15	12.63	15.64	22.79	29.69	38.630	64.00
SlpI	122.43	58.88	34.97	81.75	115.55	153.97	261.14
SlpIcap	75.66	13.27	46.13	66.99	77.60	86.03	95.94

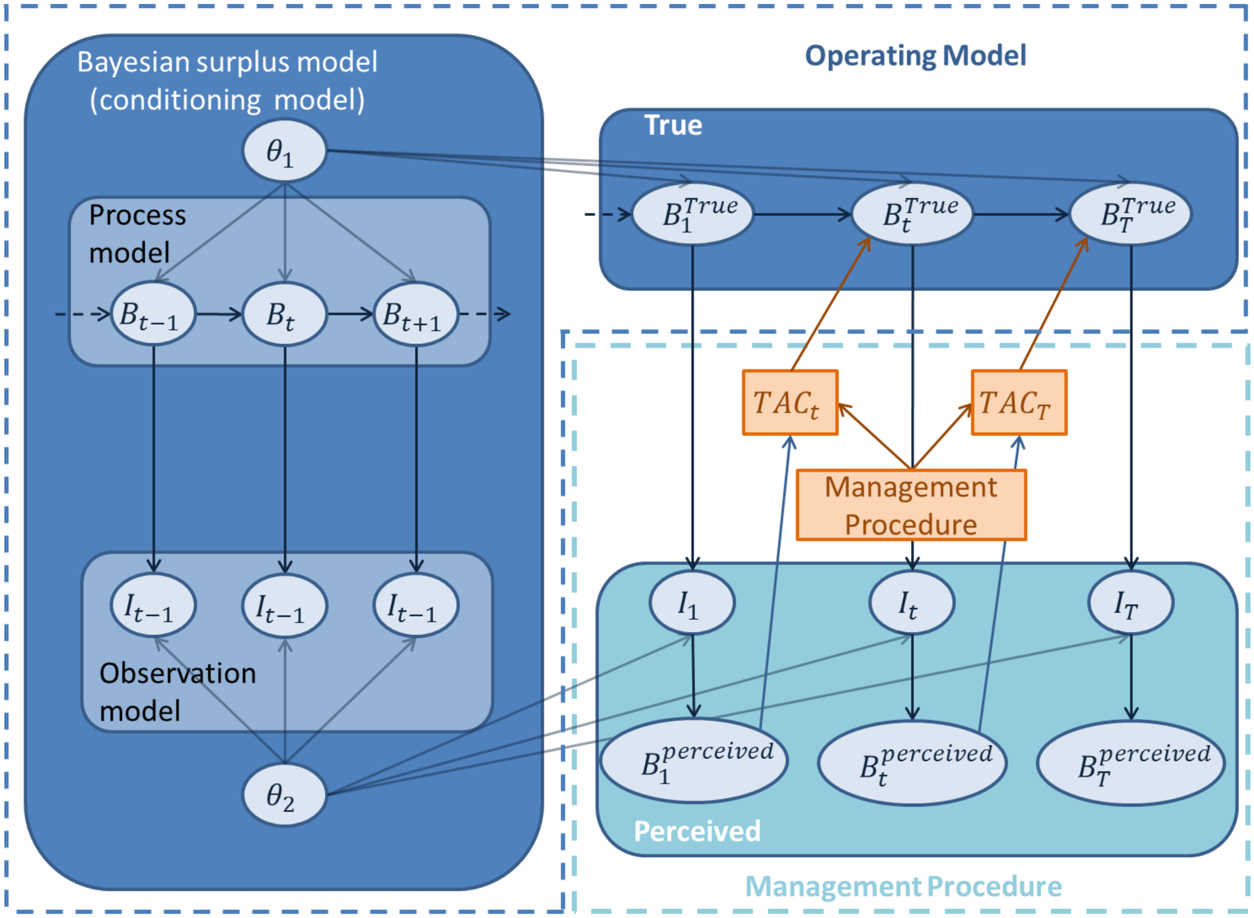

Figure 1: Conceptual framework for Management strategy evaluations. In this preliminary study, the Schaefer (symmetrical) form of a Bayesian surplus model is the only OM tested. Parameters of the process model (including the process error) and the observation models (including the observation error) are estimated using historical datasets (catches and surveys). The parameters from the process model are used to simulate/forecast a “true” population. Using the observation model parameters, a perceived population is generated from the true population. This management procedure applied to this perceived population determine the TAC that will be applied to the “true” population the following year.

