Northwest Atlantic Fisheries Organization

Serial No. N6336 **NAFO SCR Doc. 14/040**

SCIENTIFIC COUNCIL MEETING – JUNE 2014

Operating Models for Management Strategy Evaluations of Div. 3LN Redfish

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INTRODUCTION

The NAFO Joint Working Group on Risk-Based Management Strategies which met 5-7 February 2014 in Halifax, Nova Scotia, Canada identified the development of a risk-based management strategy for 3LN redfish as a priority (NAFO FC/SC Doc. 14/02). The following request had been made by FC to SC to be addressed in June 2014:

The Fisheries Commission requests the Scientific Council to explore models that could be used to conduct a Management Strategy Evaluation for Div. 3LN redfish and report back through the Working Group on Risk- Based Management Strategies during their next meeting.

The 3LN Redfish stock is subject to a recently re-opened fishery and the response of the stock to fishing at higher levels is uncertain at this stage. The latest assessment for 3LN redfish carried out in 2014 current assessment by NAFO SC (NAFO SCS Doc. 14/17) concludes that the biomass is above B_{MSY} and the F is well below F_{MSY}.

SC was been asked by the Joint WG to evaluate a simple step-wise TAC increase strategy. This strategy is intended to initially focus on the short to medium term. A review evaluation would be recommended at the end of the 7 year period. The Joint WG has also specified objectives and performance statistics to be applied in the MSE.

The objectives are to:

- Maintain the stock at or above B_{MSY},
- Achieve a TAC of 20 000t within 7 years and,
- Maintain a TAC at or above 20 000t for subsequent years.

The rationale for 20 000t is that it represents the approximate average catch for the period 1965-1985 – a prolonged period of relative stability in the TAC/resource which may represent a period of MSY-like conditions. The current average fish size in the stock and fishery is small because of good recruitment and a slow increase in the TAC should continue to promote survival and growth. This should result in an increased SSB.

The performance statistics are as follow:

- Low (30%) probability of exceeding F_{MSY} in any year
- Very low (10%) probability of declining below B_{Lim} in the next 7 years
- Less than 50% probability of declining below 80% B_{MSY} in the next 7 years

The Harvest Control Rule proposed by the FC-SC commission (stepwise HCR) is to increase the TAC in constant increments starting in 2015 – i.e. TAC y+1= TAC y + 1,900t to a maximum of 20 000 tons. Three additional HCRs were also tested:

- Stepwise slow HCR: similar to HCR 1 but increments every second year to a maximum of 18 100 tons (Ávila de Melo et al., 2014)
- Constant TAC HCR: Constant TAC (20 000 tons)
- Constant F HCR: Constant F (2/3 F_{MSY})

The following sections describe 6 Operating Models (OMs) used to test management strategies on the redfish stock of NAFO Division 3LN.

OPERATING MODELS

1st Operating model: 2012 ASPIC approved assessment model updated with 2013 data (ASPIC-2012-UPDATED)

1. Background

A non-equilibrium (dynamic) surplus production model (ASPIC; Prager, 1994) was accepted for the assessment of the status of the stock in 2012 (NAFO SC, 2012) based on the formulation adopted on the "The 2nd Take of the 2008 Assessment of Redfish in NAFO Divisions 3LN," reported in Ávila de Melo and Alpoim, (2010). This model has been updated to include 2012 and 2013 catch and survey data. This OM is subsequently referred to as ASPIC-2012-UPDATED

2. Data used

The ASPIC-2012-UPDATED input series are summarized below (Ávila de Melo et al., 2012):x

- STATLANT catches(1959-2013) and CPUE(1959-1994)
- Spring survey on Div. 3LN combined (1991-2005,2007-2013)
- Autumn survey on Div. 3N (1991, 1993-2010,2012-2013)
- Autumn survey on Div 3L (1985-1986, 1990-1994, 1996-2009-2011-2013)
- Russian survey on Div. 3LN combined (1984-1991)
- Winter survey in Div. 3L (1985-1986,1990)
- Summer surveys in Div. 3L (1978-1979,1981,1984-1985,1990-1991,1993)

These data are to some extent spatially explicit since surveys carried out in one of the Divisions are related to the total biomass of redfish in 3LN.

In this assessment, some data points considered as outliers are removed from the dataset in order for the ASPIC model to converge (see above for summary of the data used, Avila de Melo et al., 2012). These years are assumed to have higher values because of one or two large redfish hauls which are not representative of the average density in the stratum. In the 2012 assessment, the Spanish spring survey in Div. 3N was tentatively incorporated in the stock assessment but it was decided not to keep these data in the model at that time (Ávila de Melo and Alpoim, 2012).

3. Modelling framework:

The ASPIC package (http://nft.nefsc.noaa.gov/ASPIC.html) was used to fit the logistic form of a surplus production model (Schaefer, 1954) relying on the minimization of an objective function (see Prager, 1994 for detailed description of the algorithm).

ASPIC constrains catchabilities according to the initial values. The minimum value of q (q^{min}) is the initial value (q^{init}) divided by 100. If q^{init} is higher or equal to 0.5 the maximum value of catchability must be be smaller than $6 \times q^{init}$. If q^{init} is between 0.1 and 0.5, the catchability is bounded to be smaller than 1.2. If q^{init} is smaller than 0.1 then the catchability is bounded to be smaller than 0.5.

Table 1: Summary of the initial values and minimum and maximum boundaries for all catchabilities in the ASPIC framework

Catchabilities	q^{init}	q^{min}	q^{max}
q^{CPUE}	9.007×10^{-6}	9.007×10^{-8}	0.5
q^{3LN_sp}	6.58×10^{-1}	6.58×10^{-3}	3.948
q^{3N_aut}	7.59×10^{-1}	7.59×10^{-3}	4.554
q^{3LN_rus}	6.58×10^{-1}	6.58×10^{-3}	3.948
q^{3L_win}	3.22×10^{-1}	3.22×10^{-3}	1.2
q^{3L_sum}	2.75×10^{-1}	2.75×10^{-3}	1.2
q^{3L_aut}	2.75×10^{-1}	2.75×10^{-3}	1.2

Additionally ASPIC allows the user to constrain some of the other parameters. In the 2012 assessment, MSY is bounded between 5×10^3 and 5×10^4, K is bounded between 10^5 and 10^6 and F maximum value is 6 (Ávila de Melo and Alpoim 2012).

2nd Operating model: ASPIC 2014 approved assessment model (ASPIC-2014)

1. Background

The 2012 version of the ASPIC has difficulty in fitting the observed data from the second half of the 2000s onwards for all the ongoing surveys. The approved 2012 assessment excluded the entire Spanish survey series and several recent survey data points were omitted which show large inter annual biomass jumps in both the spring and autumn Canadian surveys, either for Div. 3LN (spring) or Div. 3L and N separately (autumn) (Ávila de Melo et al, 2012). In 2014, a new application of ASPIC attempting to deal with these issues was agreed upon. This OM is subsequently referred to as ASPIC-2014.

2. Data used) and CPUE(1959-1994)

The 2014 input series are summarized below (Ávila de Melo et al., 2014):

- STATLANT catches(1959-2013)) and CPUE(1959-1994)
- Spring survey on Div. 3LN combined (1991-2005,2007-2013)
- Autumn survey on Div. 3LN (1993-2013)
- Autumn survey on Div 3L (1985-1986, 1990)
- Russian survey on Div. 3LN combined (1984-1991)
- Winter survey in Div. 3L (1985-1986,1990)
- Summer surveys in Div. 3L (1978-1979,1981,1984-1985,1990-1991,1993)
- Spanish surveys in Div. 3N (1995-2013)

3. Modelling framework:

The ASPIC package (http://nft.nefsc.noaa.gov/ASPIC.html)was used to fit the logistic form of a surplus production model (Schaefer, 1954) relying on the minimization of an objective function (see Prager, 1994 for detailed description of the algorithm). A major change was introduced by fixing MSY at 21 000 tons whereas in previous assessments of this stock it had been treated as an estimable parameter (Ávila de Melo et al. 2014).

3rd operating model: ASPIC-like model in a Bayesian framework (ASPIC-BAYES-2012-UPDATED)

1. Background

The Bayesian framework is a very convenient approach for dealing with uncertainties and missing data in a consistent way and also has flexibility to construct and test various models. One of the key elements of this approach is that it considers all unknowns as probability distributions and is therefore very convenient when dealing with risk. This makes this approach a strong candidate for an operating model. This first Bayesian model is as similar as possible to the accepted 2012 assessment updated to 2014 (i.e. ASPIC-2012-UPDATED) and includes all the constraints applied in that model. This OM is subsequently referred to as ASPIC-BAYES-2012-UPDATED.

2. Data used

Same datasets as the ASPIC-2012-UPDATED.

3. Modelling Framework

The population biomass in 3LN is written as follows:

(Eq. 1) $$Log(P\_3LN_t) = \mu\_3LN_t + \eta_t$$

Where μ_3LN_t is the average relative abundance calculated as a surplus model with a Schaefer (1954) functional form:

(Eq. 2) $$\mu\_3LN_t = Log\left(P\_3LN_{t-1} + r \cdot P\_3LN_{t-1} \cdot (1 - P\_3LN_{t-1}) - \frac{C\_3LN_{t-1}}{K\_3LN}\right)$$

Where P_3LN_{t-1} and C_3LN_{t-1} denote exploitable biomass (as a proportion 3LN division's carrying capacity K_3LN) and catch respectively, for year t-1. Carrying capacity, K_3LN, is the level of stock biomass at equilibrium prior to commencement of the fishery (carrying capacity), r is the intrinsic rate of population growth and $MSY = \frac{r \times K\_3LN}{4}$.

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

(Eq. 3) $$\eta_t|\sigma^P \sim Normal(0, \sigma^P)$$

The estimated biomass P_3LN_t is related to the CPUE and various survey indices:

(Eq. 4a) $I\_CPUE_t = Log(q\_CPUE \cdot P\_3LN_t) + \varepsilon_t^{CPUE}$
(Eq. 4b) $I\_can\_spr\_3LN_t = Log(q\_can\_spr\_3LN \cdot P\_3LN_t) + \varepsilon_t^{Ca\_spr}$
(Eq. 4c) $I\_can\_aut\_3N_t = Log(q\_can\_aut\_3N \cdot P\_3LN_t) + \varepsilon_t^{Ca\_aut\_3N}$
(Eq. 4d) $I\_can\_aut\_3L_t = Log(q\_can\_aut\_3L \cdot P\_3LN_t) + \varepsilon_t^{Ca\_aut\_3L}$
(Eq. 4e) $I\_Rus\_3LN_t = Log(q\_Rus \cdot P\_3LN_t) + \varepsilon_t^{Rus}$
(Eq. 4f) $I\_can\_win\_3L_t = Log(q\_can\_win \cdot P\_3LN_t) + \varepsilon_t^{Ca\_win}$
(Eq. 4g) $I\_can\_sum\_3L_t = Log(q\_can\_sum\_3L \cdot P\_3LN_t) + \varepsilon_t^{Ca\_sum}$

Where q are the catchabilities associated with each survey index and ε the associated observation error for each surveys. The observation errors are drawn from a Normal distribution as follow:

(Eq. 5a) $\varepsilon_t^{CPUE} | \sigma^{CPUE} \sim Normal(0, \sigma^{CPUE})$
(Eq. 5b) $\varepsilon_t^{Ca\_spr} | \sigma^{Ca\_spr} \sim Normal(0, \sigma^{Ca\_spr})$
(Eq. 5c) $\varepsilon_t^{Ca\_aut\_3N} | \sigma^{Ca\_aut\_3N} \sim Normal(0, \sigma^{Ca\_aut\_3N})$
(Eq. 5d) $\varepsilon_t^{Ca\_aut\_3L} | \sigma^{Ca\_aut\_3L} \sim Normal(0, \sigma^{Ca\_aut\_3L})$
(Eq. 5e) $\varepsilon_t^{Rus} | \sigma^{Rus} \sim Normal(0, \sigma^{Rus})$
(Eq. 5f) $\varepsilon_t^{Ca\_win} | \sigma^{Ca\_win} \sim Normal(0, \sigma^{Ca\_win})$
(Eq. 5g) $\varepsilon_t^{Ca\_sum} | \sigma^{Ca\_sum} \sim Normal(0, \sigma^{Ca\_sum})$

All priors of the model's parameters can be found in Table 2, in ASPIC-BAYES-2012-UPDATED all priors are similar to the constraints fixed in ASPIC-2012-UPDATED.

Table 2: Prior distribution of the main parameters of the ASPIC-BAYES-2012-UPDATED model. I(a,b) after a distribution indicates a censorship on the left (a) or right (b) side of the distribution.

Parameters	Prior distribution
K_{3LN}	$LogNormal(11.52,1)I(10^5, 10^6)$
MSY	$LogNormal(10,0.001)I(5000,50000)$
σ^P	$Uniform(0,10)$
q_CPUE	$Uniform(9.007 \cdot 10^{-5}, 0.5)$
$q\_can\_spr\_3LN$	$Uniform(9.58 \cdot 10^{-3}, 3.948)$
$q\_can\_aut\_3N$	$Uniform(7.59 \cdot 10^{-3}, 4.554)$
$q\_can\_spr\_3N$	$Uniform(6.58 \cdot 10^{-3}, 3.948)$
q_rus	$Uniform(3.22 \cdot 10^{-3}, 1.2)$
q_can_win	$Uniform(2.75 \cdot 10^{-3}, 1.2)$
$q\_can\_sum\_3L$	$Uniform(2.75 \cdot 10^{-3}, 1.2)$
σ^{CPUE}	$Uniform(0,10)$
σ^{Ca_spr}	$Uniform(0,10)$
$\sigma^{Ca\_aut\_3N}$	$Uniform(0,10)$
$\sigma^{Ca\_aut\_3L}$	$Uniform(0,10)$
σ^{Rus}	$Uniform(0,10)$
σ^{Ca_win}	$Uniform(0,10)$
σ^{Ca_sum}	$Uniform(0,10)$

4th operating model: ASPIC-like model in a Bayesian framework, same parameterization than the new approved stock assessment (ASPIC-BAYES-2014

1. Background

For the fourth OM we implemented the accepted 2014 assessment in a Bayesian framework. This OM is subsequently referred to as ASPIC-BAYES-2014.

2. Data used

Same datasets as the ASPIC-2014.

3. Modelling Framework

Similar to ASPIC-BAYES-2012-UPDATED, except that MSY is fixed at 21 000 tons and the boundaries of K_{3LN} are extended to be: $K_{3LN} \sim LogNormal(11.52,1)I(10^5, 6 \cdot 10^6)$ (see table 3 for full changes, Ávila de Melo et al., 2014).

5th operating model: ASPIC-like model in a Bayesian framework with all available data (ASPIC-BAYES-FULL)

1. Background

In this OM, the full time-series of all surveys and catches indices available for 3LN redfish are used and the constraints the constraints applied on the various parameters of the model in the 4 precedent OMs are relaxed. This OM is subsequently referred to as ASPIC-BAYES-FULL.

2. Data used

- STATLANT catches(1959-2013) and CPUE(1959-1994)
- Spring survey in Div. 3LN combined (1991-2005,2007-2013)
- Autumn survey in Div. 3N (1991-2013)
- Autumn survey in Div 3L (1985-1986, 1990-2013)
- Russian survey in Div. 3LN combined (1984-1991)
- Winter survey in Div. 3L (1985-1986,1990)
- Summer surveys in Div. 3L (1978-1979,1981,1984-1985,1990-1991,1993)
- Spanish surveys in Div. 3N (1995-2013)
- Spanish surveys in Div. 3L (2006-2013)

3. Modelling Framework

Same equations as the ASPIC-BAYES-2012 OM with in addition the relationship between the Spanish surveys and the redfish Biomass in 3LN:

(Eq. 6) $$I\_Spa_t = Log(q\_spa \cdot P\_3LN_t) + \varepsilon_t^{Spa}$$

And the associated observation error:

(Eq. 7) $$\varepsilon_t^{Spa} | \sigma^{Spa} \sim Normal(0, \sigma^{Spa})$$

In the precedent Bayesian OMs, the priors were constrained in a similar fashion than their ASPIC equivalent. In the ASPIC-BAYES-FULL OM the prior distributions for the different parameters of the model have been loosened (see Table 3 for comparison) in order to let the data "speak for itself". Note that the prior for K was not modified since it already covered a reasonable range of values.

Table 3: Prior distribution of the main parameters of the ASPIC-BAYES-2012 and ASPIC-BAYES-FULL models. I(a,b) after a distribution indicates a censorship on the left (a) or right (b) side of the distribution, Lognormal(c,d) indicates a distribution with a mean c and precision d in log scale.

Parameters	Prior ASPIC-BAYES-2014	Prior ASPIC-BAYES-FULL
K_{3LN}	$LogNormal(11.52,1)I(100000,6000000)$	$LogNorma(11.52,1)I(100000,6000000)$
MSY	21000	$LogNormal(10,0.01)\ I(1000,)$
σ^P	$Uniform(0,10)$	$Uniform(0,10)$
$Log(q\_CPUE)$	$Log(Uniform(9.007 \cdot 10^{-5}, 0.5))$	$Uniform(-17,2.33)$
$Log(q\_can\_spr\_3LN)$	$Log(Uniform(6.58 \cdot 10^{-3}, 3.948))$	$Uniform(-6.9,2.33)$
$Log(q\_can\_aut\_3L)$	N/A	$Uniform(-6.9,2.33)$
$Log(q\_can\_aut\_3N)$	N/A	$Uniform(-6.9,2.33)$
$Log(q\_rus)$	$Log(Uniform(6.58 \cdot 10^{-3}, 3.948))$	$Uniform(-6.9,2.33)$
$Log(q\_can\_win)$	$Log(Uniform(3.22 \cdot 10^{-3}, 1.2))$	$Uniform(-6.9,2.33)$
$Log(q\_can\_sum\_3L)$	$Log(Uniform(2.75 \cdot 10^{-3}, 1.2))$	$Uniform(-6.9,2.33)$
$Log(q\_spa\_3L)$	N/A	$Uniform(-6.9,2.33)$
$Log(q\_spa\_3N)$	$Log(Uniform(2.75 \cdot 10^{-3}, 1.2))$	$Uniform(-6.9,2.33)$
σ^{CPUE}	$Uniform(0,10)$	$Uniform(0,10)$
σ^{Ca_spr}	$Uniform(0,10)$	$Uniform(0,10)$
$\sigma^{Ca\_aut\_3N}$	$Uniform(0,10)$	$Uniform(0,10)$
$\sigma^{Ca\_aut\_3L}$	$Uniform(0,10)$	$Uniform(0,10)$
σ^{Rus}	$Uniform(0,10)$	$Uniform(0,10)$
σ^{Ca_win}	$Uniform(0,10)$	$Uniform(0,10)$
σ^{Ca_sum}	$Uniform(0,10)$	$Uniform(0,10)$
σ^{spa_3L}	N/A	$Uniform(0,10)$
σ^{spa_3N}	N/A	$Uniform(0,10)$

6th operating model: Spatially disaggregated model (BAYES-SPATIAL)

1. Background

The different trawling sets for the surveys are done on a division basis. For some years and/or seasons the surveys are only carried out in one division. In order to include these data points without assuming different catchabilities, this operating model is structured to be consistent with the spatial structure in the data collection (i.e. look at Division 3L and 3N individually when the survey/catch data allows for it). This OM is subsequently referred to as BAYES-SPATIAL.

2. Data used

Same datasets as in ASPIC-BAYES-FULL but when possible splits survey and catch data for 3L and 3N. Raw CPUE data is not frequently proportional to abundance over the whole exploitation history of a population (Maunder and Punt, 2004) therefore it was decided to remove CPUE from this OM:

- Catches in 3L from 1959 to 2011 (STATLANT)
- Catches in 3N from 1959 to 2011 (STATLANT)
- Canadian surveys:
    - Spring 3L : 1980, 1985, 1991-2013
    - Spring 3N: 1991-2005, 2007-2013
    - Summer 3L: 1978-1979, 1981, 1984-1985, 1990-1991 and 1993
    - Summer 3N: 1991, 1993
    - Autumn 3L: 1985-1986, 1990-2013
    - Autumn 3N: 1991-2013
    - Winter 3L: 1985-1986 and 1990
- Spanish surveys:
    - Spring 3L:1995 to 2013
    - Spring 3N: 2006 to 2013
- Russian survey for 3LN combined from 1984 to 1991 (Power & Vaskov, 1992)

3. Modelling Framework

This model's equations are similar to the ones in ASPIC-BAYES-2012-UPDATED and ASPIC-BAYES-FULL. The main difference being that biomass for division 3L and 3N are estimated separately as follow:

(Eq. 8a) $Log(P\_3N_t) = \mu\_3N_t + \eta_t$

(Eq. 8b) $Log(P\_3L_t) = \mu\_3L_t + \eta_t$

Where μ_3L_t and μ_3N_t are the average relative abundance calculated as a surplus model with a Shaefer (1954) functional form:

(Eq. 9a) $\mu\_3N_t = Log\left(P\_3N_{t-1} + r \cdot P\_3N_{t-1} \cdot (1 - P\_3N_{t-1}) - \frac{C\_3N_{t-1}}{K\_3N}\right)$

(Eq. 9b) $\mu\_3L_t = Log\left(P\_3L_{t-1} + r \cdot P\_3LN_{t-1} \cdot (1 - P\_3L_{t-1}) - \frac{C\_3L_{t-1}}{K\_3L}\right)$

Where P_3L_{t-1}, P_3N_{t-1} and C_3L_{t-1}, C_3N_{t-1} denote exploitable biomass (as a proportion of each division's carrying capacity K_3L and K_3N) and catch respectively, for year *t*-1. Carrying capacity, K_3L and K_3N, are the level of stock biomass at equilibrium prior to commencement of the fishery, r is the intrinsic rate of population growth and is assumed to be the same in 3L and 3N.