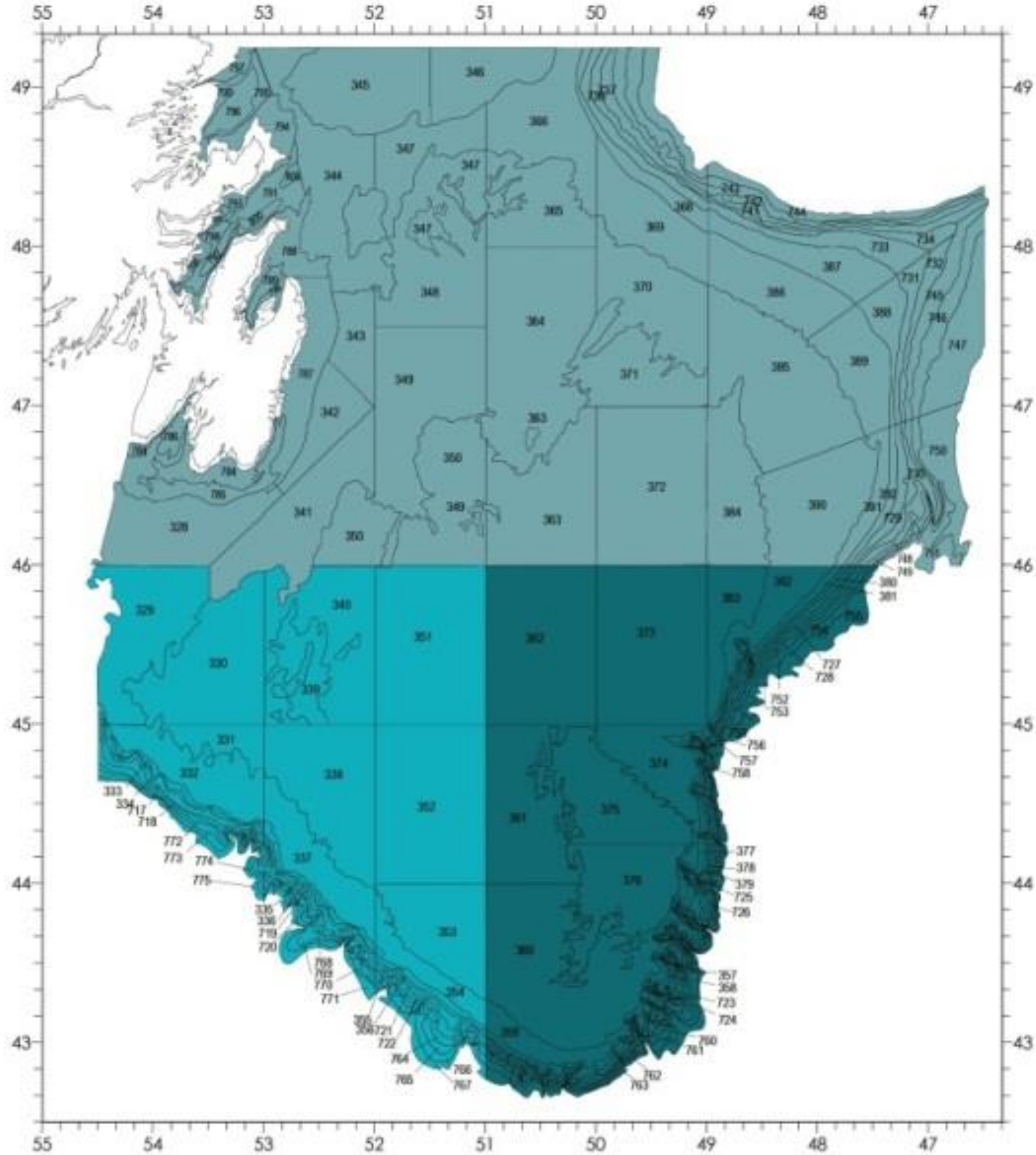

Figure 2: Grand Bank area and 3LNO NAFO Divisions.

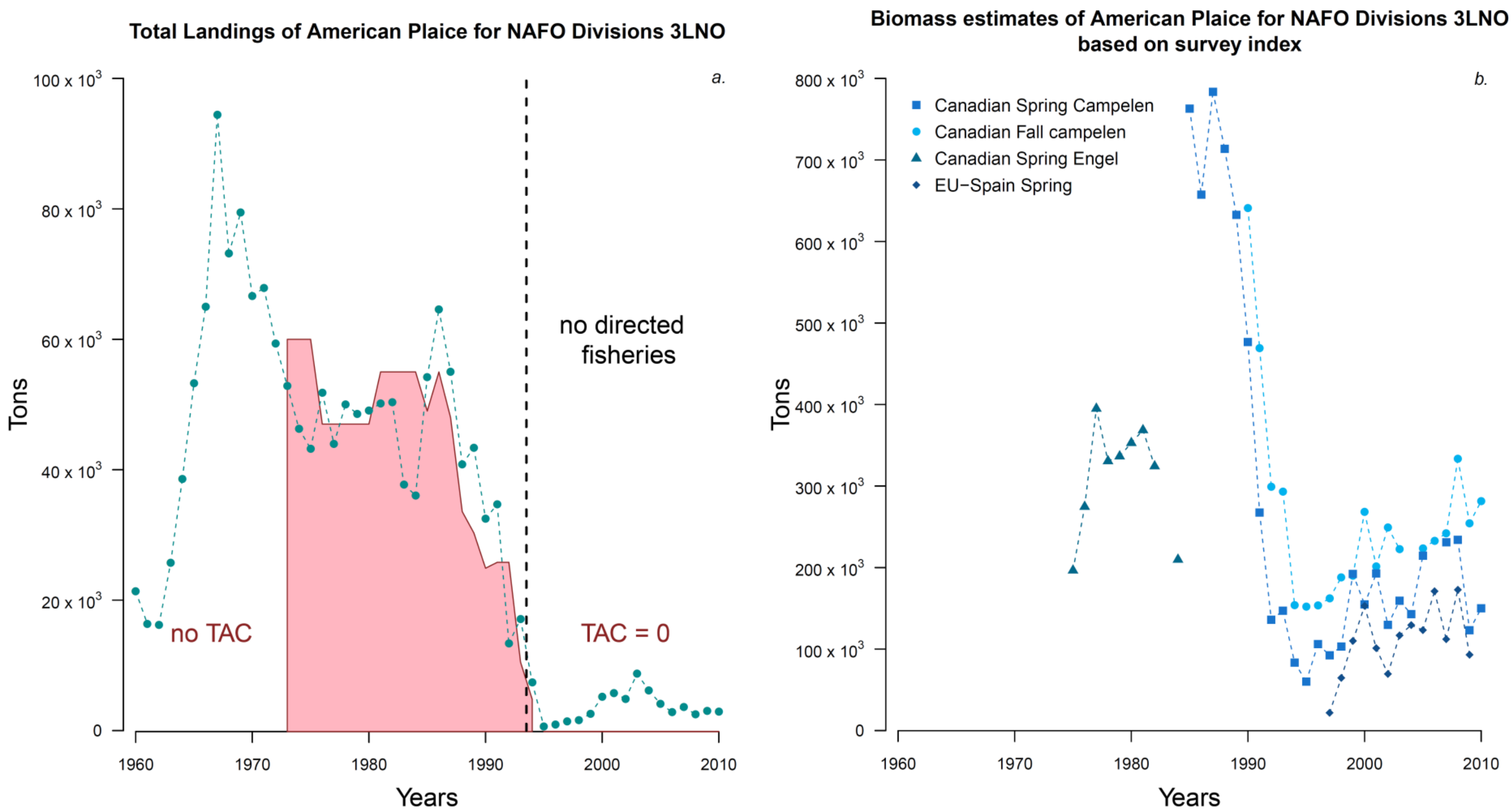

Figure 3: Data available regarding 3LNO American plaice stock: *a*) green dots indicate annual landings, pink area represents the annual Total Allowable Catch (TAC), *b*) Biomass indices based on various annual bottom trawl

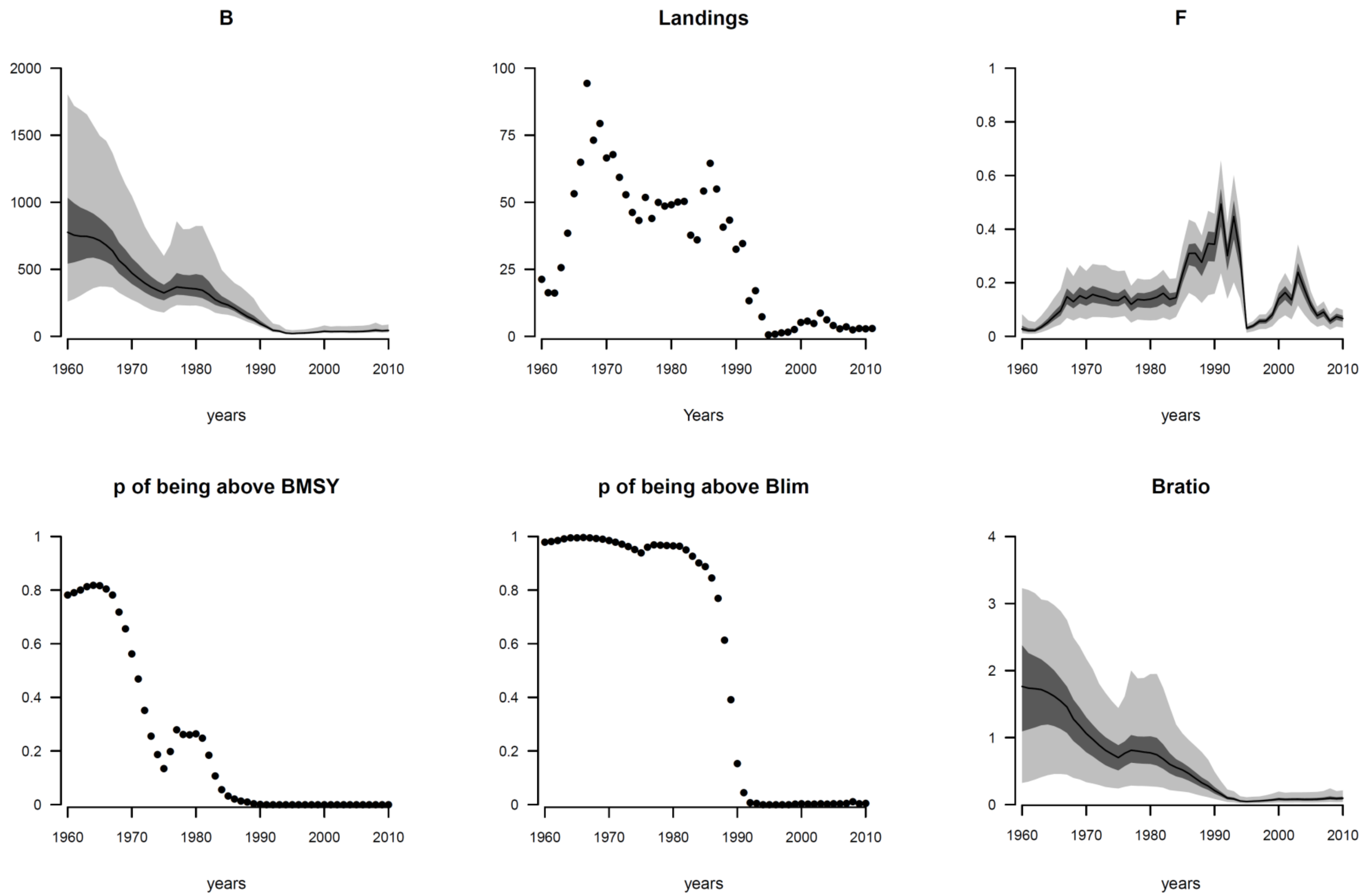

Figure 4: From left to right and top to bottom: total Biomass estimates (‘000s tons), landings, F, annual probability of being above BMSY, annual probability of being above Blim and Bratio. Light shade of grey indicates the 2.5th and 97.5th percentiles range, dark shade of grey indicates 25th and 75th percentiles range and the black line indicates the median.