We assume the variability in the biological process are similar in the two divisions occupied by the population. Therefore the process errors η_t are shared for both divisions drawn independently from a Normal distribution centered on 0 with a random residual variation σ^P as follow:

(Eq. 10) $\eta_t|\sigma^P \sim Normal(0, \sigma^P)$

The total population abundance for 3LN is calculated as follow

(Eq. 11) $P\_3LN_t = P\_3L_t + P\_3N_t$

The estimated biomass P_3L_t and P_3N_t are related to various survey index:

For 3L Division:

(Eq. 12a) $I\_can\_spr\_3L_t = Log(q\_can\_spr\_3L \cdot P\_3L_t) + \varepsilon_t^{Ca\_spr}$
(Eq. 12b) $I\_can\_sum\_3L_t = Log(q\_can\_sum\_3L \cdot P\_3L_t) + \varepsilon_t^{Ca\_sum}$
(Eq. 12c) $I\_can\_aut\_3L_t = Log(q\_can\_aut\_3L \cdot P\_3L_t) + \varepsilon_t^{Ca\_aut}$
(Eq. 12d) $I\_can\_win\_3L_t = Log(q\_can\_win \cdot P\_3L_t) + \varepsilon_t^{Ca\_win}$
(Eq. 13e) $I\_spa\_3L_t = Log(q\_spa \cdot P\_3L_t) + \varepsilon_t^{Spa}$

For 3N Division:

(Eq. 13a) $I\_can\_spr\_3N_t = Log(q\_can\_spr\_3N \cdot P\_3N_t) + \varepsilon_t^{Ca\_spr}$
(Eq. 13b) $I\_can\_sum\_3N_t = Log(q\_can\_sum\_3N \cdot P\_3N_t) + \varepsilon_t^{Ca\_sum}$
(Eq. 13c) $I\_can\_aut\_3N_t = Log(q\_can\_aut\_3N \cdot P\_3N_t) + \varepsilon_t^{Ca\_aut}$
(Eq. 13d) $I\_spa\_3N_t = Log(q\_spa \cdot P\_3N_t) + \varepsilon_t^{Spa}$

For 3LN Div. combined:

(Eq. 14) $I\_Rus\_3LN_t = Log(q\_Rus \cdot P\_3LN_t) + \varepsilon_t^{Rus}$

Where q are the catchabilities associated with each survey index (catchabilities are assumed to be different over 3L and 3N for a survey taking place at the same time) and ε the associated observation error. It is assumed that there are no differences in the observation process for the same survey carried out in 3L or 3N (e.g. the observation error for $I\_can\_sum\_3L$ and $I\_can\_sum\_3N$ are the same). The observation errors are drawn from a Normal distribution as follow:

(Eq. 15a) $\varepsilon_t^{Ca\_spr}|\sigma^{Ca\_spr}{\sim}Normal(0,\sigma^{Ca\_spr})$
(Eq. 15b) $\varepsilon_t^{Ca\_sum}|\sigma^{Ca\_sum}{\sim}Normal(0,\sigma^{Ca\_sum})$
(Eq. 15c) $\varepsilon_t^{Ca\_aut}|\sigma^{Ca\_aut}{\sim}Normal(0,\sigma^{Ca\_aut})$
(Eq. 15d) $\varepsilon_t^{Ca\_win}|\sigma^{Ca\_win}{\sim}Normal(0,\sigma^{Ca\_win})$
(Eq. 15e) $\varepsilon_t^{Spa}|\sigma^{Spa}{\sim}Normal(0,\sigma^{Spa})$
(Eq. 15f) $\varepsilon_t^{Rus}|\sigma^{Rus}{\sim}Normal(0,\sigma^{Rus})$

All priors of the model's parameters can be found in Table 4. Note that the model was slightly re-parameterised and a prior was attributed to r instead of MSY for better convergence purposes ($MSY = r \times (K\_3L + K\_3N)/4$)

Equations 8-15 can be represented graphically in a Directed Acyclic Graph (DAG, Fig. 1) to visualise the model's structure.

Table 4: Prior distribution of the main parameters of the model BAYES-SPATIAL. I(a,b) after a distribution indicates a censorship on the left (a) or right (b) side of the distribution.

Parameters	Prior distribution
r	$Gamma(0.01{,}0.01)I(0.001{,}2)$
K_3L	$LogNormal(11{,}0.01)I(,10^6)$
K_3N	$LogNormal(11{,}0.01)I(,10^6)$
σ^P	$Uniform(10^{-3},10)$
$q\_can\_spr\_3L$	$Uniform(0{,}10)$
$q\_can\_sum\_3L$	$Uniform(0{,}10)$
$q\_can\_aut\_3L$	$Uniform(0{,}10)$
$q\_can\_spr\_3N$	$Uniform(0{,}10)$
$q\_can\_sum\_3N$	$Uniform(0{,}10)$
$q_can_aut_$3N	$Uniform(0{,}10)$
q_can_win	$Uniform(0{,}10)$
q_spa	$Uniform(0{,}10)$
q_rus	$Uniform(0{,}10)$
σ^{Ca_spr}	$Uniform(10^{-3},10)$
σ^{Ca_sum}	$Uniform(10^{-3},10)$
σ^{Ca_aut}	$Uniform(10^{-3},10)$
σ^{Ca_win}	$Uniform(10^{-3},10)$
σ^{Spa}	$Uniform(10^{-3},10)$
σ^{Rus}	$Uniform(10^{-3},10)$

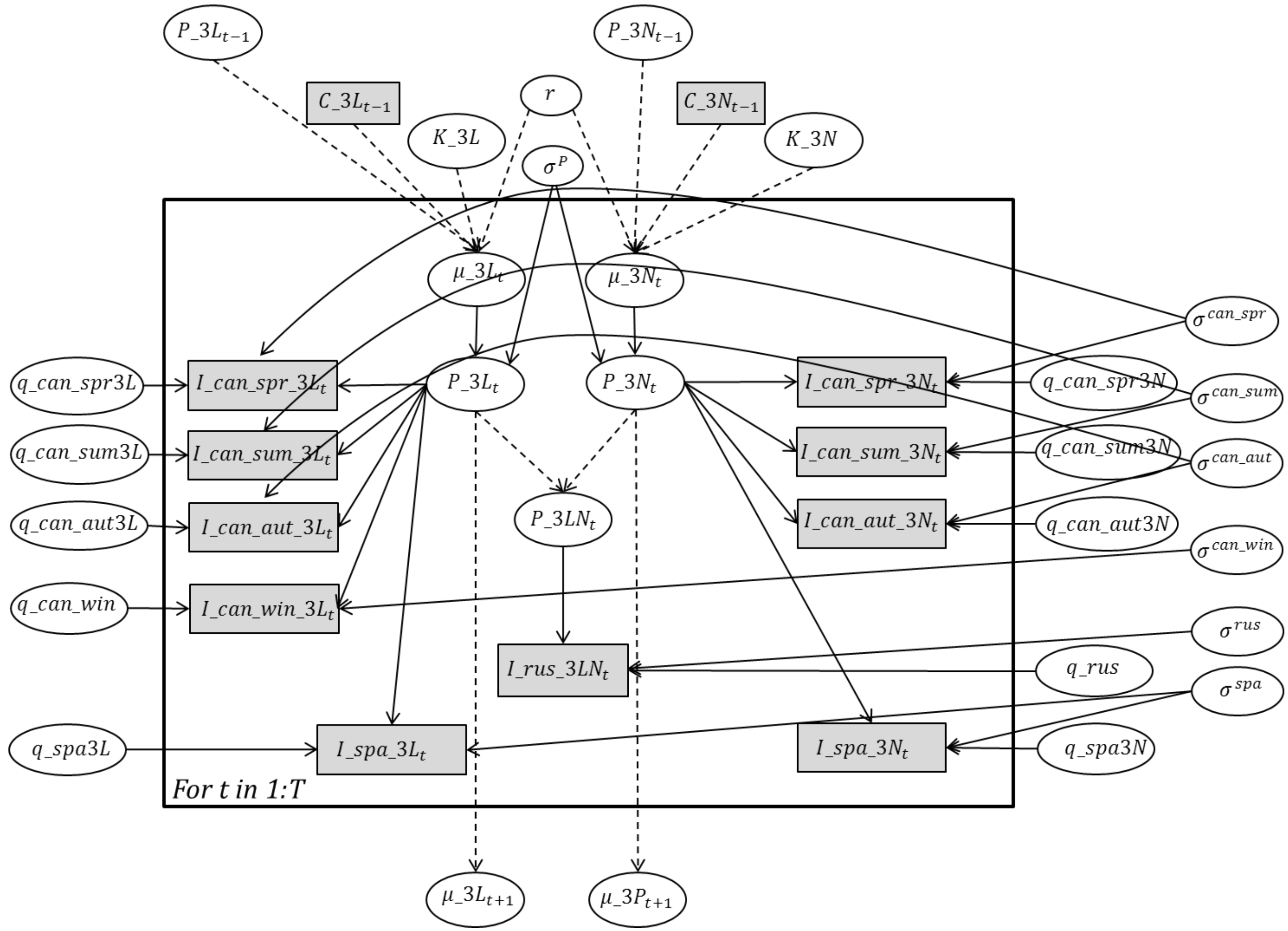


Figure 1: Directed Acyclic Graph (DAG) of the BAYES-SPATIAL model. Squares represent fixed quantities. All observed quantities are greyed. Arrows represent the parent-child dependencies between the different nodes: single arrows represent probabilistic relationship between the parent(s) and child nodes, dashed arrows indicate deterministic relationship. The frame represents a repetition of structure over years. Nodes outside the frame are unknown parameters constant across years.

Data summary

The different data set used in the 6 OMs are summarized in Table 5.

Table 5: Summary of the data set used in the 6 OMs used in this study. A cell filled with colour indicates that the data set was used in the model. Green indicates that the whole time series was used, orange indicates that some outliers were removed. Lighter shades of colour indicate that the dataset is related to one of the two NAFO division, darker shades of colour indicate that the dataset is related to the two NAFO divisions together.

		ASPIC-2012-UPDATED	ASPIC-BAYES-2012-UPDATED	ASPIC-2014	ASPIC-BAYES-2014	ASPIC BAYES FULL	BAYES-SPATIAL
Statlant Catches	3LN						
	3L						
	3N						
CPUE	3LN						
Canadian spring	3LN						
	3L						
	3N						
Canadian summer	3LN						
	3L						
	3N						
Canadian autumn	3LN						
	3L						
	3N						
Canadian winter	3L						
Russian	3LN						
Spanish	3N						

RESULTS

1. ASPIC-2012-UPDATED & ASPIC-2014

In this section the ASPIC 2012 and ASPIC 2014 outputs are compared. The estimation of the different parameters (Fig. 3 and Fig. 4) of the ASPIC 2012 and ASPIC 2014 OMs are very similar. While the data sets used are not exactly the same (see Table 5), an important difference is that MSY is fixed at 21 000 tons in the ASPIC 2014 OM. As a consequence, K and B_{MSY} show a much smaller uncertainty in the ASPIC 2014 OM (Fig. 3).

The evolution of the total biomass abundance and B_{ratio} are represented in figures 5 and 6. The ASPIC 2012 generates lower values in the older part of the time series and higher values in the recent part of the time series

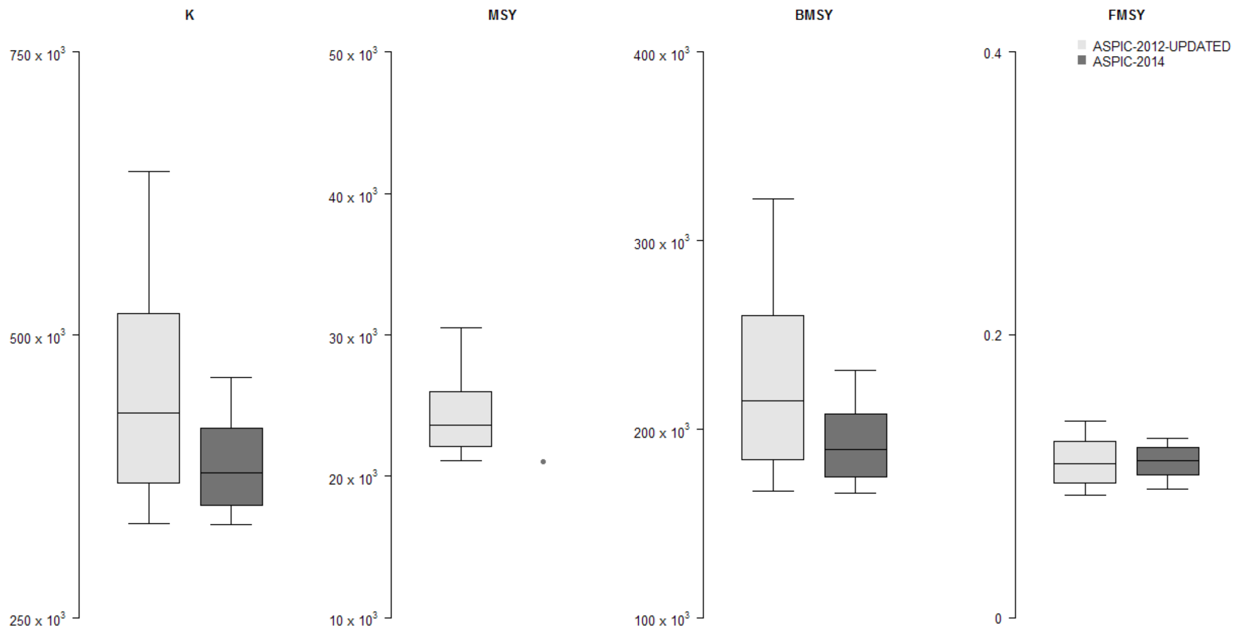


Figure 3. Estimation of different population parameters of the ASPIC-2012-UPDATED and ASPIC-2014 surplus production model: *K*, *MSY*, B_{MSY} and F_{MSY}. Light grey indicates the ASPIC-2012-UPDATED estimates and dark grey indicates the ASPIC-2014 estimates. Boxes represent the 50% lower and upper confidence intervals and the line in the middle, the median of the bootstraps, the whiskers indicate the 80% lower and upper confidence intervals.

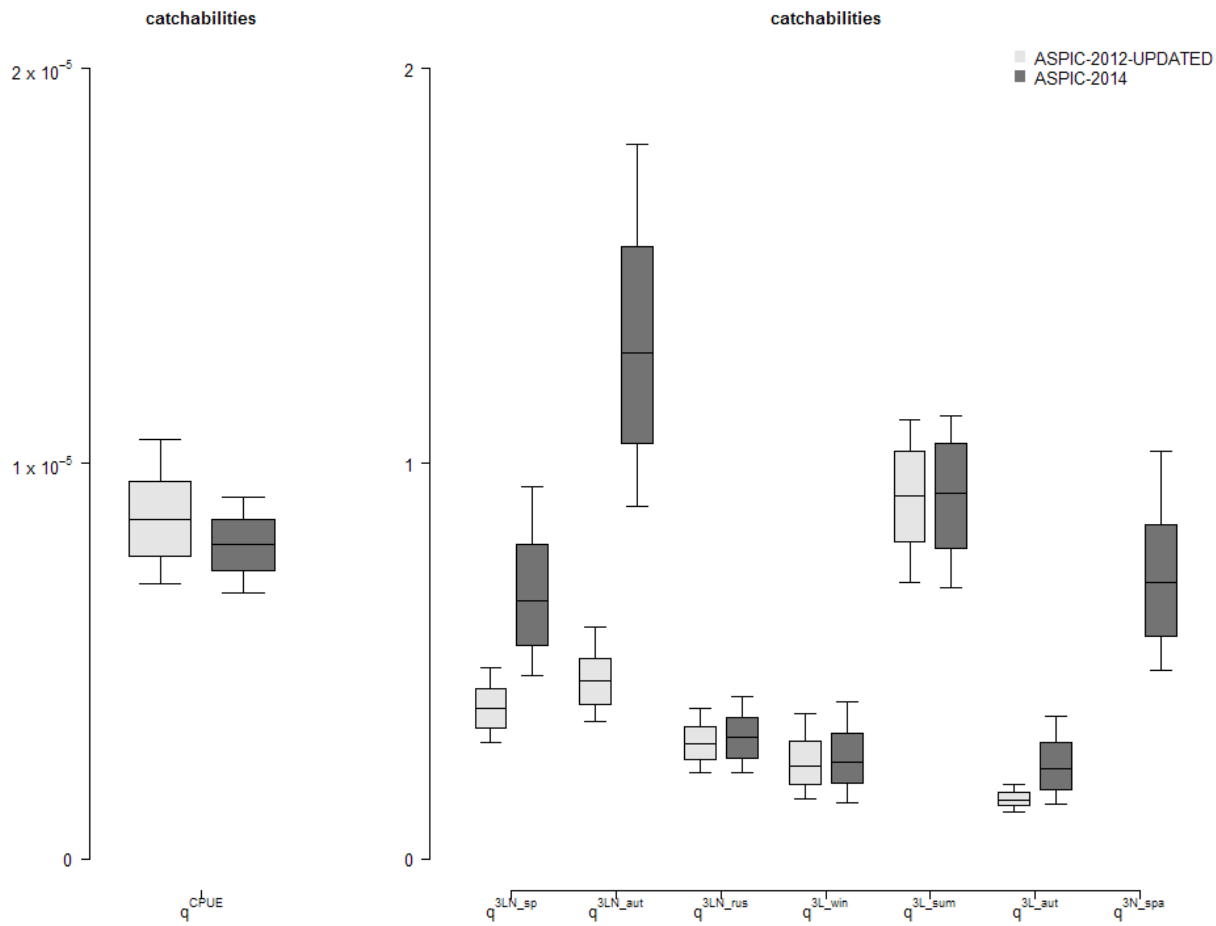


Figure 4. Estimation of the different catchabilities of the ASPIC-2012-UPDATED and ASPIC-2014 surplus production model. Light grey indicates the ASPIC-2012-UPDATED estimates and dark grey indicates the ASPIC-2014 estimates. Boxes represent the 50% lower and upper confidence intervals and the line in the middle, the median of the bootstraps, the whiskers indicate the 80% lower and upper confidence intervals.

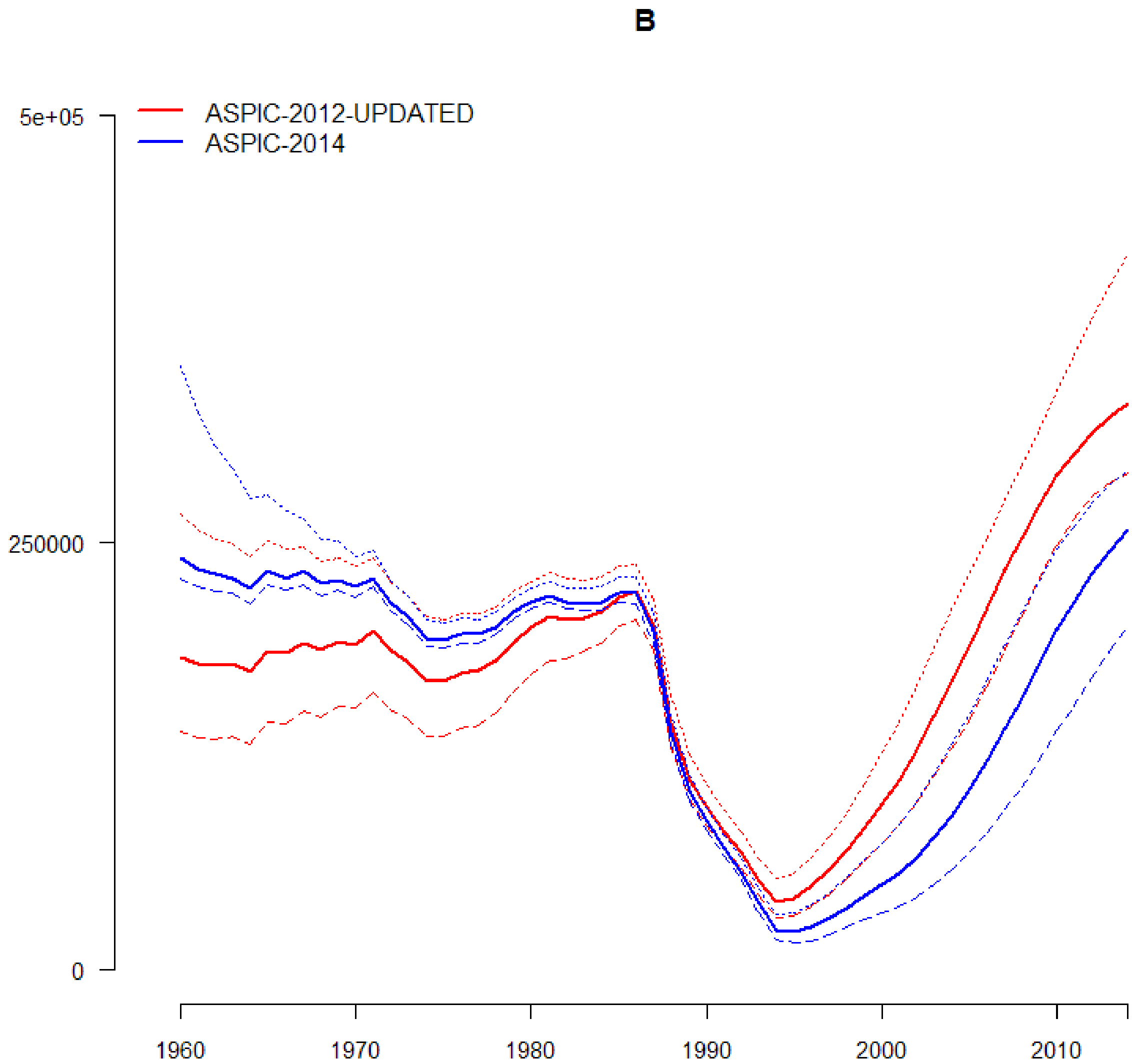


Figure 5. Evolution of the total biomass estimates of redfish in the 3LN Divisions using the ASPIC-2012-UPDATED and ASPIC-2014 surplus production models (in red and blue respectively). Plain lines are the point estimates and dashed lines are the lower and upper confidence intervals.