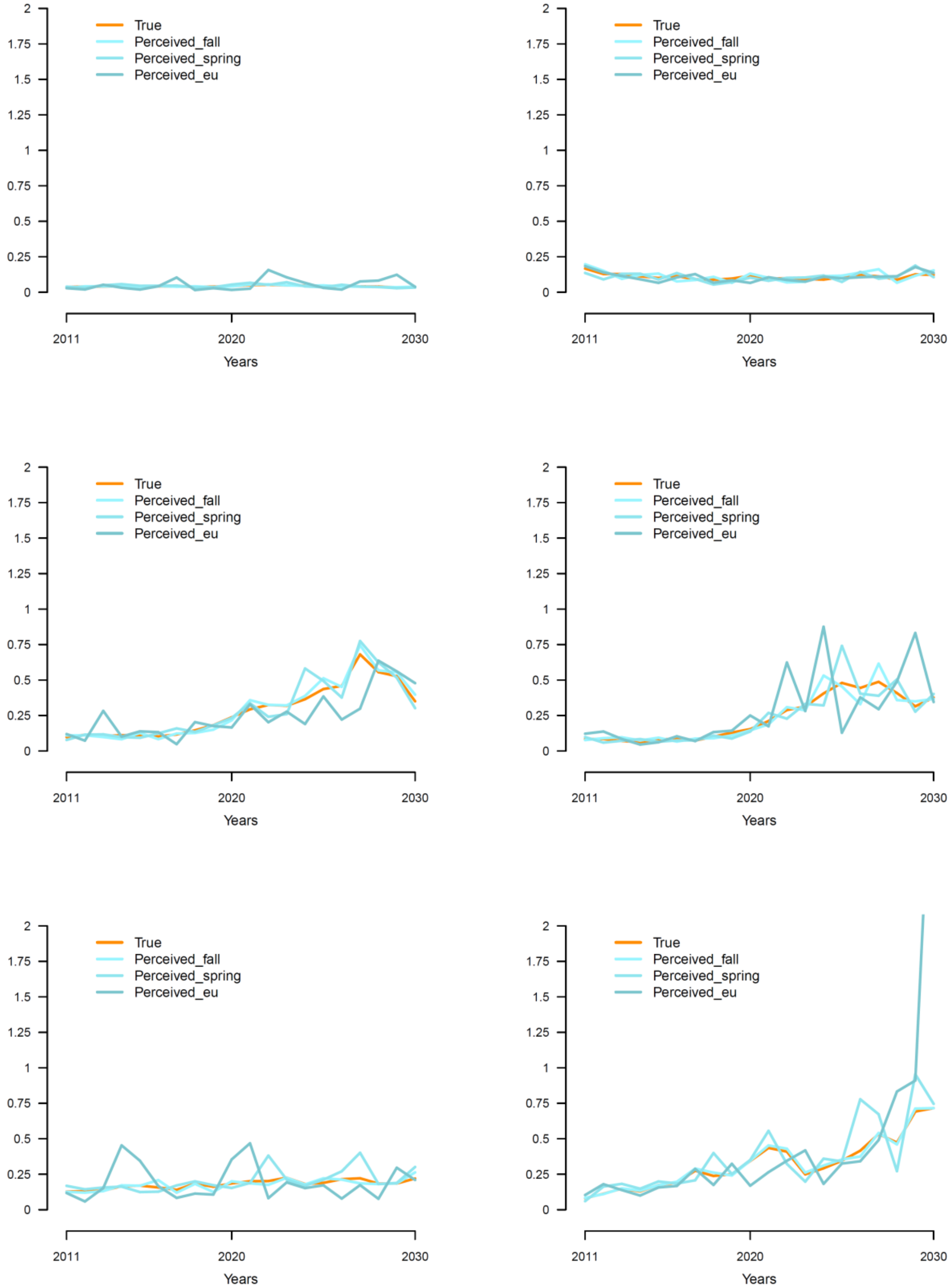

Figure 5: 6 examples of single MCMC chains representing the evolution of the "true" population and the population as perceived by the 3 types of surveys for the *cst* management procedure in relative abundance (B / K).