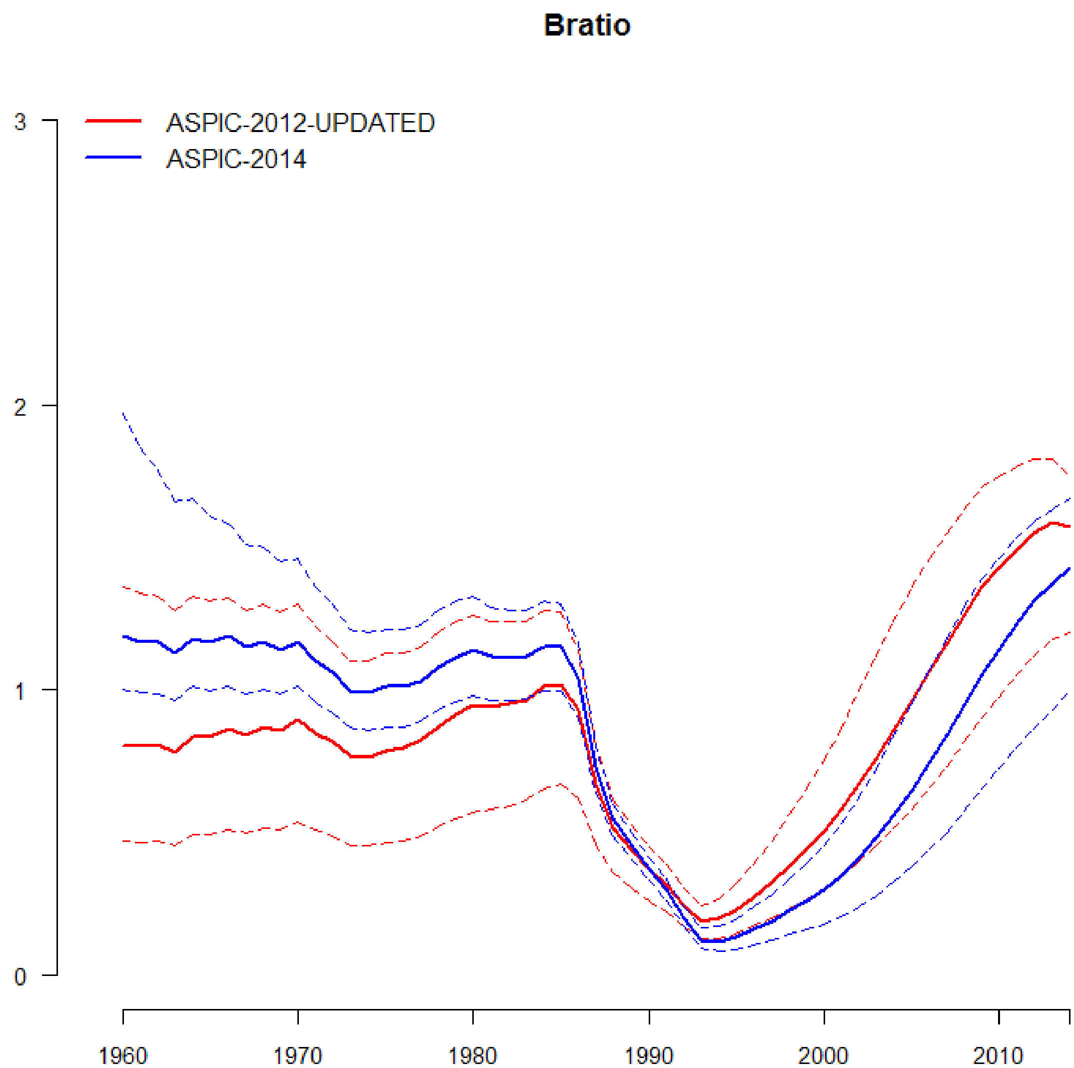


Figure 6. Evolution of B_{ratio} (B/B_{MSY}) estimates of redfish in the 3LN Divisions using the ASPIC-2012-UPDATED and ASPIC-2014 surplus production models (in red and blue respectively). Plain lines are the point estimates and dashed lines are the lower and upper confidence intervals.

2. ASPIC-BAYES-2012-UPDATED

In this section the ASPIC-2012-UPDATED and ASPIC-BAYES-2012-UPDATED outputs are compared. For illustrative purpose, the prior and posterior distributions of K and MSY are represented in Figure 7. They show a significant updating. The estimation of the population parameters (K, MSY, B_{MSY} and F_{MSY}) in both models show some slight differences (Fig. 8). Overall, K, MSY and B_{MSY} are estimated with higher values in the ASPIC-BAYES-2012-UPDATED model. This is due to the fact that parameters are not estimated in a similar fashion in the two frameworks. For example when looking at the posterior distribution of the K parameter in the ASPIC-BAYES-2012-UPDATED OM (which is bounded with the same constrains than in ASPIC-2012-UPDATED) we can see that the distribution is saturated on the right side (i.e. the data seems to indicate that K is much higher).

The catchabilities (Fig. 9) are estimated with very similar values for both OMs, although a few of them show higher uncertainties in the ASPIC-BAYES-2012-UPDATED model.

The Bayesian framework provides estimates of the observation and process error (Fig. 10). The observation errors are fairly high except for the one associated with CPUE. Additionally, the observation error associated with the 3L winter surveys is very large, however this is to be expected considering that this time series only has 3 data points.

The evolution of the total biomass abundance and B_{ratio} are represented in Figures 11 and 12. The patterns for both OMs are very similar, however the differences in the estimates of population parameters lead to higher total biomass abundance estimation in the most recent part of the time series for the ASPIC-BAYES-2012-UPDATED OM.

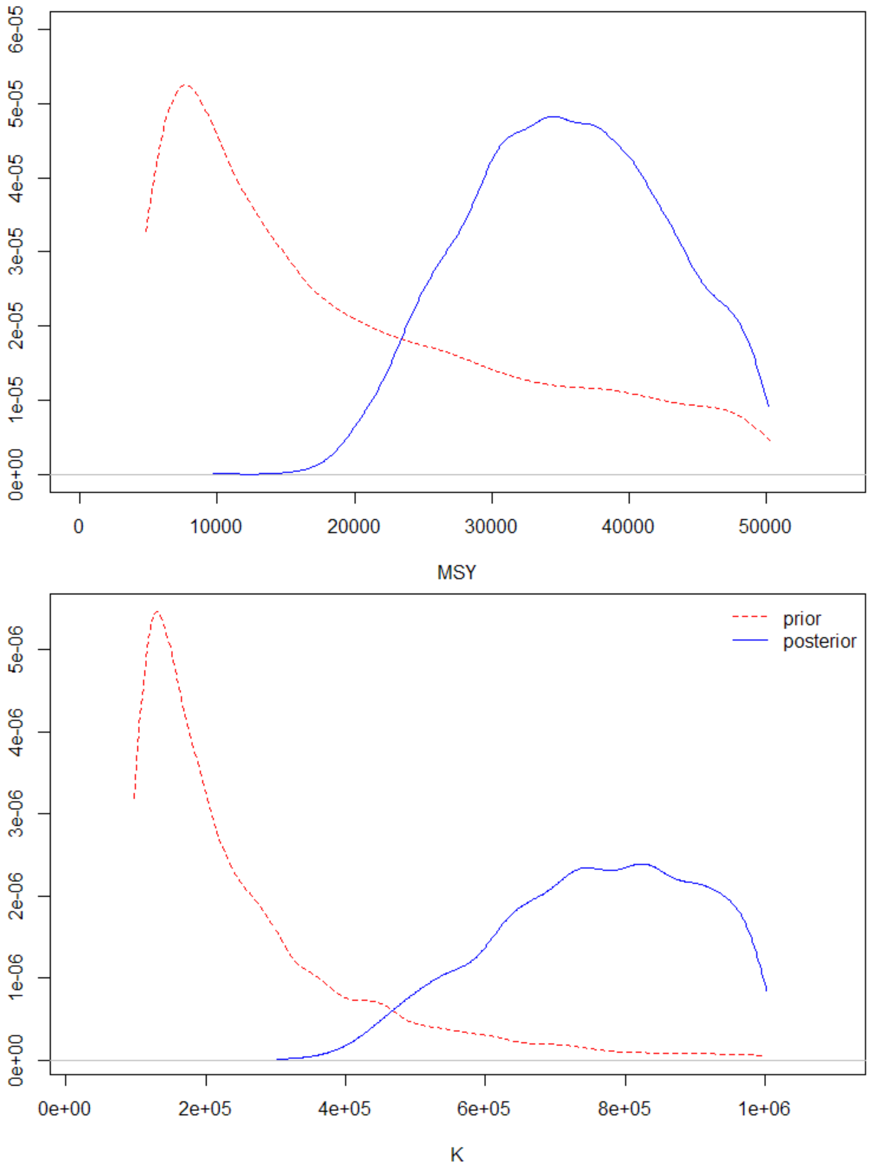


Figure 7: Prior (red dashed line) and posterior (plain blue line) distributions of MSY (top panel) and K (bottom panel).

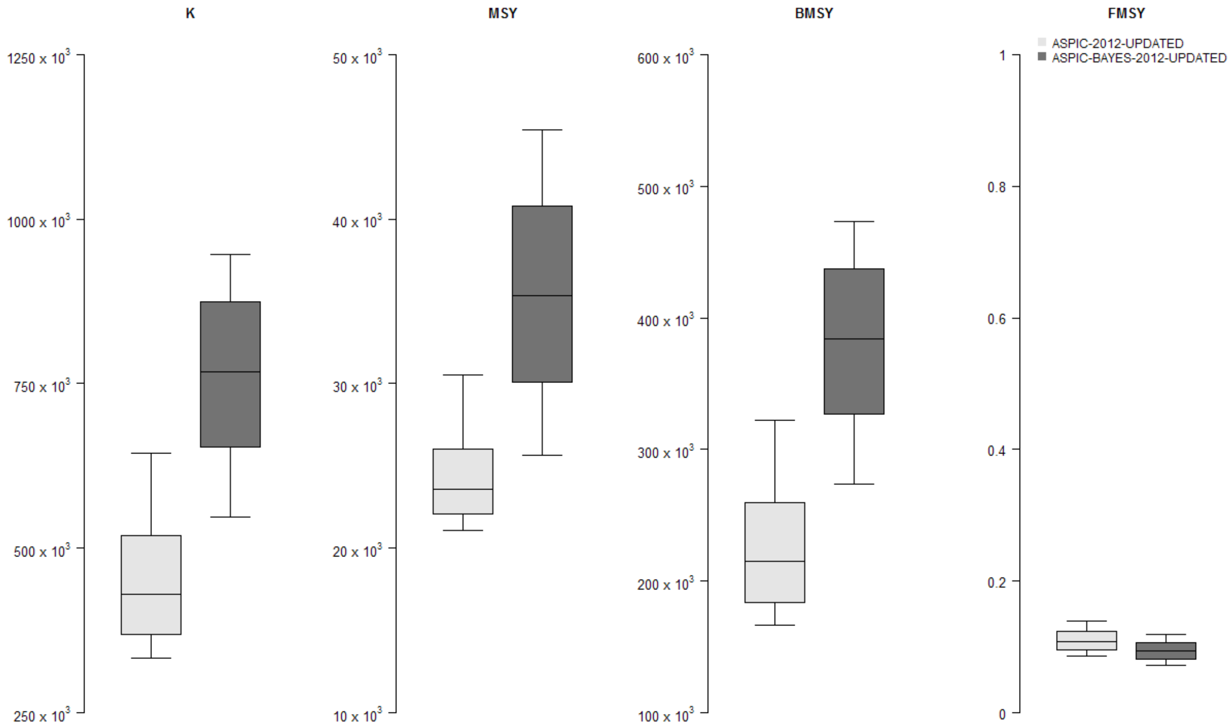


Figure 8. Estimation of the different population parameters of the surplus production model: *K*, *MSY*, B_{MSY} and F_{MSY}. Light grey indicates the ASPIC-2012-UPDATED estimates and dark grey indicates the ASPIC-BAYES-2012-UPDATED estimates. Boxes represent the 25th and 75th percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC estimates. The whiskers indicate the 10th and 90th percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC estimates.

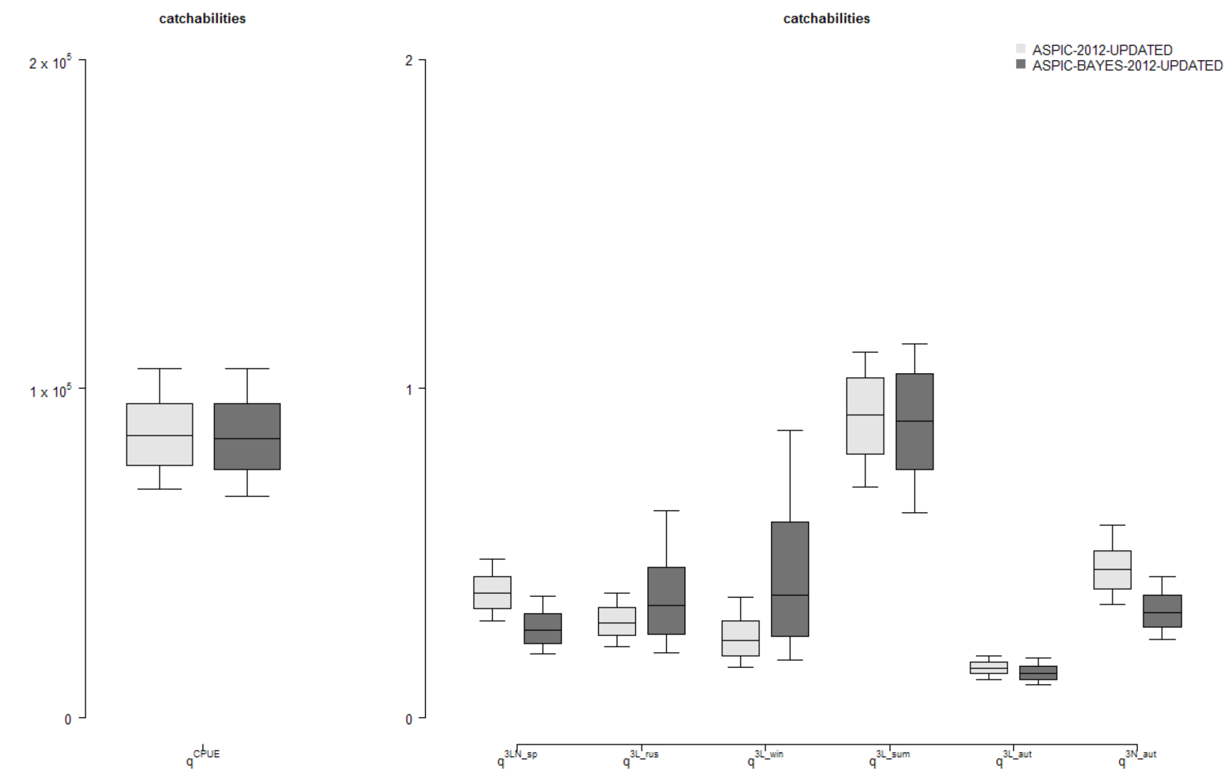


Figure 9. Estimation of the different catchabilities of the ASPIC-2012-UPDATED and ASPIC-BAYES-2012-UPDATED surplus production model. Light grey indicates the ASPIC-2012-UPDATED estimates and dark grey indicates the ASPIC-BAYES-2012-UPDATED estimates. Boxes represent the 25th and 75th percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2012-UPDATED estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2012-UPDATED estimates. The whiskers indicate the 10th and 90th percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2012-UPDATED estimates.

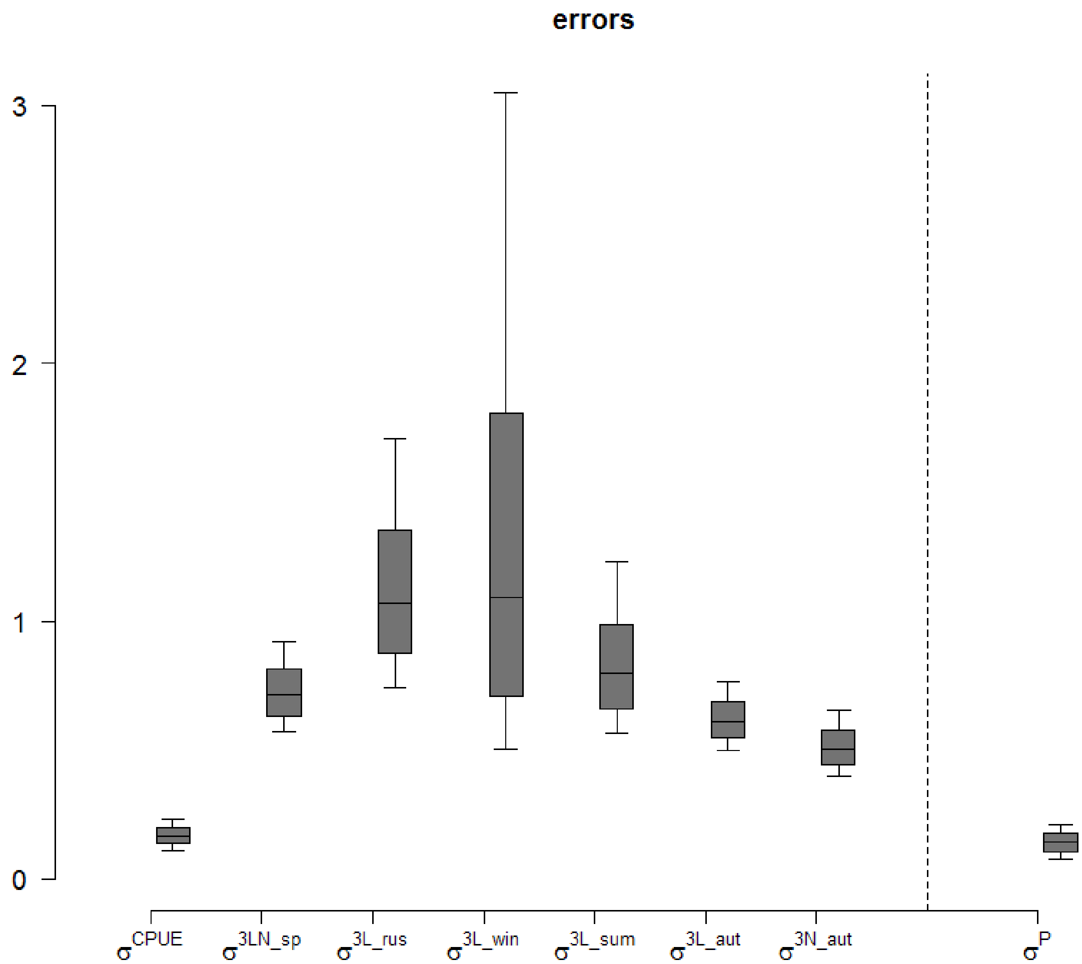


Figure 10. Estimation of the observation error associated to the surveys used in the ASPIC-BAYES-2012-UPDATED surplus production model and the process error (on the right of the dashed line). The boxes indicate the 25th and 75th percentiles of the posterior distribution, the lines in the boxes indicate the median of the posterior distributions and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

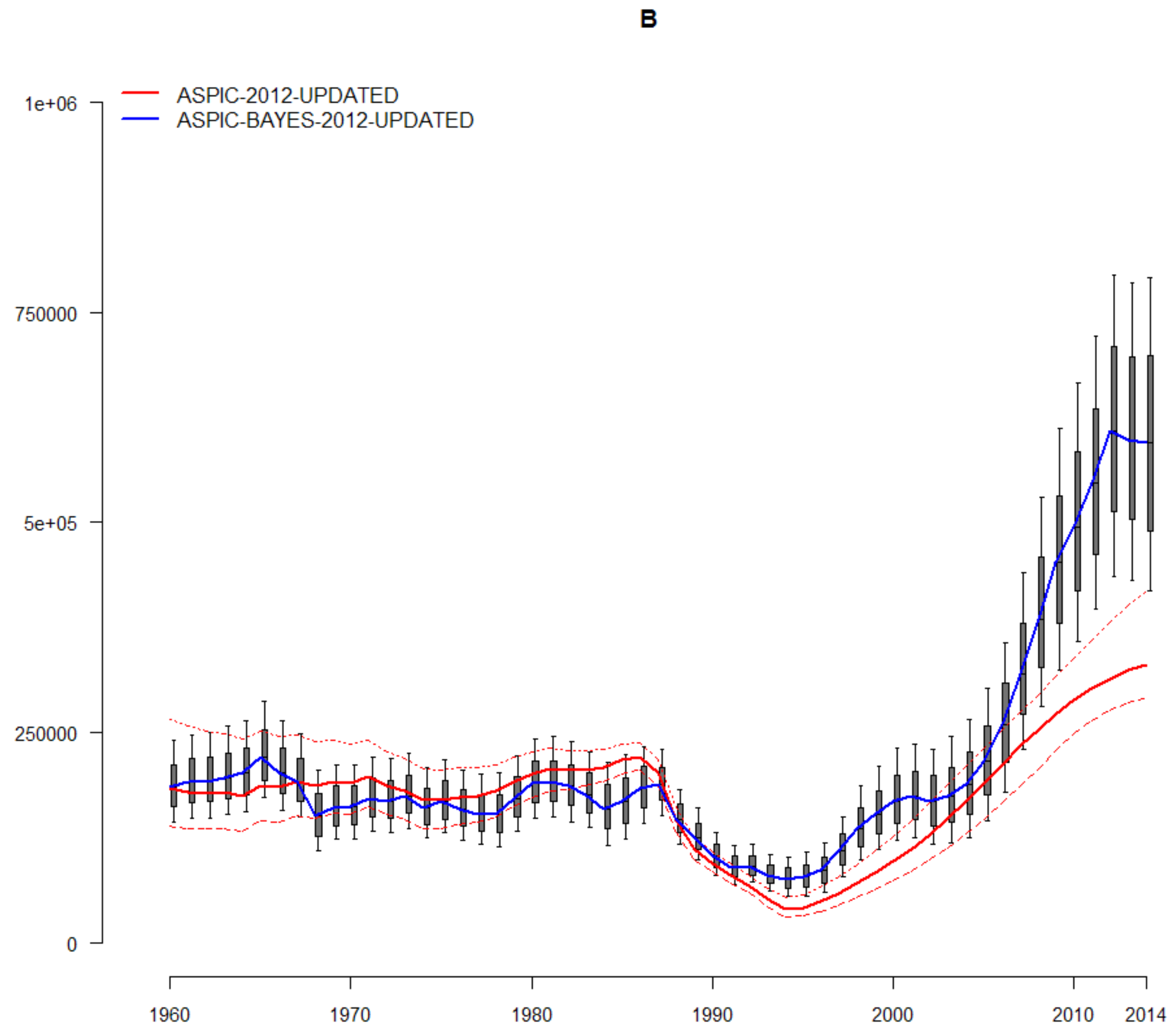


Figure 11. Evolution of the total biomass estimates of redfish in the 3LN Divisions using the ASPIC-2012-UPDATED and ASPIC-BAYES-2012-UPDATED surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

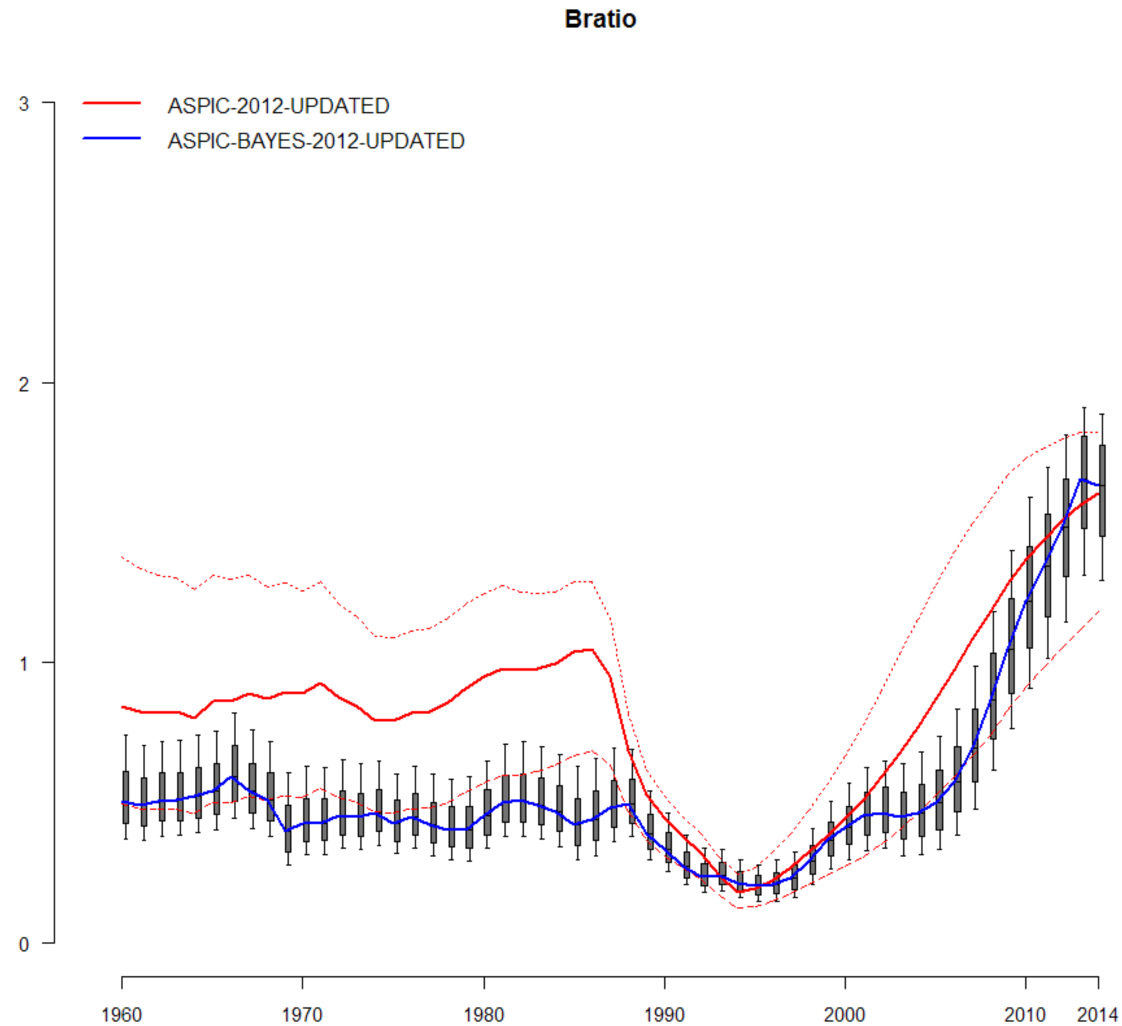


Figure 12. Evolution of B_{ratio} (B/B_{MSY}) estimates of redfish in the 3LN Divisions using the ASPIC-2012-UPDATED and ASPIC-BAYES-2012-UPDATED surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

4. ASPIC-BAYES-2014

In this section the ASPIC-2014 and ASPIC-BAYES-2014 outputs are compared. The estimation of the different population parameters in both models show some similar differences to those encountered between the ASPIC-2012-UPDATED and ASPIC-BAYES-2012-UPDATED OMS (Fig. 13). Overall, *K* and BMSY are estimated with much higher values (average values almost 2 times higher) in the ASPIC-BAYES-2014 model. This is due to differences in the way parameters are estimated in the two frameworks. For example, when looking at the posterior distribution of the *K* parameter in the ASPIC-BAYES-2014 OM (which is bounded with the same constrains as in ASPIC-2014) we can see that the distribution is saturated on the right side (i.e. the data seems to indicate that *K* is much higher).

Estimates of catchabilities (Fig. 14) are very similar for both OMs, although a few of them show higher uncertainties in the ASPIC-BAYES-2012-UPDATED model.

The Bayesian framework allows access to the observation and process error (Fig. 15). The observation errors are higher and more uncertain than the ones estimated in the ASPIC-BAYES-2012-UPDATED OM (Fig. 10 and 15).

The evolution of the total biomass abundance and B_{ratio} are represented in Figures 16 and 17. The patterns for both OMs are very similar however the differences in the population parameter estimates lead to higher total biomass abundance estimation in the most recent part of the time series for the ASPIC-BAYES-2014 OM. Additionally, in the last 2 years there is a decrease in the total biomass abundance that is not observed in the ASPIC-2014 OM.

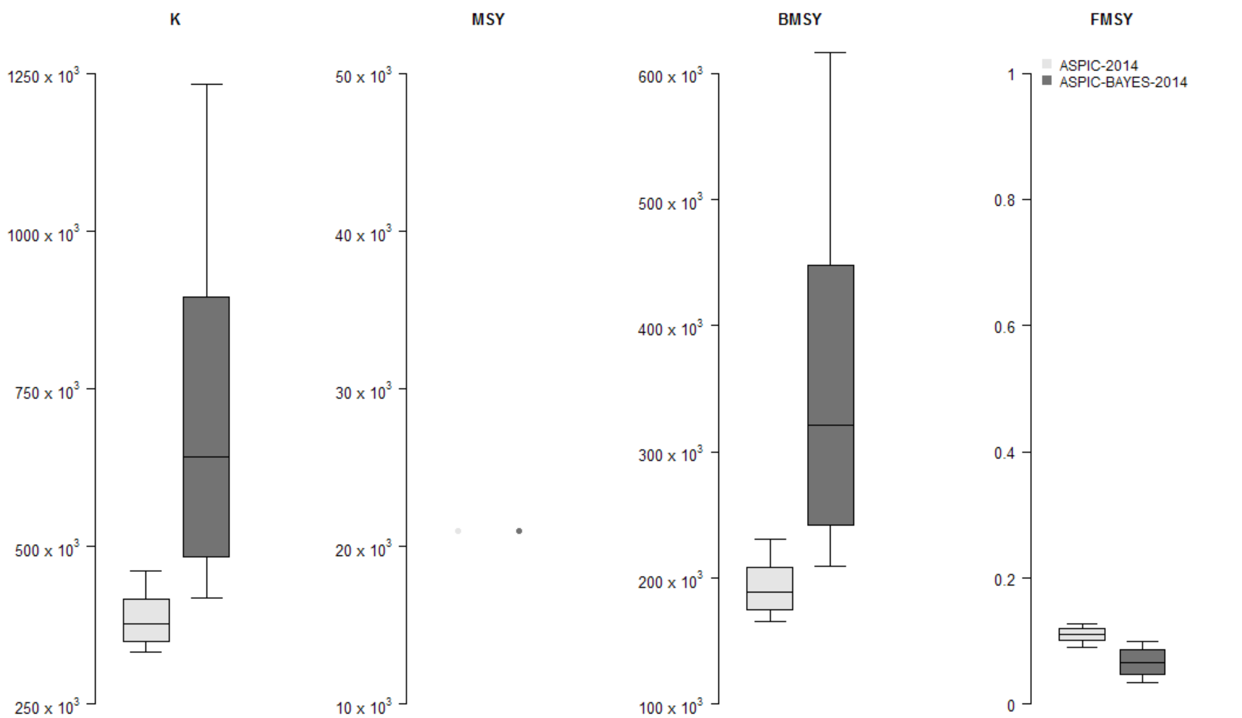


Figure 13. Estimation of the different population parameters of the ASPIC-2014 and ASPIC-BAYES-2014 surplus production model: *K*, *MSY*, B_{MSY} and F_{MSY} (for these 2 models *MSY* is fixed). Light grey indicates the ASPIC-2014 estimates and dark grey indicates the ASPIC-BAYES-2014 estimates. Boxes represent the 25th and 75th percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2014 estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2014 estimates. The whiskers indicate the 10th and 90th percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2014 estimates.

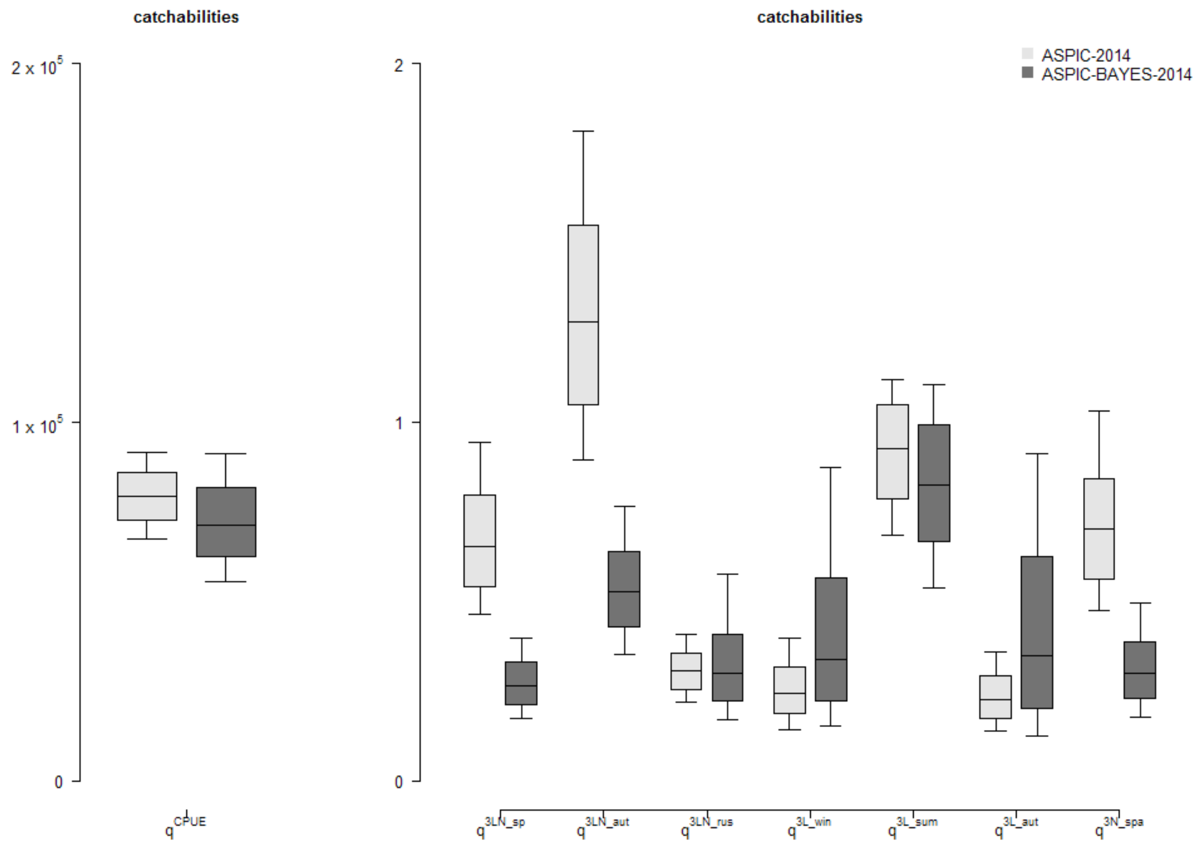


Figure 14. Estimation of the different catchabilities of the ASPIC-2014 and ASPIC-BAYES-2014 surplus production model. Light grey indicates the ASPIC 2014 estimates and dark grey indicates the ASPIC-BAYES-2014 estimates. Boxes represent the 25^{th} and 75^{th} percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2014 estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2014 estimates. The whiskers indicate the 10^{th} and 90^{th} percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2014 estimates.

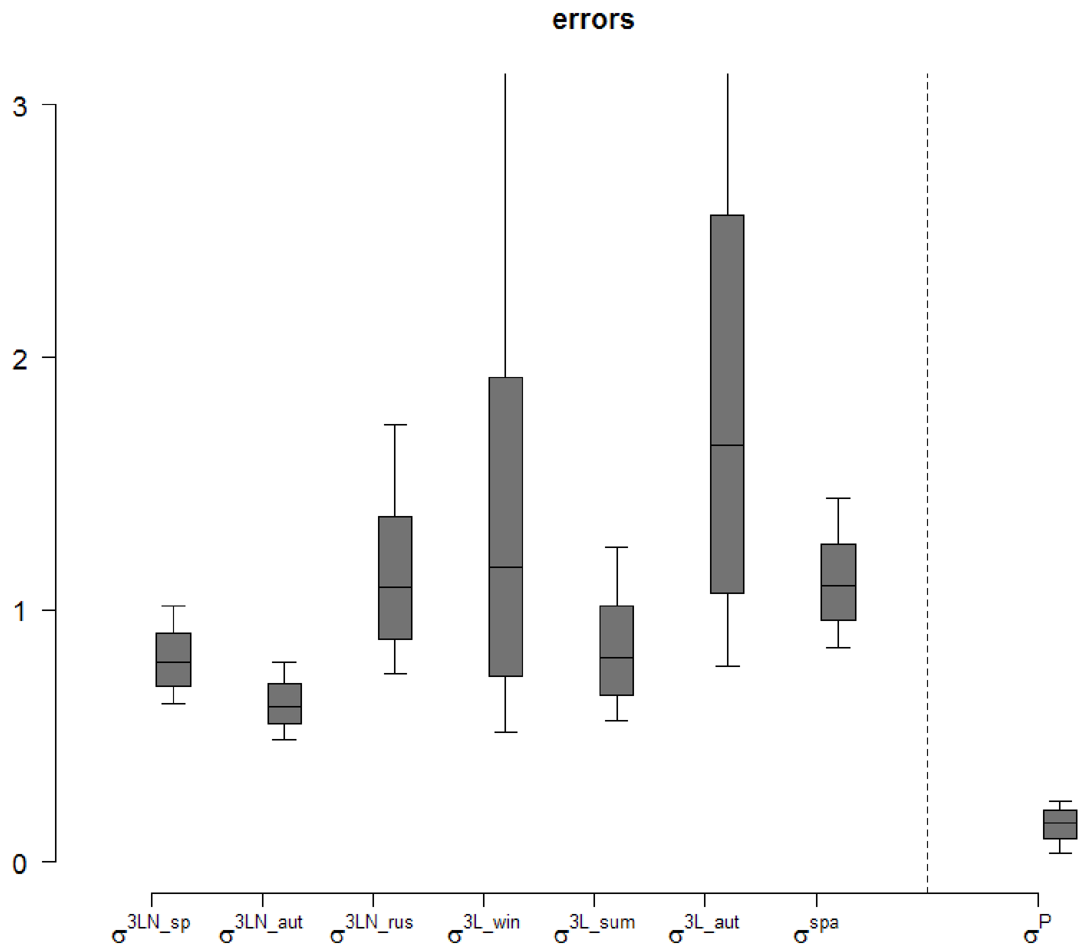


Figure 15. Estimation of the observation error associated to the surveys used in the ASPIC-BAYES-2014 surplus production model and the process error (on the right of the dashed line). The boxes indicate the 25th and 75th percentiles of the posterior distribution, the lines in the boxes indicate the median of the posterior distributions and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

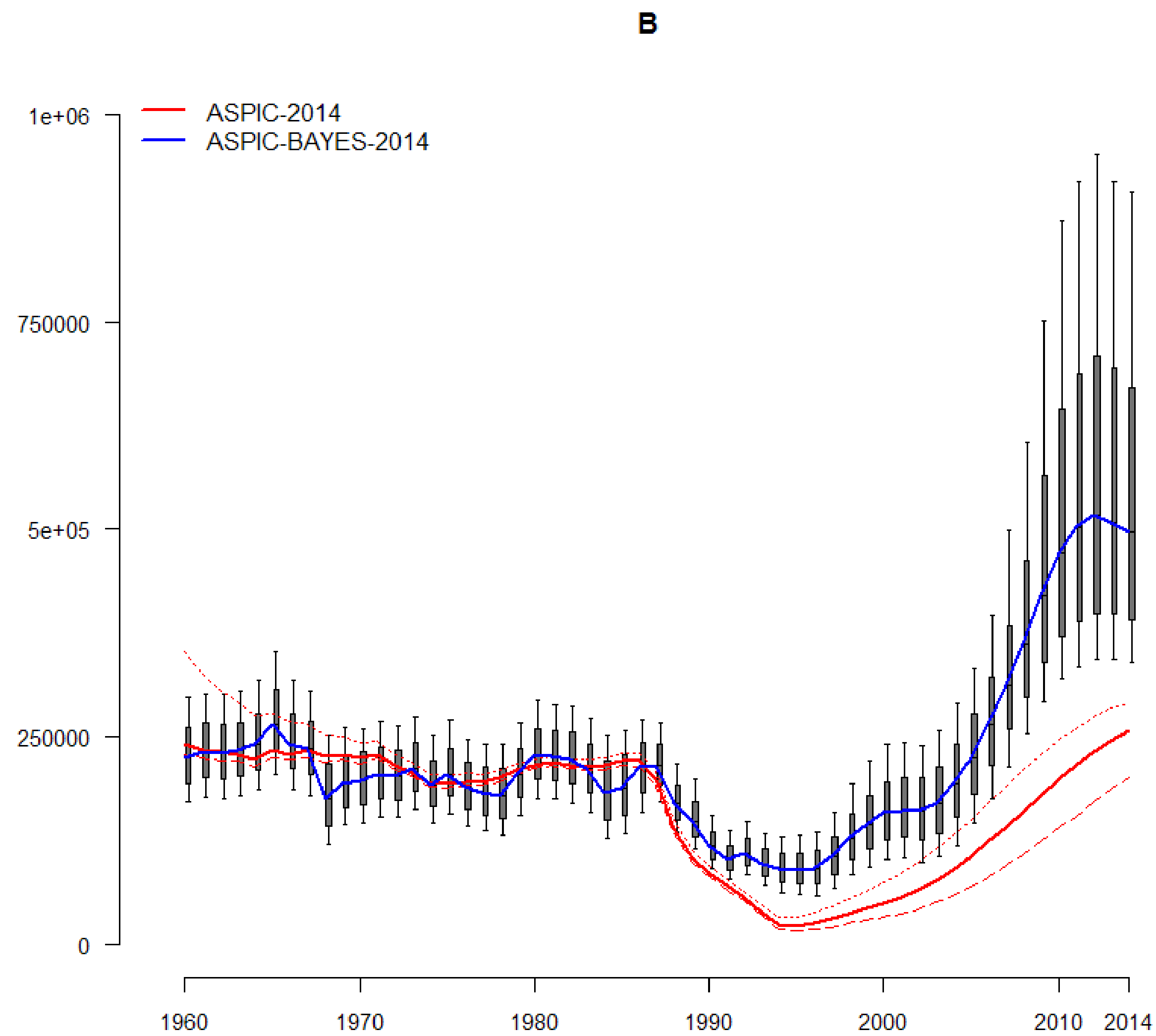


Figure 16. Evolution of the total biomass estimates of redfish in the 3LN Divisions using the ASPIC-2014 and ASPIC-BAYES-2014 surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