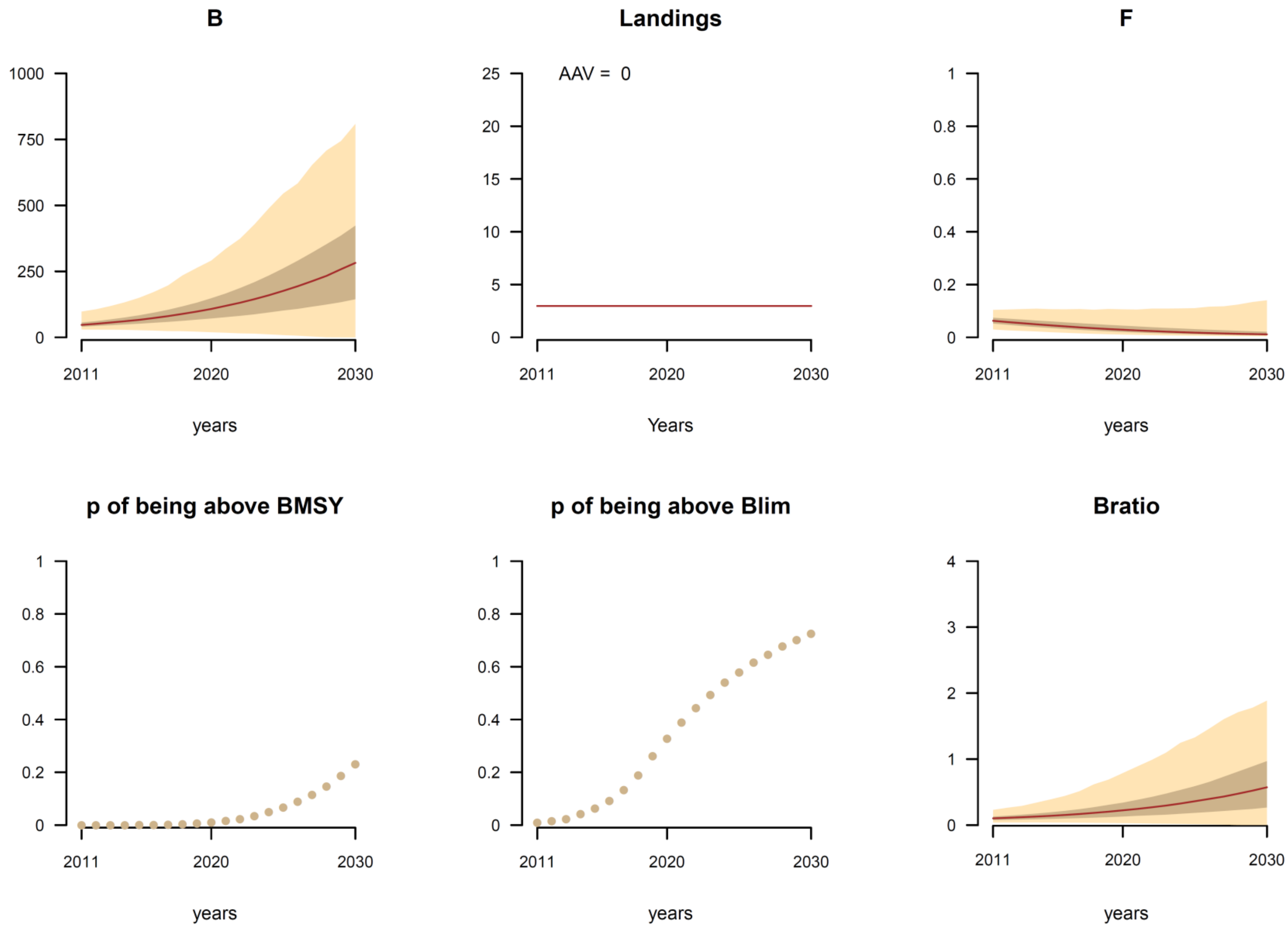

Figure 6: From left to right and top to bottom: total Biomass estimates, landings, F, annual probability of being above BMSY, annual probability of being above Blim and Bratio under *cst* management procedure. Light shade of brown indicates the 2.5th and 97.5th percentiles range, dark shade of brown indicates 25th and 75th percentiles range and the dark brown line indicates the median.