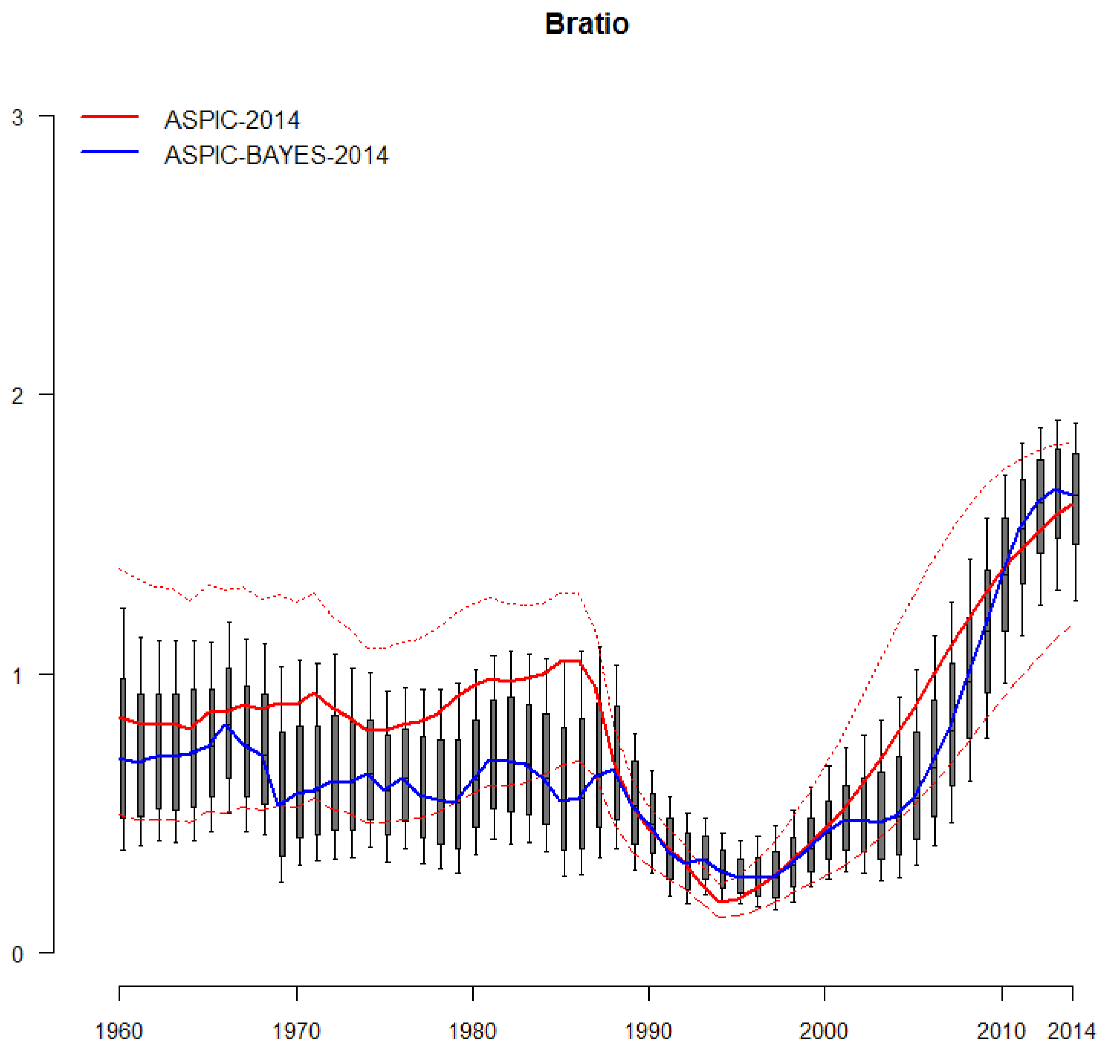


Figure 17. Evolution of B_{ratio} (B/B_{MSY}) estimates of redfish in the 3LN Divisions using the ASPIC-2014 and ASPIC-BAYES-2014 surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

5. ASPIC-BAYES-FULL

In this section the ASPIC-2014 (current stock assessment) and ASPIC-BAYES-FULL outputs are compared. Due to the saturation of some of the posterior distribution in the ASPIC-BAYES-2012 & 2014 OMs, the ASPIC-BAYES-FULL was designed to provide posterior distribution of parameters of interest freed of some of the constraints implemented in ASPIC-2012-UPDATED, ASPIC-2014, ASPIC-BAYES-2012-UPDATED and ASPIC-BAYES-2014. For illustrative purpose, the prior and posterior distributions of K and MSY are represented in Figure 18

The estimation of the different population parameters in the ASPIC-BAYES-FULL OM (Fig. 19) do not show signs of saturations anymore in the posterior distribution, however the values are much higher than the ones found in ASPIC-2014.

The catchabilities (Fig. 20) are a bit more complicated to compare since the data sets used in both models are different. However, the estimations are in the same range.

The Bayesian framework allows having access to the observation and process error. The observation errors estimations are similar to the ones estimated in the ASPIC-BAYES-2012 OM (Fig. 10 and 21).

The evolution of the total biomass abundance and B_{ratio} are represented in figures 22 and 23. The pattern of the the total biomass abundance for both OMs is similar however due to the much higher *K* in the ASPIC-BAYES-FULL OM, the recent biomass abundance is about 5 times higher than in the ASPIC-2014 OM.

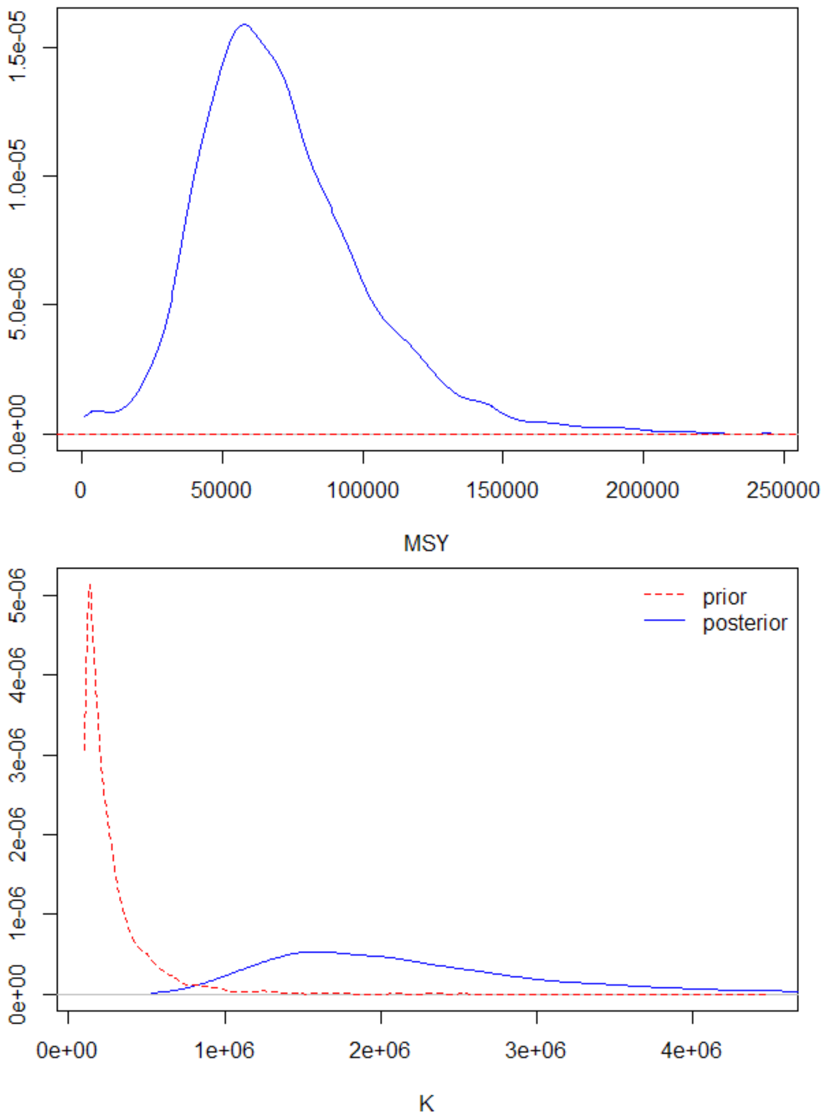


Figure 18: Prior (red dashed line) and posterior (plain blue line) distributions of MSY (top panel) and K (bottom panel).

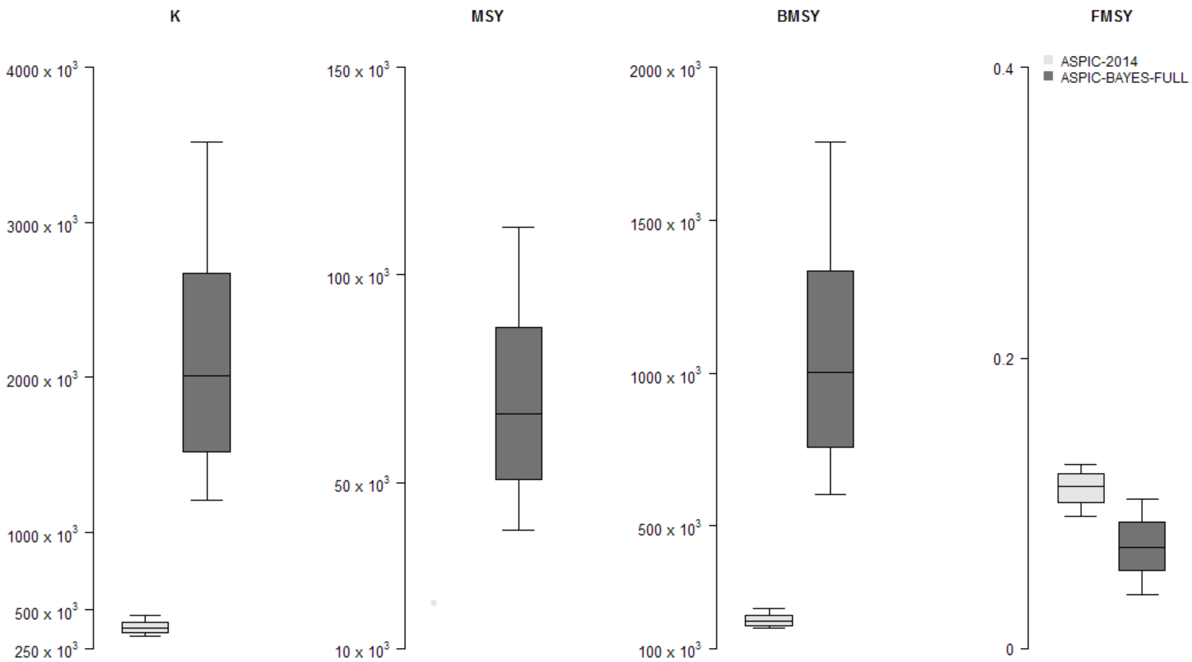


Figure 19. Estimation of the different population parameters of the of the ASPIC-2014 and ASPIC-BAYES-FULL surplus production model: *K*, *MSY*, B_{MSY} and F_{MSY} (*MSY* is fixed for ASPIC-2014). Light grey indicates the ASPIC-2014 estimates and dark grey indicates the ASPIC-BAYES-FULL estimates. Boxes represent the 25$^{\mathrm{th}}$ and 75$^{\mathrm{th}}$ percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2014 estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2014 estimates. The whiskers indicate the 10$^{\mathrm{th}}$ and 90$^{\mathrm{th}}$ percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2014 estimates.

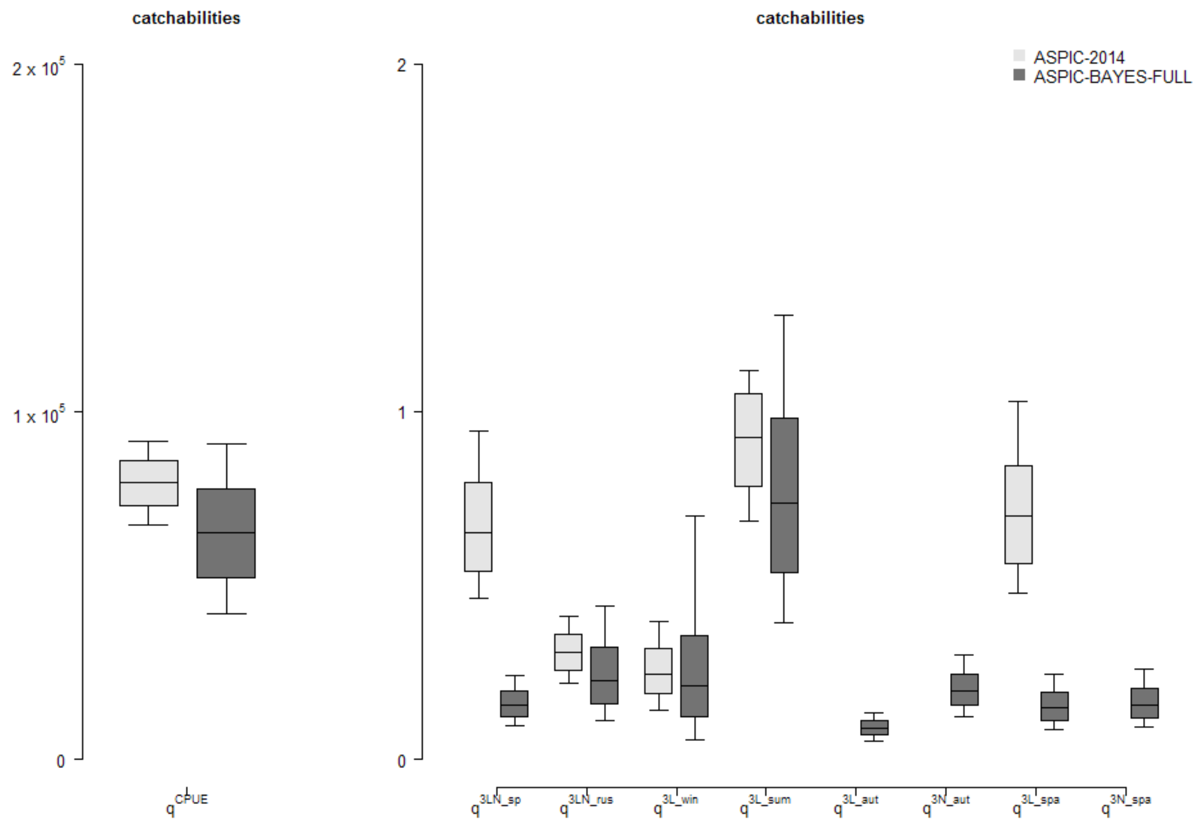


Figure 20. Estimation of the different catchabilities of the ASPIC-2014 and ASPIC-BAYES-FULL surplus production model. Light grey indicates the ASPIC-2014 estimates and dark grey indicates the ASPIC-BAYES-FULL estimates. Boxes represent the 25th and 75th percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2014 estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2014 estimates. The whiskers indicate the 10th and 90th percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2014 estimates.

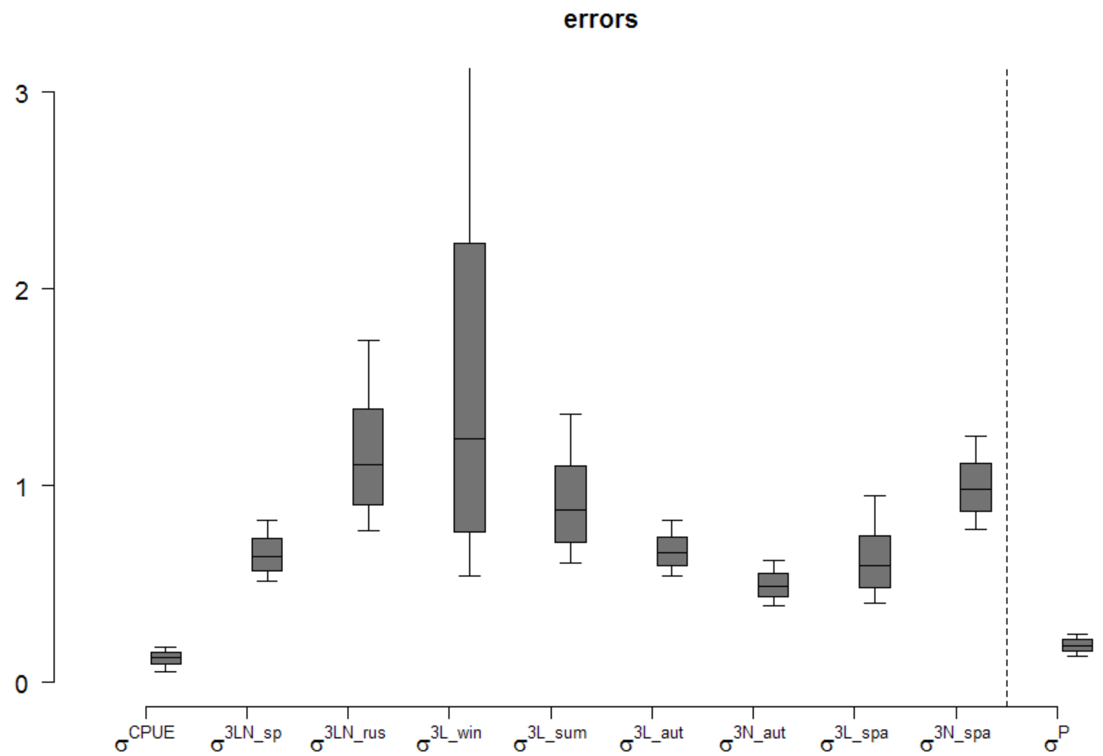


Figure 21. Estimation of the observation error associated to the surveys used in the ASPIC-BAYES-FULL surplus production model and the process error (on the right of the dashed line). The boxes indicate the 25th and 75th percentiles of the posterior distribution, the lines in the boxes indicate the median of the posterior distributions and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

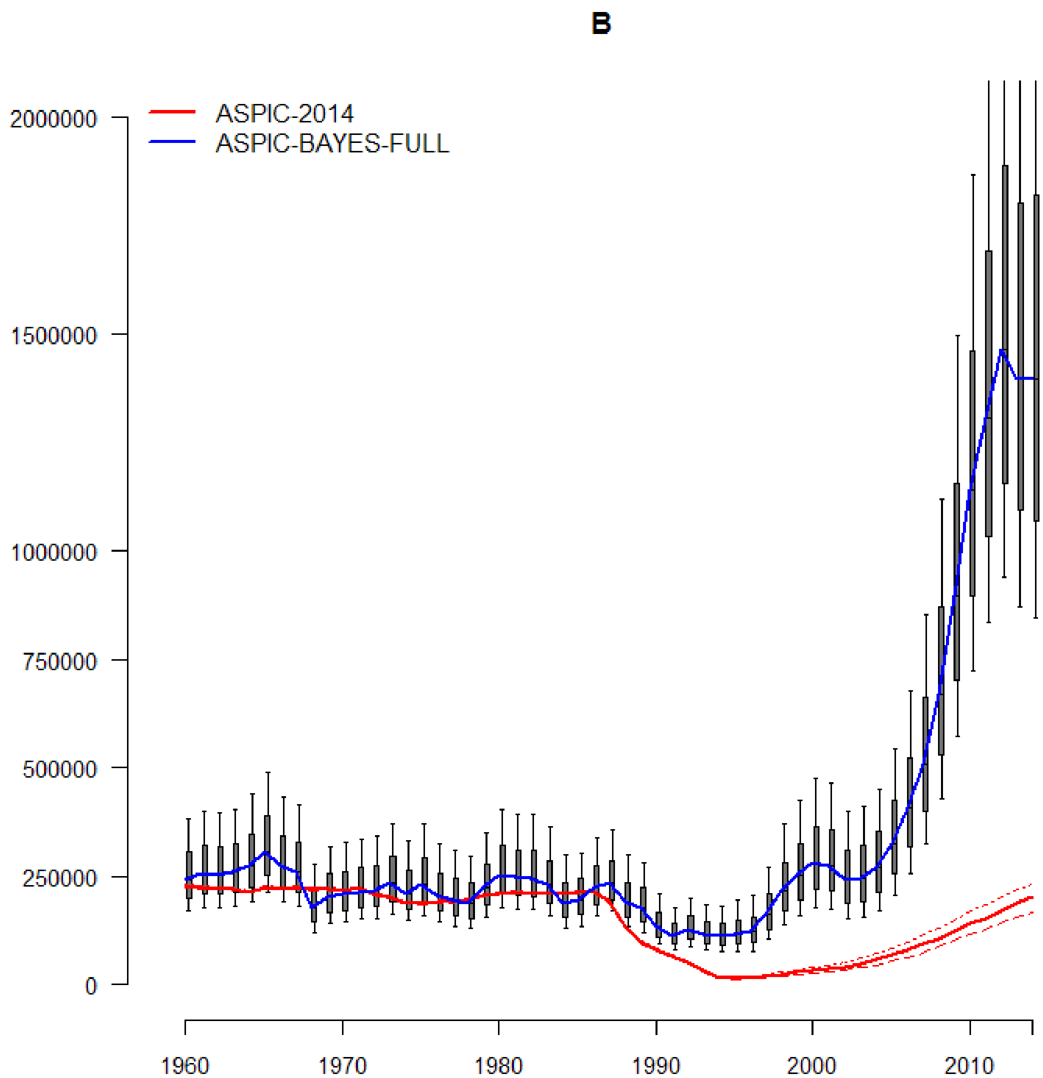


Figure 22. Evolution of the total biomass estimates of redfish in the 3LN Divisions using the ASPIC-2014 and ASPIC-BAYES-FULL surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