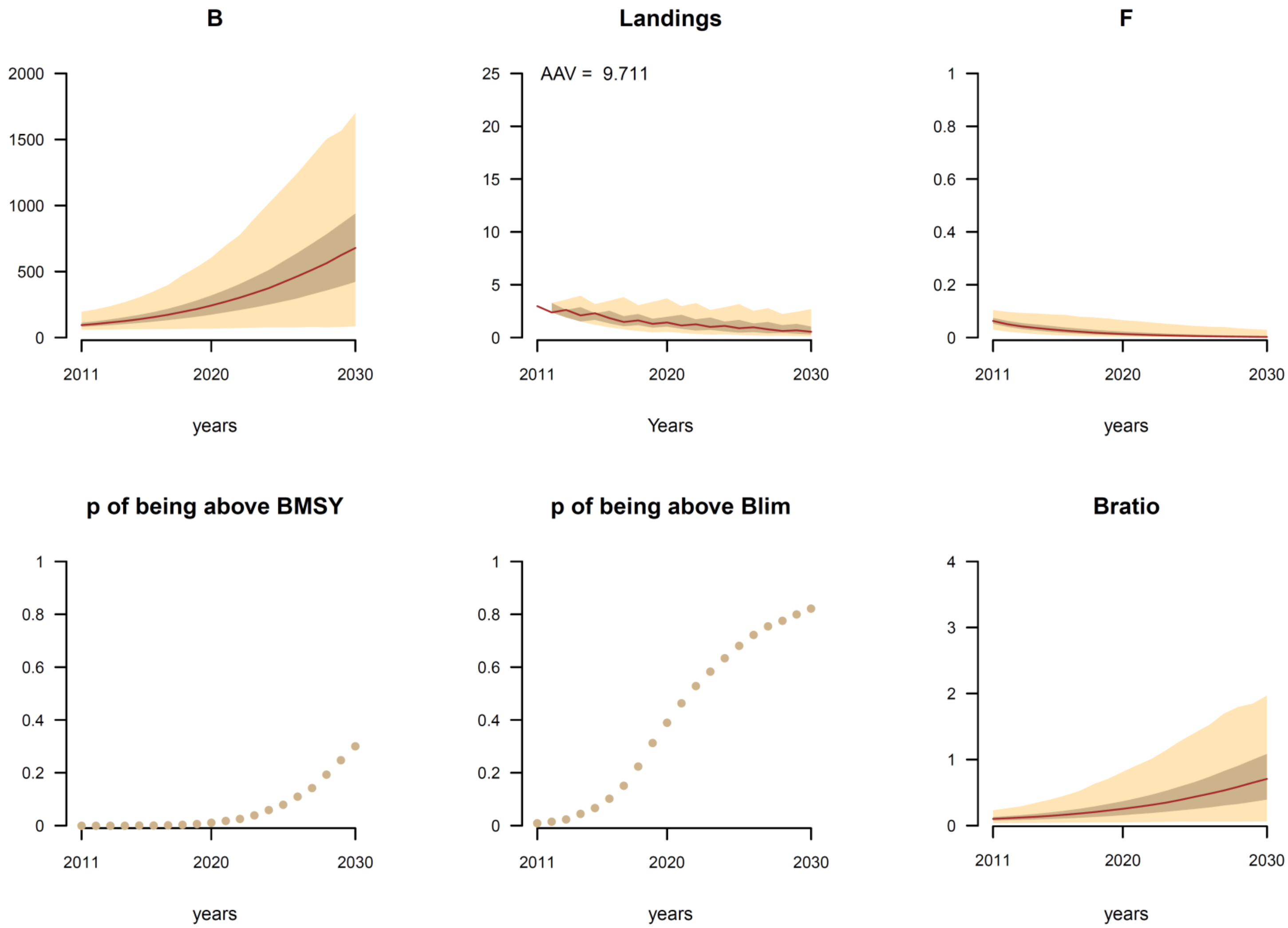

Figure 7: From left to right and top to bottom: total Biomass estimates, landings, F, annual probability of being at BMSY, annual probability of being at Blim and Bratio under *AvgI* management procedure. Light shade of brown indicates the 2.5th and 97.5th percentiles range, dark shade of brown indicates 25th and 75th percentiles range and the dark brown line indicates the median.

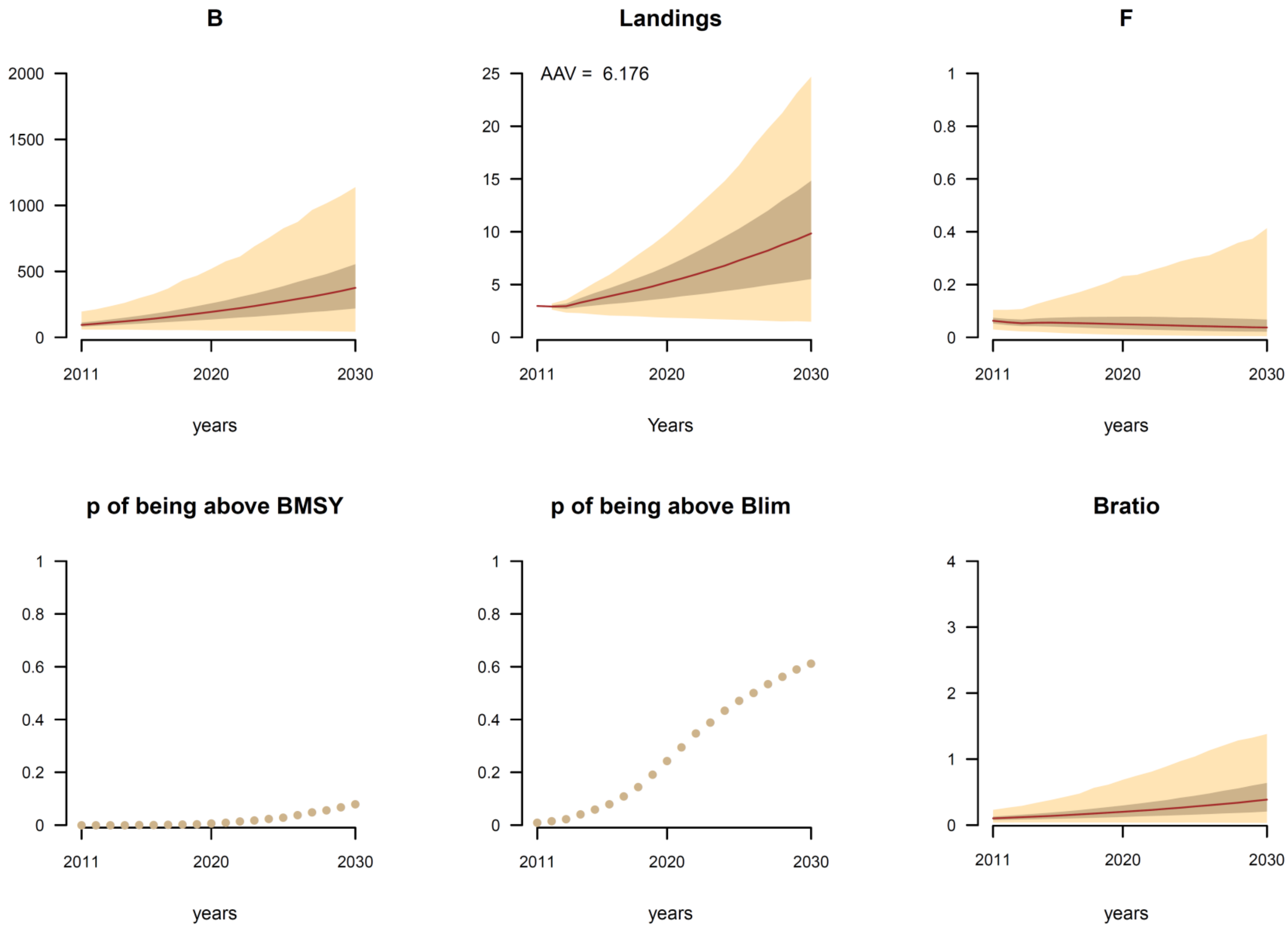

Figure 8: From left to right and top to bottom: total Biomass estimates, landings, F, annual probability of being above BMSY, annual probability of being above Blim and Bratio under *SlpI* management procedure. Light shade of brown indicates the 2.5th and 97.5th percentiles range, dark shade of brown indicates 25th and 75th percentiles range and the dark brown line indicates the median.

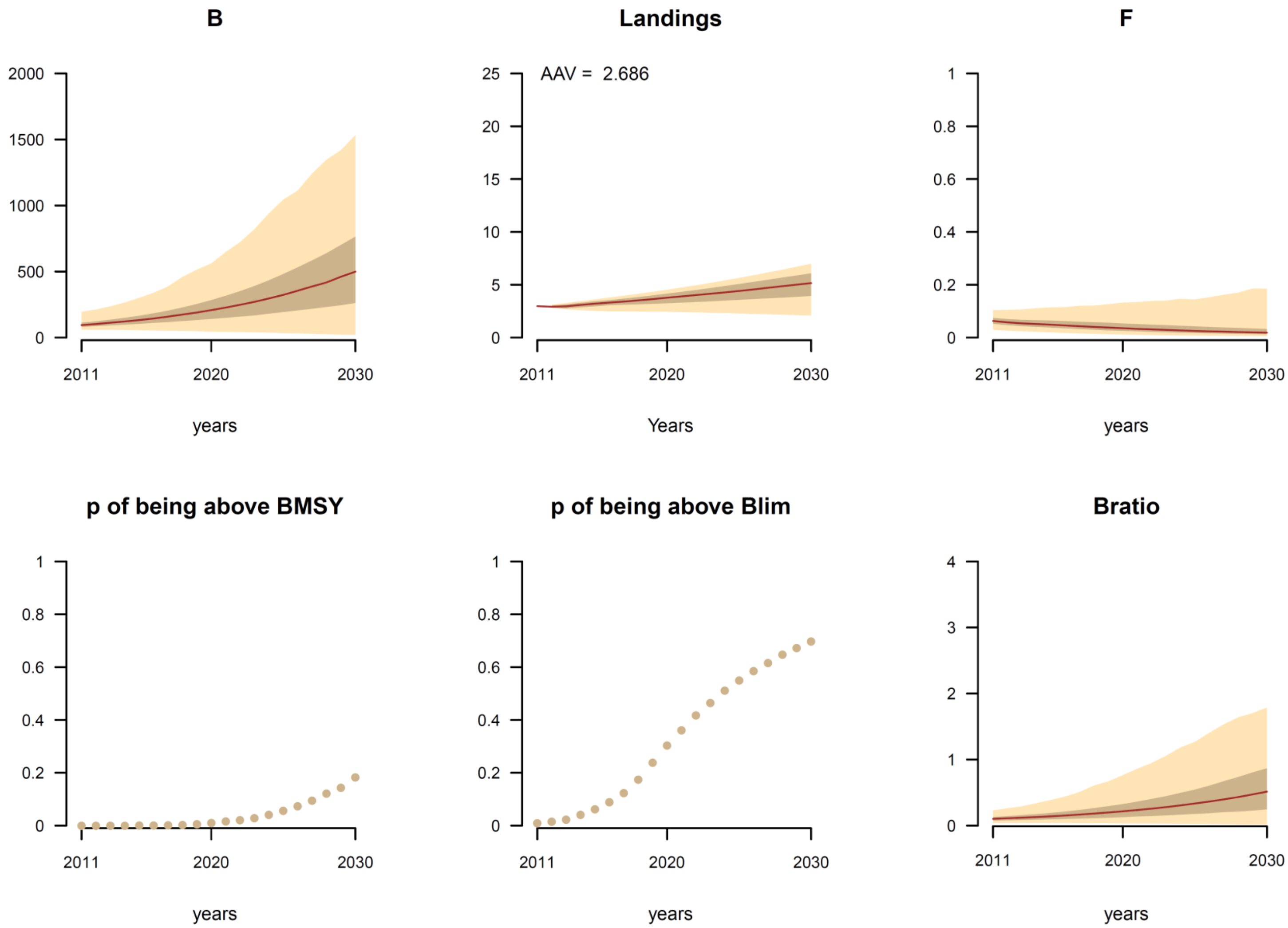

Figure 9: From left to right and top to bottom: total Biomass estimates, landings, F, annual probability of being above BMSY, annual probability of being above Blim and Bratio under *SlpIcap* management procedure. Light shade of brown indicates the 2.5th and 97.5th percentiles range, dark shade of brown indicates 25th and 75th percentiles range and the dark brown line indicates the median.