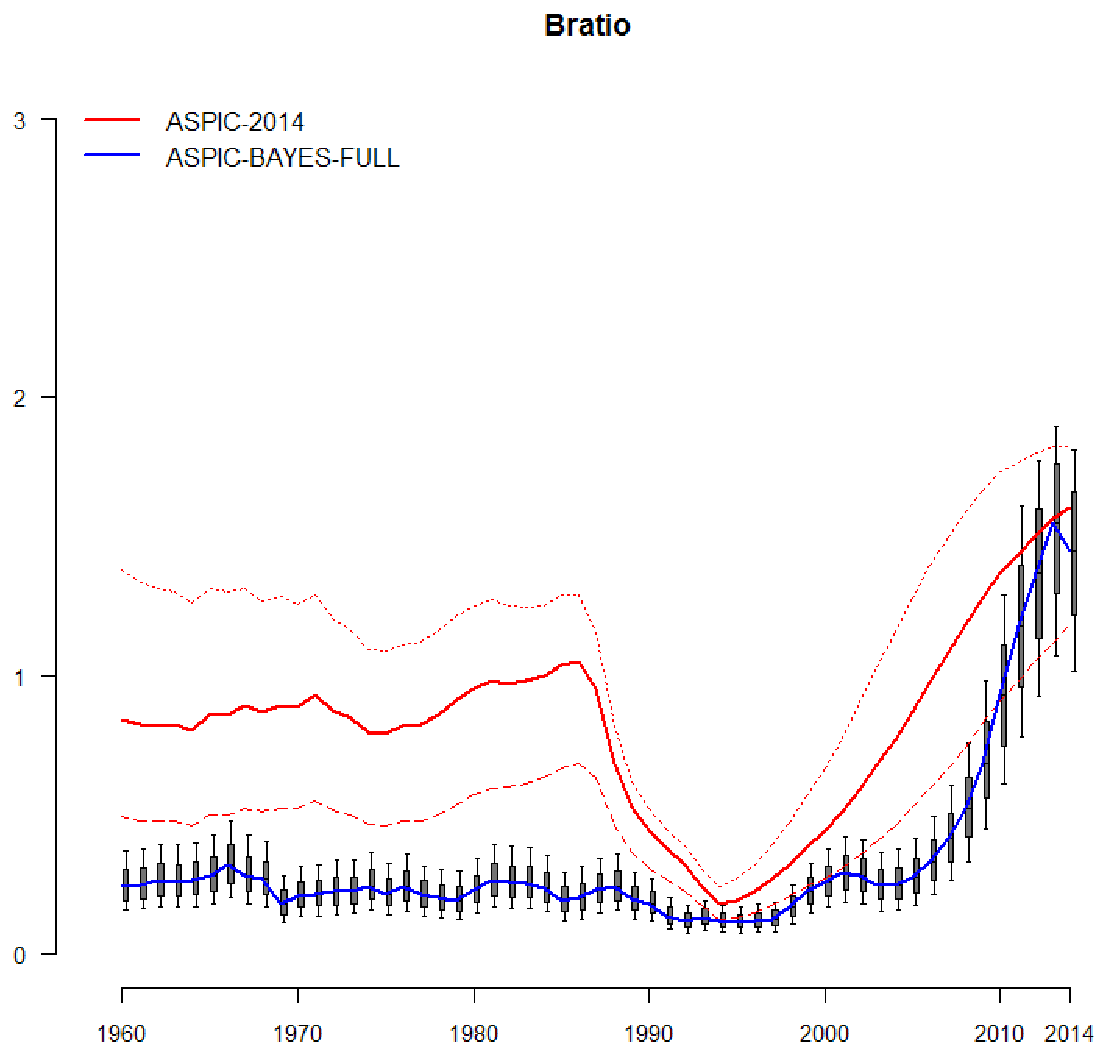


Figure 23. Evolution of B_{ratio} (B/B_{MSY}) estimates of redfish in the 3LN Divisions using the ASPIC-2014 and ASPIC-BAYES-FULL surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

6. BAYES-SPATIAL

In this section the ASPIC-2014 (current stock assessment) and BAYES-SPATIAL outputs are compared. For illustrative purpose, the prior and posterior distributions of r, K_3L and K_3N are represented in Figure 24.

Similarly to the other Bayesian OMs, the estimation of the different population parameters in the BAYES-SPATIAL OM (Fig. 25) are higher than their ASPIC counterparts. Additionally, for illustration purposes, the population parameters specific each divisions are represented.

The catchabilities (Fig. 26) are not compared because there is almost no correspondence in the data sets used in the 2 OMs, so only the BAYES-SPATIAL catchabilities are presented. All of them are estimated with good precision except for the ones associated with the 3N summer and 3L winter surveys (very few data points for these surveys).

The observation errors estimations are on average smaller than all the other Bayesian OMs (Fig. 27). Only one of them is highly uncertain due to the lack of data points (3L winter surveys).

The evolution of the total biomass abundance and B_{ratio} are represented in figures 28 and 29. The pattern of the total biomass abundance for both OMs is similar however, similarly to the previous models, the higher K leads to a higher total biomass abundance in the most recent part of the time series.

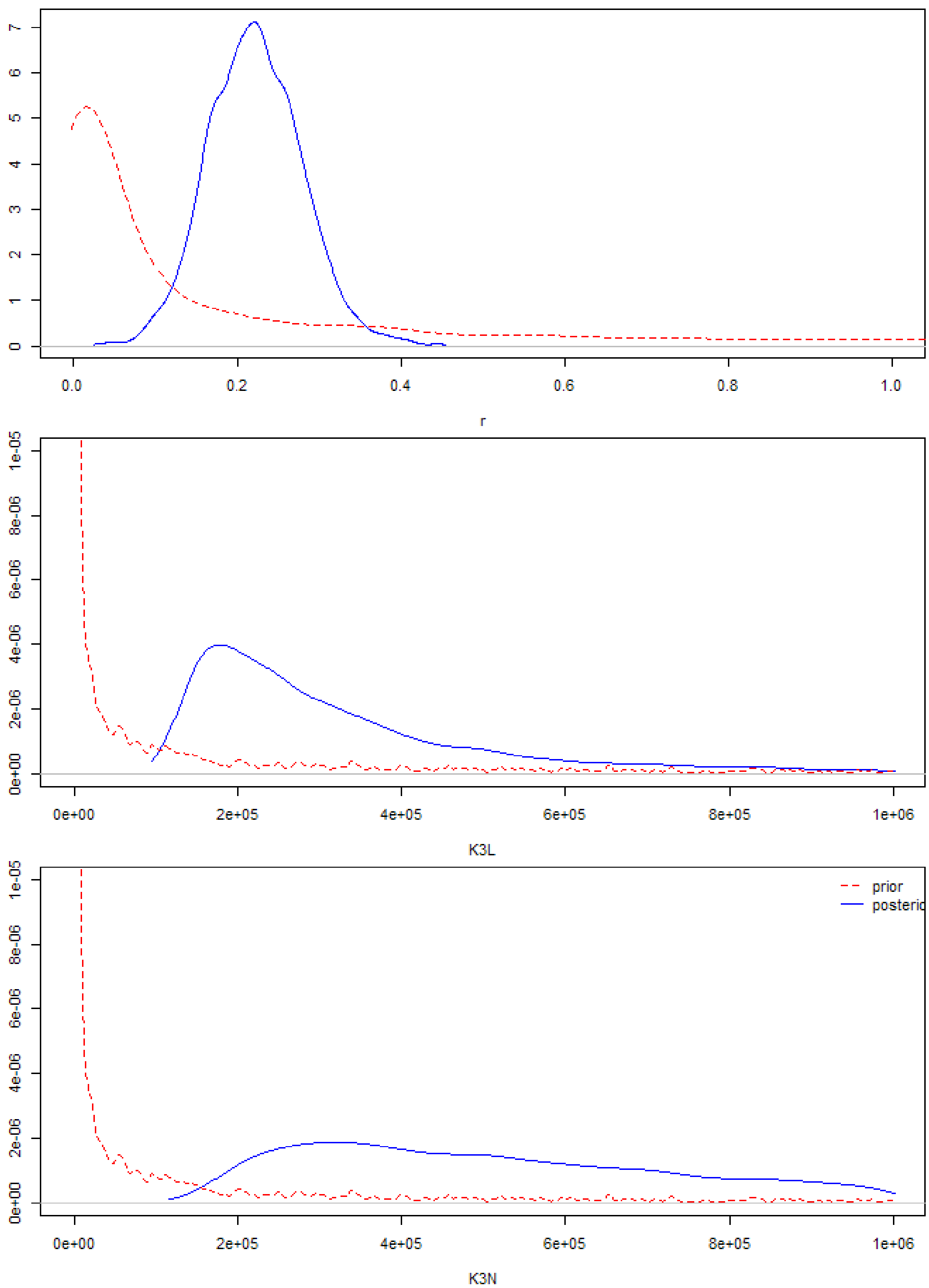
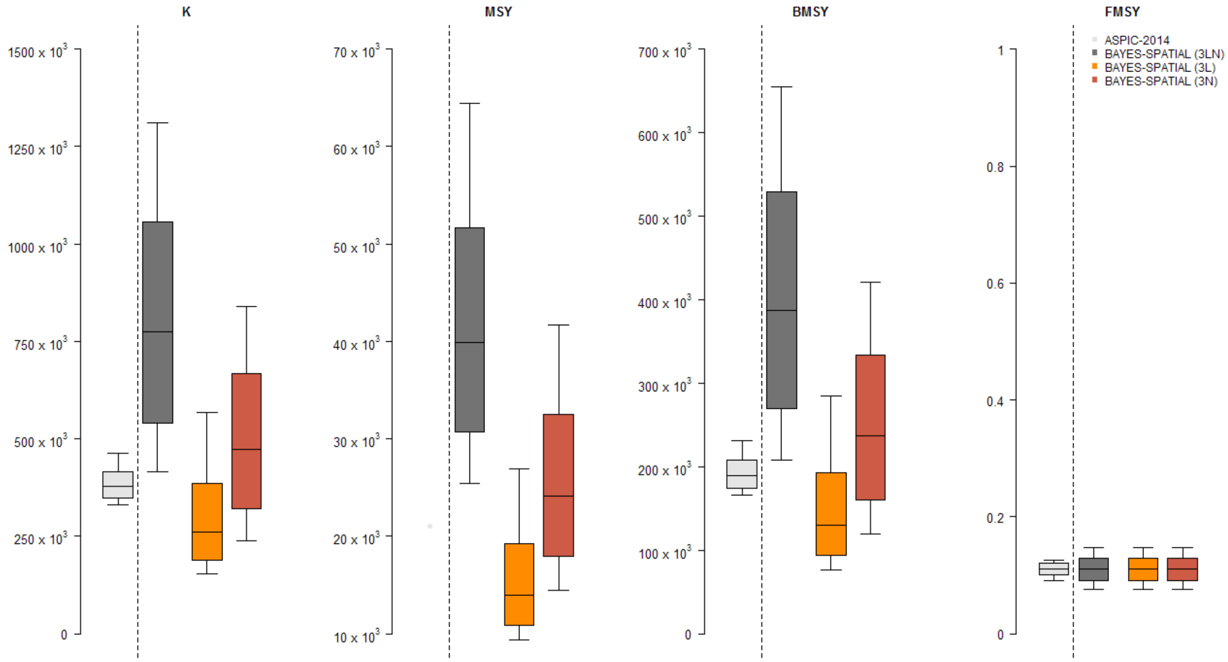


Figure 24: Prior (red dashed line) and posterior (plain blue line) distributions of r (top panel) and K_3L and K_3N (middle and bottom panel respectively).



x

Figure 25. Estimation of the different population parameters of the ASPIC-2014 and BAYES-SPATIAL surplus production model: *K*, *MSY*, B_{MSY} and F_{MSY} (*MSY* is fixed for ASPIC-2014). Light grey indicates the ASPIC-2014 estimates and dark grey indicates the BAYES-SPATIAL estimates, orange and pink indicate the parameter estimates for division 3L and 3N respectively. Boxes represent the 25th and 75th percentiles for the Bayesian estimates and the 50% lower and upper confidence intervals for the ASPIC-2014 estimates. The line in the middle is the median of the posterior distribution for Bayesian estimates and the median of the bootstraps for the ASPIC-2014 estimates. The whiskers indicate the 10th and 90th percentiles of the posterior distribution for the Bayesian estimates and the 80% lower and upper confidence intervals for the ASPIC-2014 estimates.

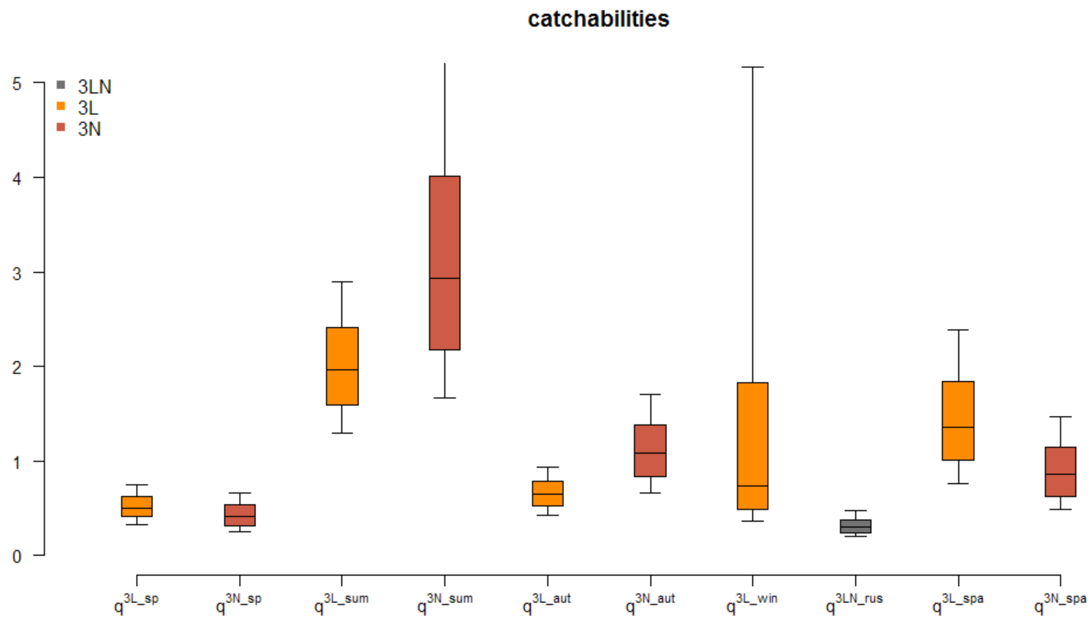


Figure 26. Estimation of the different catchabilities of the BAYES-SPATIAL surplus production model. Boxes represent the 25th and 75th percentiles, the line in the middle is the median of the posterior distribution and the whiskers indicate the 10th and 90th percentiles of the posterior distribution.

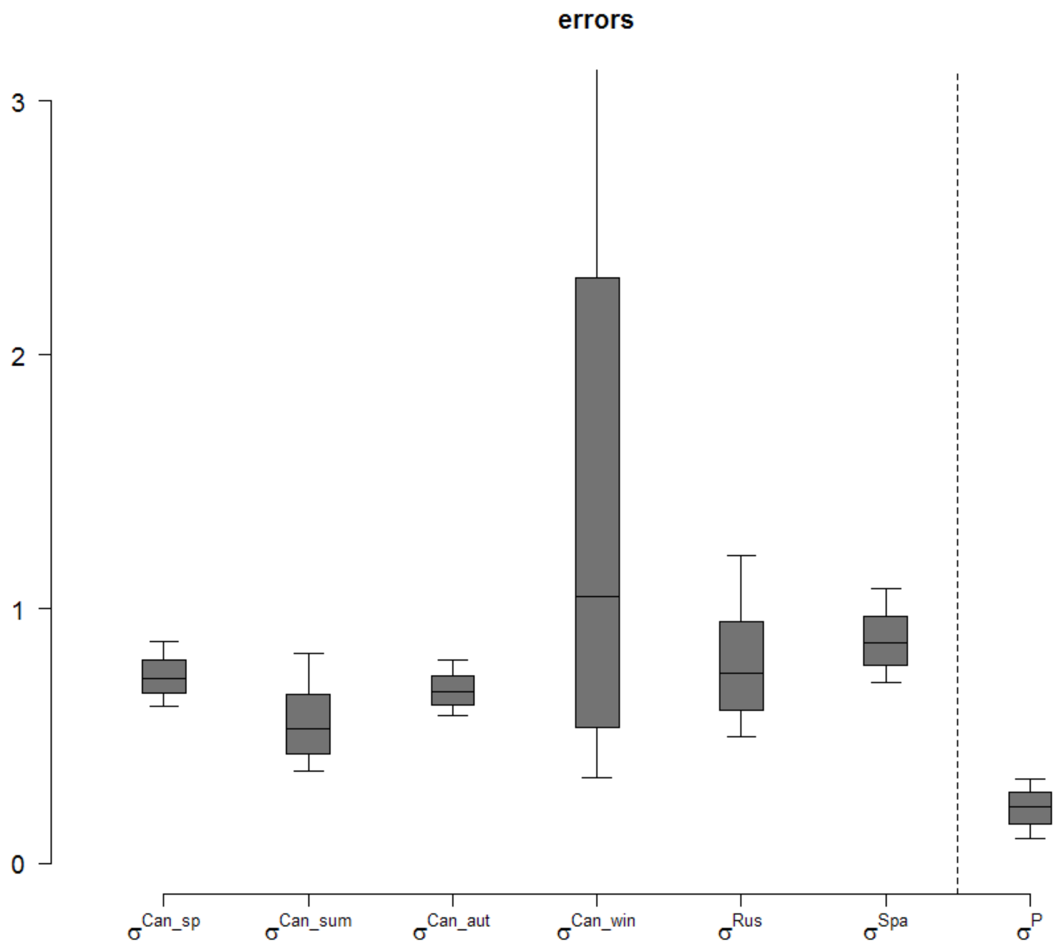


Figure 27. Estimation of the observation error associated to the surveys used in the BAYES-SPATIAL surplus production model and the process error (on the right of the dashed line). The boxes indicate the 25th and 75th percentiles of the posterior distribution, the lines in the boxes indicate the median of the posterior distributions and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

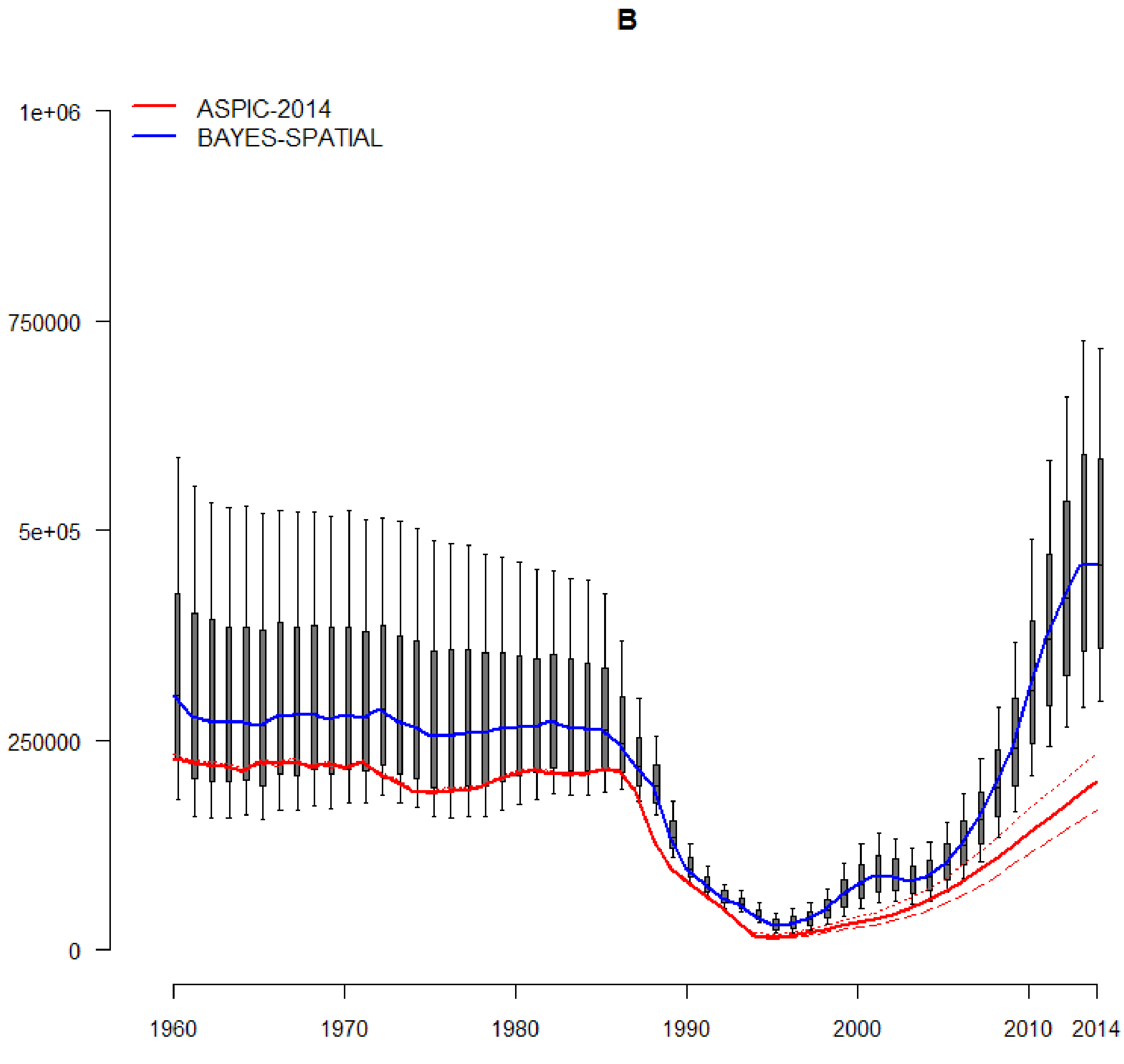


Figure 28. Evolution of the total biomass estimates of redfish in the 3LN Divisions using the ASPIC-2014 and BAYES-SPATIAL surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