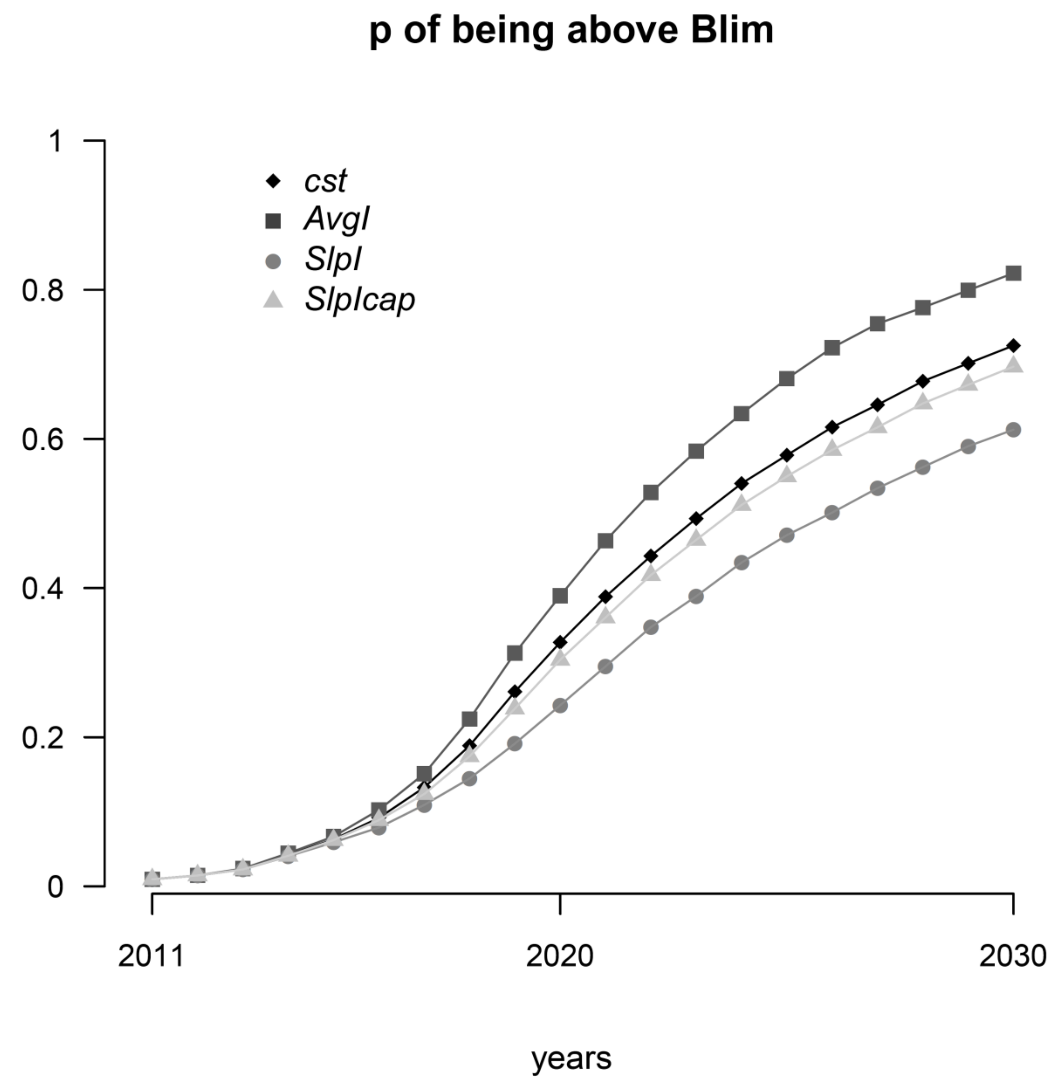

Figure 10: Evolution of the probability of being at Blim over the 20 years forecast under the 4 HCR tested: *cst*, *AvgI*, *SlpI* and *SlpIcap*.

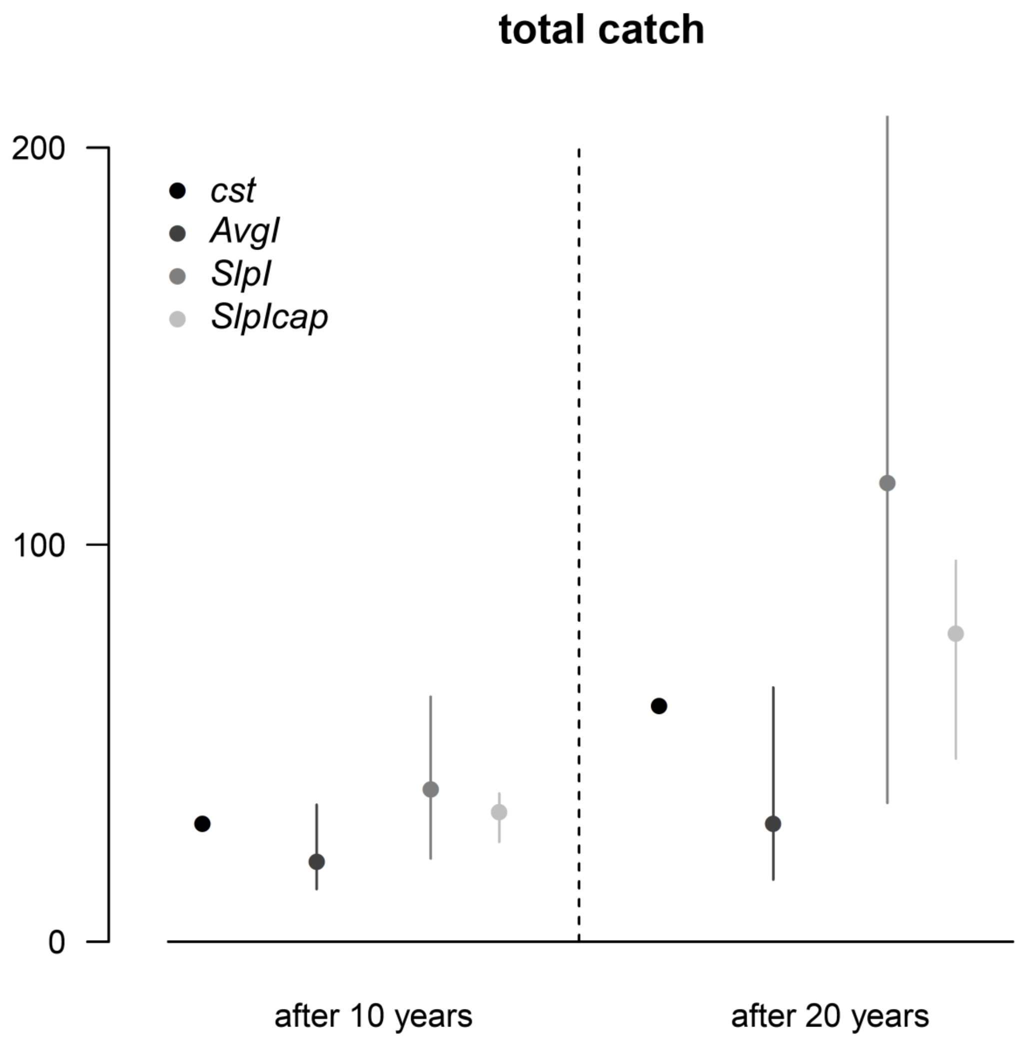

Figure 11: Cumulated catch after 10 and 20 years under under the 4 HCR tested: *cst*, *AvgI*, *SlpI* and *SlpIcap*.