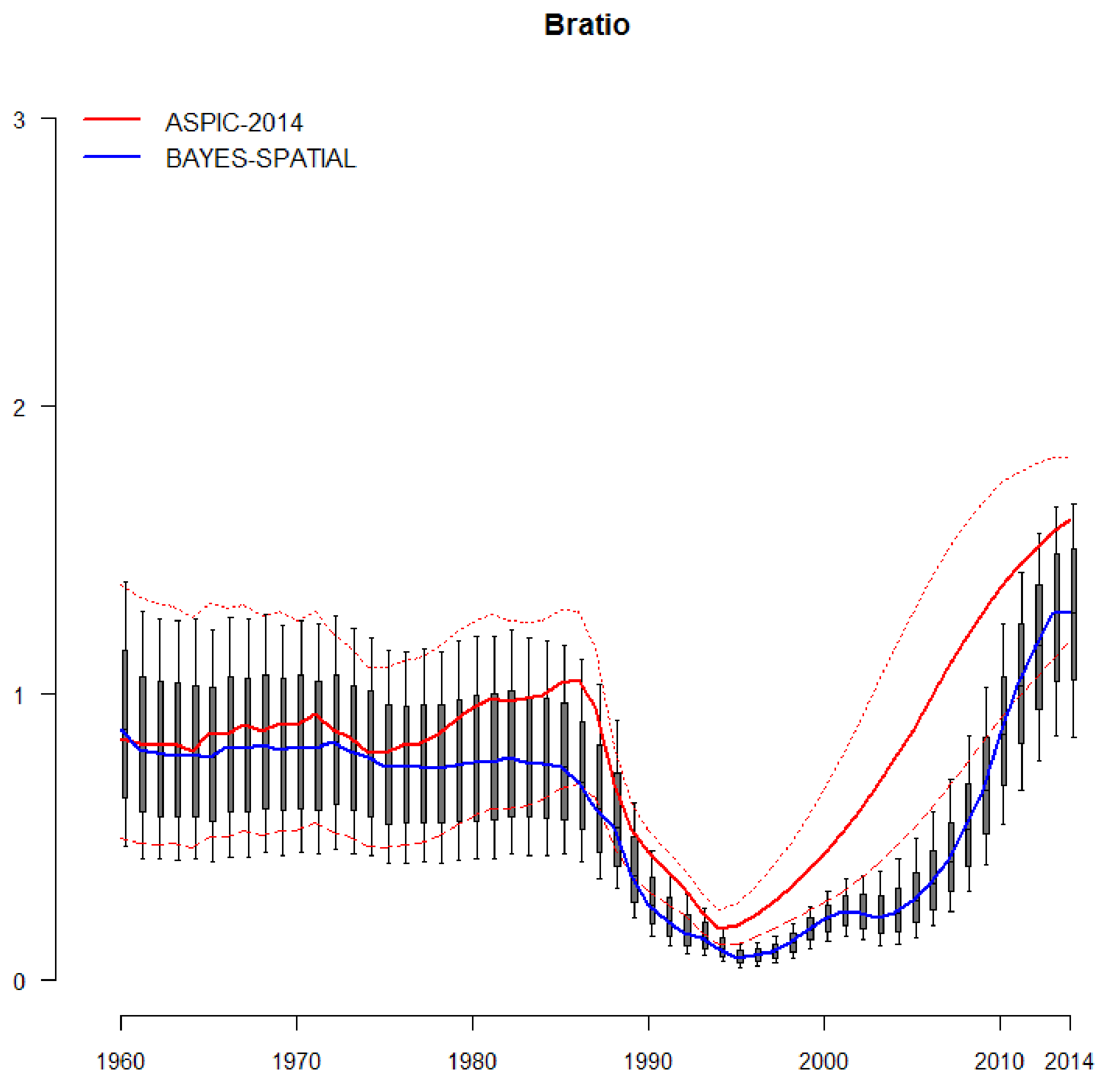


Figure 29. Evolution of B_{ratio} (B/B_{MSY}) estimates of redfish in the 3LN Divisions using the ASPIC-2014 and BAYES-SPATIAL surplus production models (in red and blue respectively). Plain red line indicates the point estimates and red dashed lines are the lower and upper confidence intervals. The blue plain line is the median of the posterior distribution, the boxes indicate the 25th and 75th percentiles of the posterior distribution and the whiskers indicate the 10th and 90th percentile of the posterior distribution.

MSE Background

There are five key elements in the MSE approach(Smith, 1994) :

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.

Elements 1 to 3 have been agreed on during the February 2014 meeting of the NAFO FC-SC (NAFO FC/SC Doc. 14/02). After discussion (SC Ad Hoc Working Group on Management Strategies for Redfish in Div. 3LN, 1st meeting, 13th May 2014; NAFO SCS Doc. 14/17) it was decided to use 4 management strategies:

- HCR1: increase the TAC in constant increments starting in 2015 – i.e. TAC y+1= TAC y + 1,900t to a maximum of 20 000 tons.
- HCR2: similar to HCR 1 but increments every second year to a maximum of 18 100 tons (Ávila de Melo et al., 2014)
- HCR3: Constant TAC (20 000 tons)
- HCR4: Constant F (2/3 FMSY). Note that this HCR would normally take into account observation error (i.e. F is determined based on the perceived stock size to generate a TAC which is then applied to the real stock generating a real F that is different from the perceived F). It is assumed here that the true F can be determined.

The robustness and relative performance of these management strategies are evaluated by means of the three chosen performance statistics (NAFO FC/SC Doc. 14/02):

i. Low (<30%) probability of exceeding Fmsy in any year
ii. Very low (<10%) probability of declining below Blim in the next 7 years
iii. Less than 50% probability of declining below 80% Bmsy in the next 7 years

The Management Strategy Evaluation (MSE) conceptual framework involves two main components: a set of OMs and a management strategy or procedure (Fig. 30). The OMs describe the dynamic of the population while taking in account some form of uncertainty (e.g. process error, observation error). The OMs are used to simulate the stock's dynamics and are conditioned on the available information (data and expert knowledge) to be a realistic representation of the stock. The different suggested OMs for the 3LN redfish stock are described above.

The OMs are used to simulate/forecast the future "true" population. Depending on the type of HCR, the MSE will involve, or not, a layer of "perceived" population. The perceived population is generated by using observation model error (i.e. the simulation of what would be the survey conditionally on the "true" population). If the HCR is dependent on the state of the population (i.e. feedback control rule) the TAC (or exploitation rate, etc.) will be determined based on the perceived population and then applied to the true population. If the HCR is independent of the population state (e.g. constant TAC or the Joint WG proposed step-wise HCR) then there is no need to generate a perceived population (this is the case in this study).

Due to the differences in the modelling frameworks (ASPIC OMs versus the Bayesian OMs) the true population is generated in slightly different ways: for the ASPIC OM, individual bootstraps are used while for the Bayesian OMs, single draws from the joint marginal distribution are used.

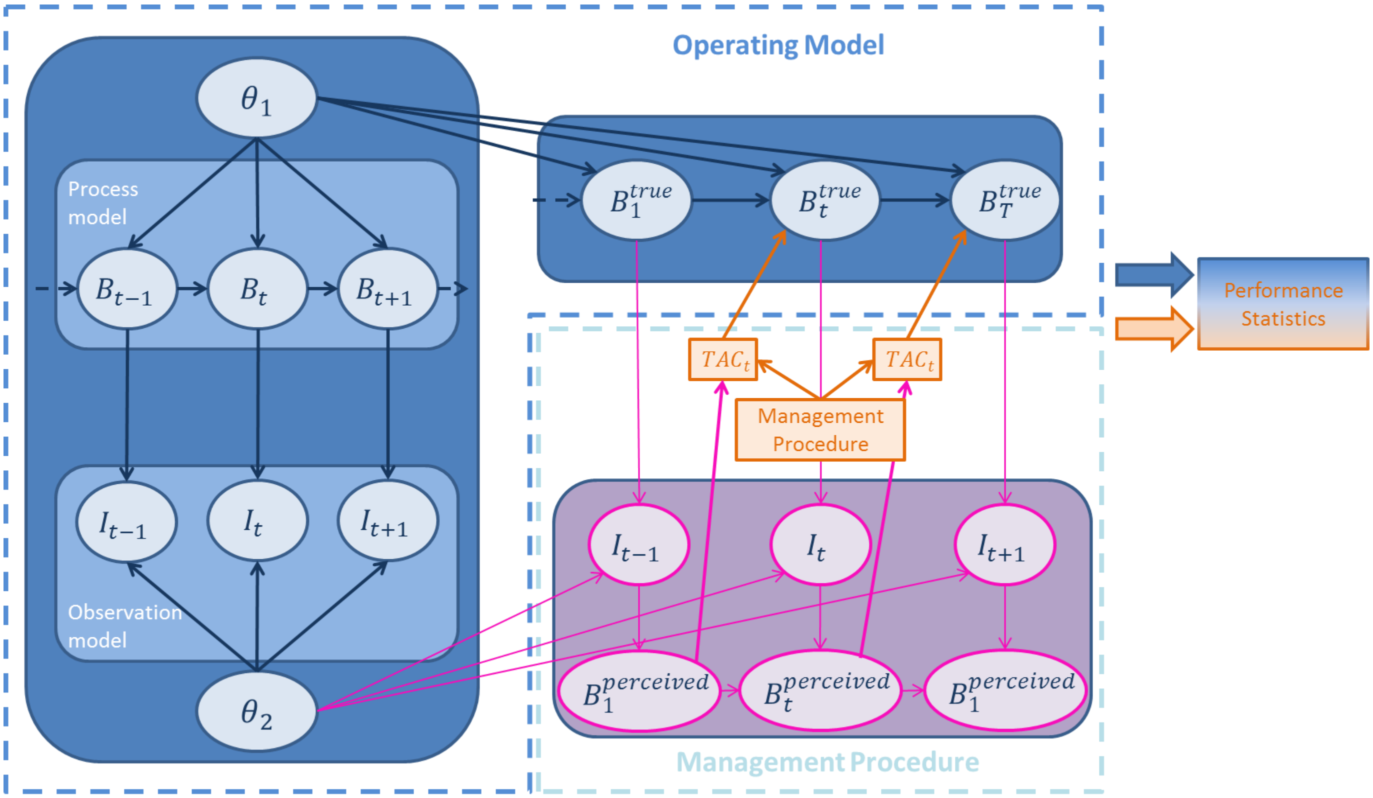


Figure 30: Conceptual framework for Management Strategy Evaluation (MSE). The simulated "real world" is captured by an operating model (OM). The parameters estimates of each OM are used to simulate/forecast a "true" population. Observation model error (θ_2) can be used to generate the "perceived" stock. Management procedure can be based on the "perceived" view of the stock (feedback harvest control rule, in pink in the figure) or can be independent of the perceived stock (e.g constant TAC over time). Performance statistics based on the catch and/or state of the "true" population are calculated for each OM. Note that here the TAC is used for illustration purpose and other management metrics could be used.

MSE Results

In this section we present the outputs of the MSE. For each OMs, 12 years projections were carried out and 3 performance statistics were calculated for each years under 4 HCRs.

The projections for the models using the Bayesian framework were done using the posterior distributions of the different parameters (5000 chains).

The ASPIC framework did not provide a tool to make projections and their associated uncertainties. Therefore, for the ASPIC OMs, the abundance projections were assumed to be drawn from a Log-Normal distribution with the same variance than variance of the 1000 bootstraps of the last year biomass calculated by ASPIC.

a. ASPIC-2012-UPDATED

For the ASPIC-2012-UPDATED OM, the 4 HCRs tested over 12 years (2015 to 2026) generated performance statistics under the thresholds decided during the FC-SC working group meeting in February 2014 (NAFO FC/SC Doc. 14/02). All probabilities tend to increase over the projection time (Fig. 31).

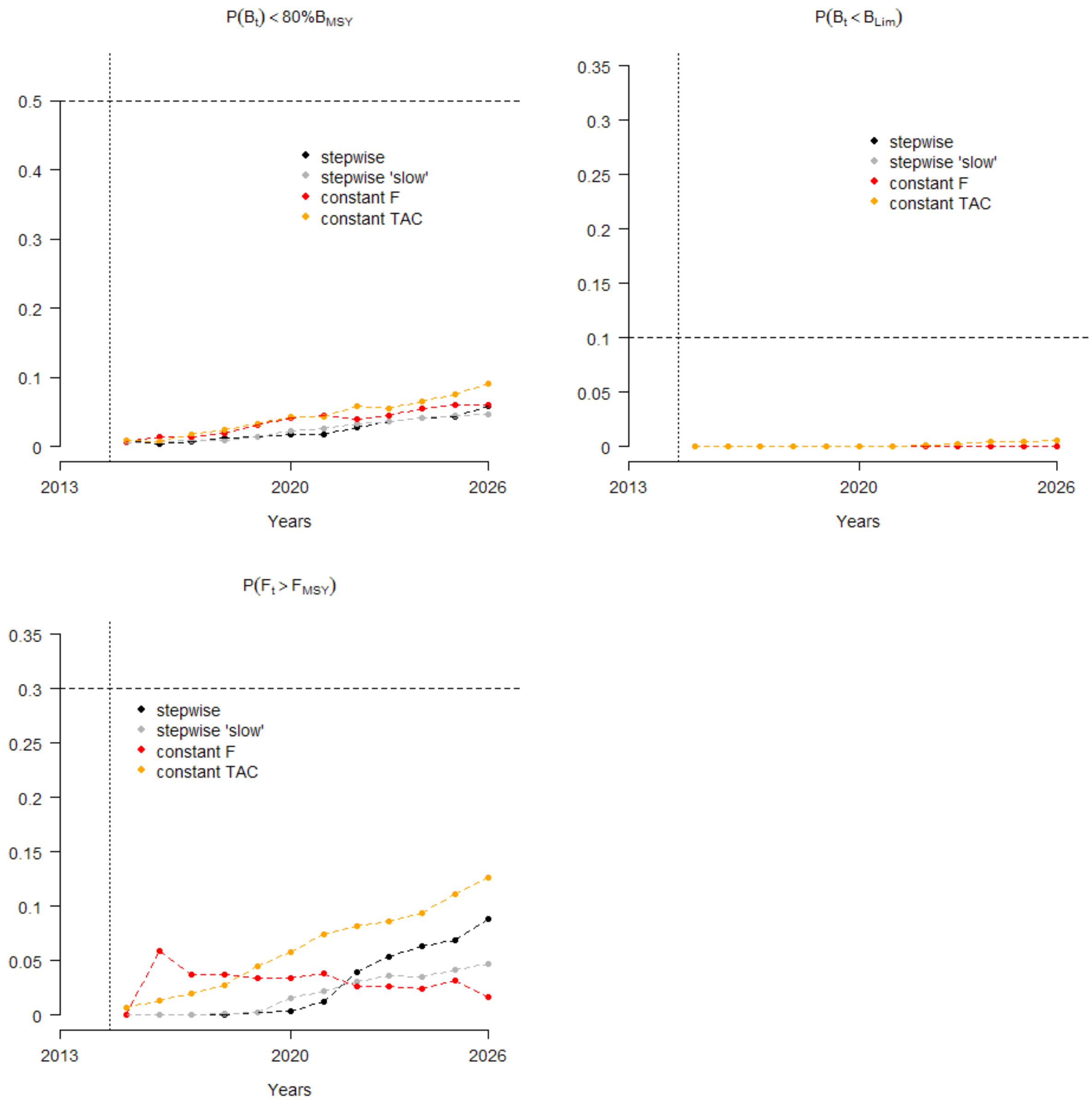


Figure 31. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the ASPIC-2012-UPDATED surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

b. ASPIC-2014

For the ASPIC-2014 OM, the 4 HCRs tested over 12 years (2015 to 2026) generated performance statistics different than the ones observed for the ASPIC-2012-UPDATED OM (Fig. 32). Overall, the probabilities of B < 80% of B_{MSY} and $B < B_{Lim}$ were under the threshold approved during the FC-SC working group meeting in February 2014 (0.5) but much higher than for the ASPIC-2012-UPDATED OM. In the HCR3 scenario (constant TAC of 20 000 tons) the probability to observe $F > F_{MSY}$ breaks the 30% threshold after 6 years.

All probabilities tend to increase over the projection time period except for the probability to observe $F > F_{MSY}$ under HCR4 which increases for 3 of the HCRs but levels off for one of the HCRs. The TACs for the HCR4 (2/3 F_{MSY}) are summarized in table 7 for comparison with the other HCRs.

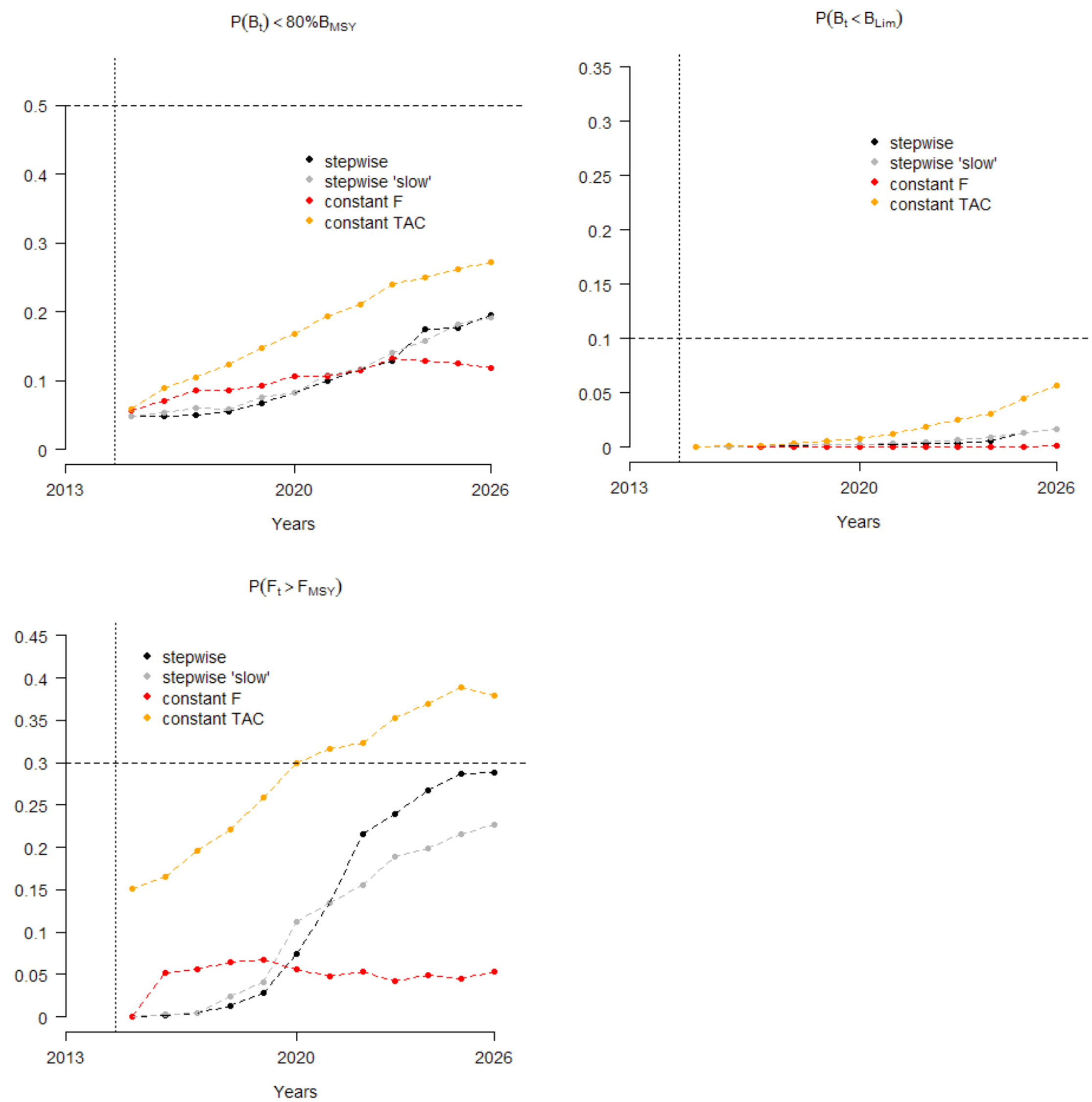


Figure 32. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the ASPIC-2014 surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

c. ASPIC-BAYES-2012-UPDATED

For the ASPIC-BAYES-2012-UPDATED OM, the 4 HCR tested over 12 years (2015 to 2026) generated performance statistics under the thresholds decided during the FC-SC working group meeting in February 2014. All probabilities tend to increase over the projection time period (Fig. 33).

The TACs for the HCR4 (2/3 F_{MSY}) are summarized in table 6 for comparison with the other HCRs.

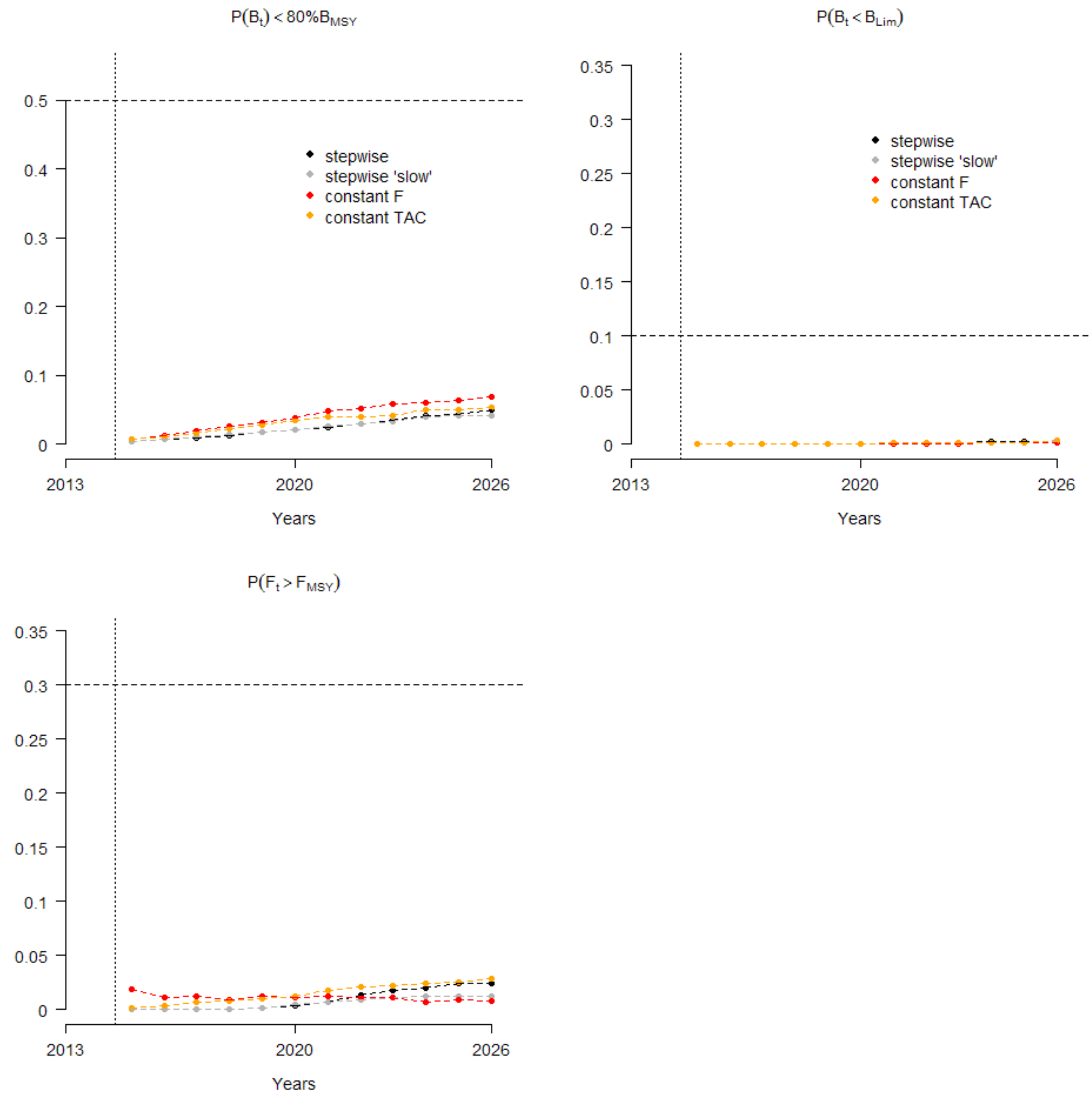


Figure 33. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the ASPIC-BAYES-2012-UPDATED surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

d. ASPIC-BAYES-2014

For the ASPIC BAYES 2014 OM, the 4 HCR tested over 12 years (2015 to 2026) generated performance statistics similar to the ones observed for the ASPIC 2014 OM (Fig. 34). Overall, the probabilities of B < 80% of B_{MSY} , B < B_{Lim} and F > F_{MSY} were under the threshold approved during the FC-SC working group meeting in February 2014.

All probabilities tend to increase over the projection time period except for the probability to observe F > F_{MSY} under HCR4 which decreases slowly. The TACs for the HCR4 (2/3 F_{MSY}) are summarized in table 7 for comparison with the other HCRs.

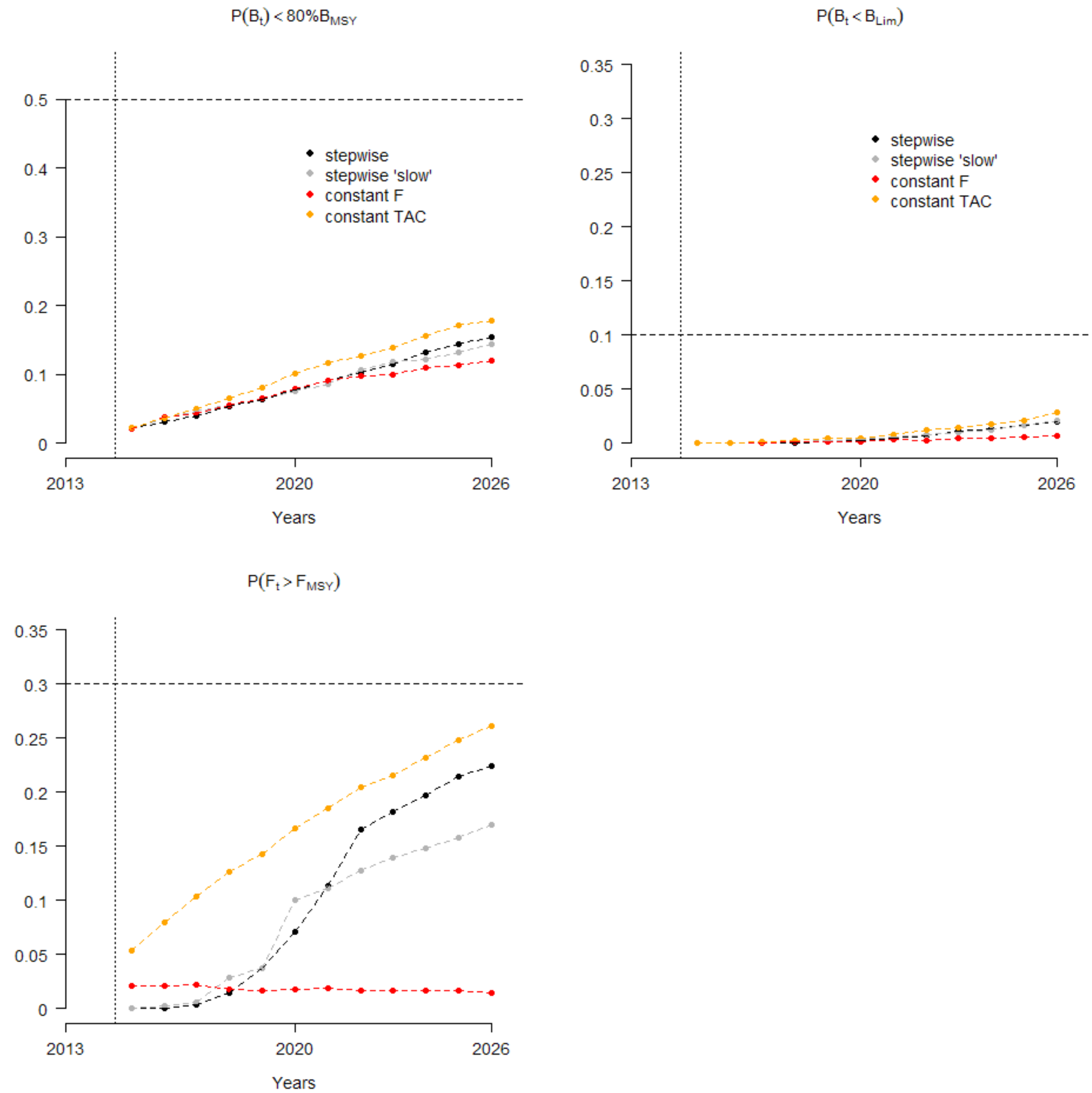


Figure 34. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the ASPIC BAYES 2014 surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

e. ASPIC-BAYES-FULL

For the ASPIC-BAYES-FULL OM, the 4 HCR tested over 12 years (2015 to 2026) generated performance statistics similar (pattern-wise) to the ones observed for the ASPIC-2012-UPDATED OM (Fig. 35). Overall, the probabilities of B < 80% of B_{MSY} , B < B_{Lim} and F > F_{MSY} were under the threshold approved during the FC-SC working group meeting in February 2014.

All probabilities tend to be stable over the projection time period except for the probability to observe B < B_{Lim} which slowly increase under HCR4. The TACs for the HCR4 (2/3 F_{MSY}) are summarized in table 7 for comparison with the other HCRs.

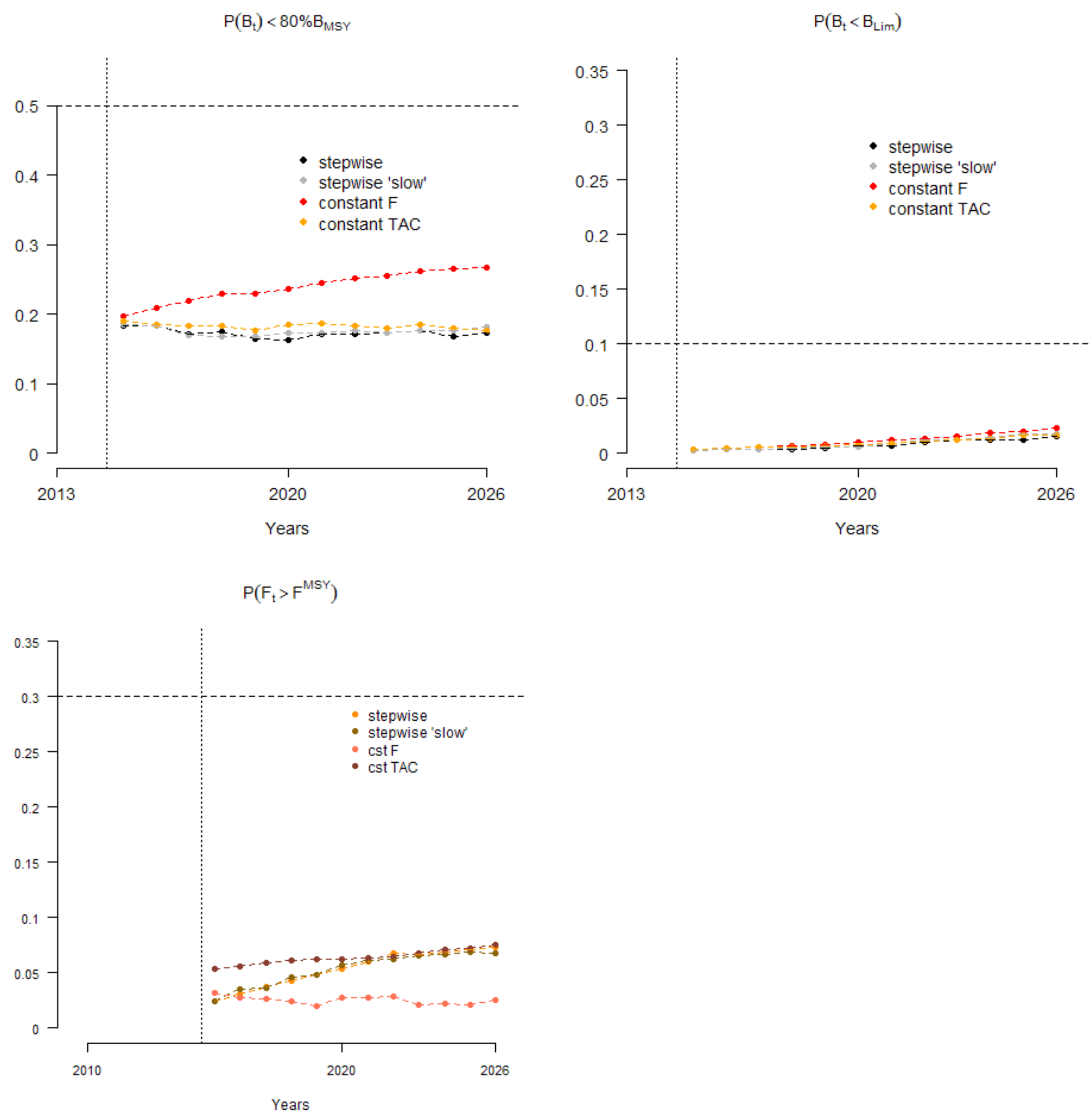


Figure 35. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the ASPIC-BAYES-FULL surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

f. BAYES-SPATIAL

For the BAYES-SPATIAL OM, the 4 HCR tested over 12 years (2015 to 2026) generated performance statistics similar (patternwise) to the ones observed for the ASPIC-2012-UPDATED OM (Fig. 36). Overall, the probabilities of B < 80% of B_{MSY} , $B < B_{Lim}$ and $F > F_{MSY}$ were under the threshold approved during the FC-SC working group meeting in February 2014.

All probabilities tend to be stable over the projection time period. The TACs for the HCR4 (2/3 F_{MSY}) are summarized in table 7 for comparison with the other HCRs.

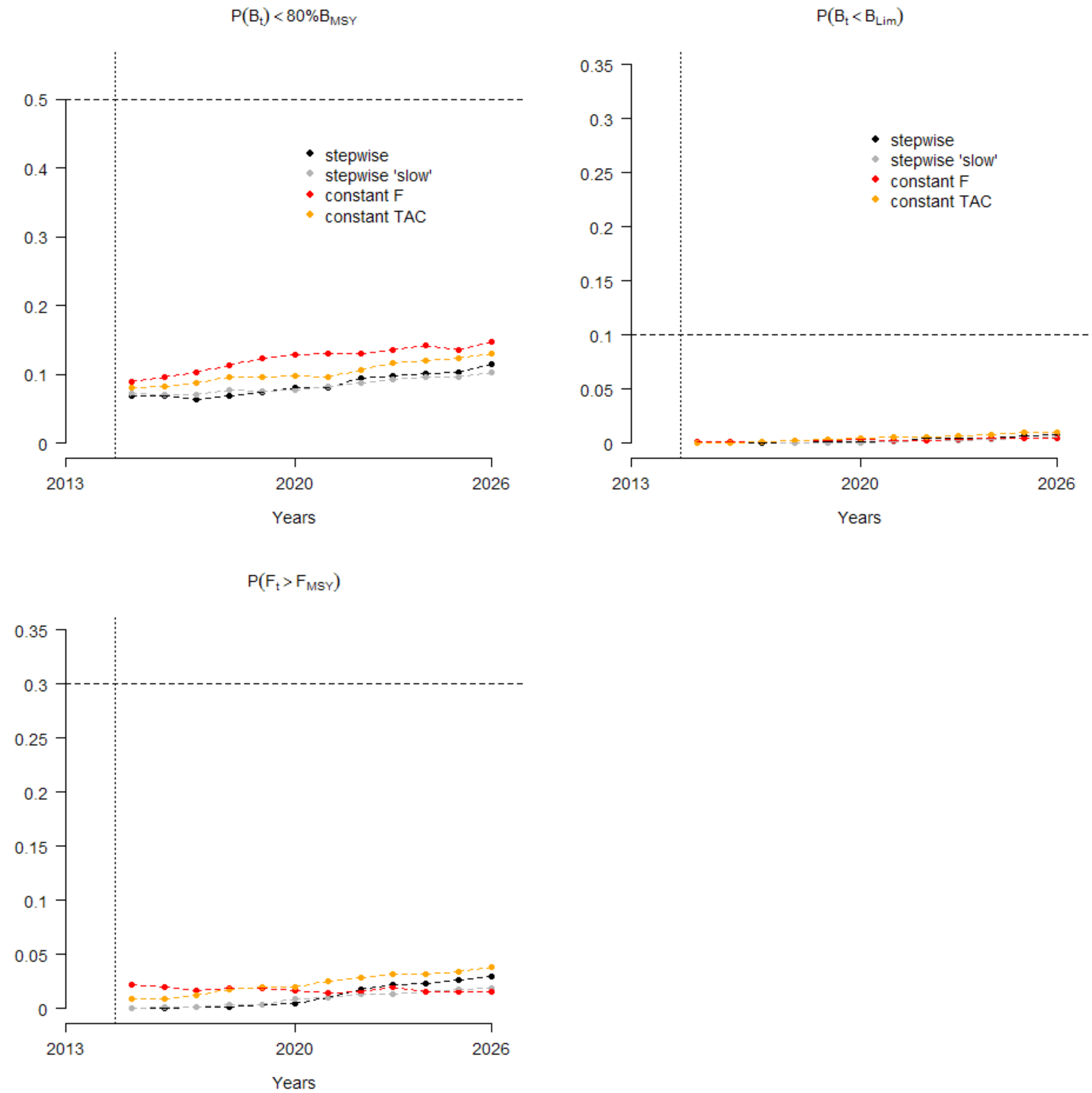


Figure 36. Evolution of the 3 performance statistics (From 2015 to 2028) used to evaluate the success or failure of the 4 management strategies applied to the BAYES-SPATIAL surplus production model: probability to observe a total biomass lower than 80% of B_{MSY} (left panel), probability to observe a total biomass lower than B_{Lim} (middle panel) and probability to observe a fishing mortality higher than F_{MSY} (right panel). The dashed lines indicate the threshold decided during the FC-SC working group meeting in February 2014.

Discussion

In this study, an MSE was carried out using six OMs and four different HCRs. All OMs were some form of surplus production model. Two of them were implemented using the ASPIC software (ASPIC-2012-UPDATED and ASPIC-2014). ASPIC-2014 is the currently accepted stock assessment. The four other OMs were implemented in a Bayesian framework, two of them were the Bayesian version of the ASPIC OMs (ASPIC-BAYES-2012-UPDATED and ASPIC-BAYES-2014), one of them included all datasets and had loose constraints on all prior distributions (ASPIC-BAYES-FULL) and the last one was a spatially disaggregated model (BAYES-SPATIAL). The HCR included two stepwise increasing TAC strategies (HCR1 and HCR2) a constant TAC strategy (HCR3) and a constant F strategy (HCR4).

For all OMS, projections were made for a 12 years time period and performance statistics ($P(B < 0.8 \cdot B_{MSY}) < 0.5$, $P(B < B_{Lim}) < 0.1$ and $P(F > F_{MSY}) < 0.3$) were calculated annually and compared to the different threshold agreed on during the FC-SC meeting in February 2014.

There was only scenario where one of the thresholds was broken. For the ASPIC 2014 OM under the constant TAC HCR (HCR3), after 6 years of such a regime of exploitation, the probability of observing a fishing mortality higher than F_{MSY} was greater than 0.3. Other than this scenario, all 4 HCRs applied to the 6 OMs generated performance statistics within the desired thresholds.

While we believe that this set of OMs makes sense because of the way the different OMs are somehow related, there is room for discussion regarding these choices and further options could be examined. For instance, one of the main hypotheses for all the OMs is that the population follows a logistic growth. One could argue that this is not necessarily the case and maybe different growth shape should be considered. As an exploratory exercise, a Schaefer-Pella-Tomlinson model was tested (in this model, the production equation has an additional parameter that allows asymmetry in the production curve) however, the asymmetry parameter was found to not be significantly different from 1.

Additionally, when comparing the ASPIC 2012 and ASPIC 2014 to the ASPIC BAYES 2012 and ASPIC BAYES 2014 respectively, it appeared that some of the parameters estimations showed some differences (e.g. K and B_{MSY}). The values obtained for the Bayesian models were significantly higher than their ASPIC counterparts and more importantly the posterior distributions showed some saturation on the right side of the distribution. This means that the script for the Bayesian modelling does not work exactly in the same fashion as the ASPIC modelling (at the time of the study, the specifics of the internal scripts of ASPIC were not available) and this should be investigated in order to i) be able to do an exact version of the ASPIC in the Bayesian framework and ii) know how exactly ASPIC works and what are all the underlying hypothesis.

The ASPIC BAYES FULL OM was written in order to look more into the saturation issue of some of the parameters posterior distribution by removing constraints on the different prior distribution. It was found that when these constraints were removed the saturation issues disappeared but the parameters estimations were unrealistically high according to all experts present at the SC meeting in June 2014. The data that is collected seems to indicate that the carrying capacity K or MSY are much higher than the current assessment indicates. Maybe surplus production models are not appropriate for this particular stock and data sets or it would need to be adapted, one option might be to look at a change in the carrying throughout the time series.

The 6 OMs that were investigated have shown similar trends regarding the evolution of the total biomass of the 3LN redfish stock (i.e. an increase in the last 10 years following a period of low abundance). However the abundance estimates in the more recent part of the time series showed some significant differences depending on the model considered. As mentioned above, this is mostly due to some high values encountered in the recent surveys and the logistic structure of the model which leads to higher estimations of MSY and K. This is an ongoing issue for this stock which has led to this year new stock assessment where MSY is fixed at 21 000 tons (based on the history of the fishery, Ávila de Mel et al., 2014). While this fixes the issues related to parameter estimation, it fails to bring some answers regarding the underlying population dynamics that lead to these recent survey observations.

This study shows that the stepwise increment HCR suggested by the FC-SC WG performs well no matter what OM is used, and therefore there is no counter-indication to use it. However it would be helpful to investigate alternative models that could explain the recent observed data in the surveys.

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