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Bayesian modelling of PFA abundance and forecasting Southern NEAC and northern NEAC complexes

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Introduction

Qualitative catch advice has been provided for the Faroes fishery based on status of the stock complexes relative to stock complex conservation limits. Quantitative catch advice has been provided for the West Greenland Commission fishery using two forecast models; one for the non-maturing 1SW salmon of North American origin, the other for 1SW non-maturing salmon from the southern NEAC complex (one of the four stock complexes in NEAC but the only one which is affected by the West Greenland fishery). Both models are based on generally similar data and similar approaches, including a lagged spawner variable to define the spawning stock, and a recruitment variable termed the PFA (Pre-Fishery Abundance), with a function relating the spawning component to the recruitment.

Models have not been proposed for the maturing 1SW stock complex from southern NEAC nor for any of sea age groups in the northern NEAC stock complex.

The following document proposes models which could be used to provide quantitative forecasts for both sea age groups in the southern NEAC and northern NEAC complexes.

WGNAS model for southern NEAC non-maturing 1SW samon

The pre-fishery abundances (PFA) of salmon from countries in the NEAC area were based on a run reconstruction model described by Potter et al. (1998, 2004). PFA in the NEAC area is defined as the number of 1SW recruits on January 1st in the first sea winter. The reconstruction begins with catch in numbers of 1SW and MSW salmon in each country. These are raised to take account of minimum and maximum estimates of non-reported catches and exploitation rates of the two sea-age groups. The values are raised to take account of the natural mortality between January 1st in the first sea winter and the mid-point of the respective national fisheries. PFA estimates are developed for the maturing 1SW and non-maturing 1SW components from the southern and northern NEAC stock complexes.

The spawner variable is defined in terms of the total eggs which would have contributed to the PFA abundance. The spawner abundances by age group (1SW, MSW) are converted to eggs based on biological characteristics of the age groups specific to each country (or region). The eggs are lagged forward based on the smolt age distributions of the spawners in each country. The lag consists of the smolt age plus two years (one for the year of egg deposition plus one for the first year at sea), with the smolt age proportions assumed constant for each region and age group.

The Working Group has considered a model to forecast the PFA of non-maturing (potential MSW) salmon from the Southern European stock group (ICES, 2002, 2003). The number of years for which forecasts may be provided is limited by the Spawner (lagged egg) parameter within the model. The time series for this parameter extends only as far as those lagged eggs assigned to 1-year old smolts from the most recent available spawning year, currently lagged eggs for 2009 derived from 2006 spawner estimates. To allow PFA forecasts for 2010, lagged egg production assigned to 1-year old smolts for 2010 for each home water country was estimated by taking the average of the previous 5 years.

The full model takes the form:

$$PFA = Spawners^{\lambda} \times e^{\beta_0 + \beta_2 \log(PFAm) + \beta_3 Year + \xi}$$

where *Spawners* are expressed as lagged egg numbers (all age groups),

PFAm is pre-fishery abundance of maturing 1SW salmon

Parameter selection was achieved by adding variables (*Spawners, PFAm* and *Year*) until the addition of others did not result in an increase in the explanatory power of the model. The model was fitted to data from 1978 to the most recent year and the parameters retained have always been *Spawners* (*LSeggs*)and *Year*. The final model took the form:

$\mathrm{Ln}(PFA_t/LSeggs_t) = \alpha + \beta * Ln(LSeggs_t) + \delta * Year_t + \varepsilon$

The year coefficient estimate is negative resulting in a continued decline in recruitment rate over time. The Working Group had also only used the midpoints of the lagged eggs and the midpoint of the PFA reconstructions for the southern NEAC non-maturing component.

Alternative Models for NEAC

The proposed models for the Northern NEAC complex and the Southern NEAC complex have exactly the same structure and are run independently. A Directed Acyclic Graph (DAG) for the model is provided in Figure 1.

Equations (1)-(8) stand for both the Northern and the Southern NEAC complexes. For purpose of clarity, the subscript n (for North) and s (for South) are ommited in the equations.

1. From lagged eggs to returns

Lagged Eggs → PFA

Lagged eggs

Lagged Eggs are calculated by pooling 1SW and MSW lagged eggs (lagged eggs are in thousands in the model) (Table 1). It is therefore assumed that 1SW and MSW lagged eggs have exactly the same contribution to maturing and non maturing *PFA*.

(1) $$LE_t = LE_{1,t} + LE_{2,t}$$

Non maturing and maturing PFA

The next stage after lagged eggs is the *PFA*, defined as the number of recruits on january 1st after the first winter at sea. The model considers both the maturing *PFA* (denoted *PFAm*) and the non maturing PFA (denoted *PFAnm*).

For each year t, a proportional relationship is assumed between LE_t and the expected means of the maturing PFA, with a productivity factor $\alpha_{m,t}$ (in the log-scale). Two hypotheses about the time-structure of the productivity parameter $\alpha_{m,t}$ are contrasted (see below). The productivity is considered to be random and i.i.d with multiplicative log-normal errors with variance σ^2_{PFA} :

(2) $$PFAm_t = LE_t \cdot e^{\alpha_{m,t}} \cdot e^{\varepsilon_{m,t}} \qquad with \quad \varepsilon_{m,t} \overset{i.i.d}{\sim} N(0, \sigma^2{}_{PFA})$$

Similarly, for each year t, a proportional relationship is assumed between LE_t and the expected means of the non maturing *PFA*, with a productivity factor $\alpha_{nm,t}$. The productivity is considered to be noised with i.i.d. multiplicative log-normal random errors with the same variance σ^2_{PFA} :

(3) $$PFAnm_t = LE_t \cdot e^{\alpha_{nm,t}} \cdot e^{\varepsilon_{nm,t}} \qquad with \quad \varepsilon_{nm,t} \overset{i.i.d}{\sim} N(0, \sigma^2{}_{PFA})$$

The random environmental noise in the productivity of maturing and non maturing PFA are assumed independent.

However, the productivity for maturing and non maturing *PFA* are not modelled independently. The productivity of non maturing *PFA* is modelled as:

(4) $$\alpha_{nm,t} = \alpha_{m,t} + \log\left(\frac{1 - p.PFAm_t}{p.PFAm_t}\right)$$

such that the expected rate of maturing *PFA vs* total *PFA* productivity is $p.PFAm_t$:

(5) $$\frac{e^{\alpha_{m,t}}}{e^{\alpha_{m,t}} + e^{\alpha_{nm,t}}} = p.PFAm_t$$

Therefore, the hypothesis underlying this model is that the time variability of the productivity for maturing and non maturing PFA will be closely related. From the equation (4), a high productivity for maturing PFA will correspond to a high productivity of non maturing PFA. However, time variations of the parameter $p.PFAm_t$ introduce some flexibility in the synchrony of the maturing and non maturing productivity.

Modelling the rate of maturing PFA $p.PFAm_t$

The rate of maturing PFA, $p.PFAm_t$, are supposed to vary by time following an exchangeable hierarchical structure.

Modelling the time structure of the productivity parameter $\alpha_{m,t}$

Two alternative models for the productivity parameter were tested for the Southern NEAC complex: the Random walk model and the Shifting Level model (for the Northern NEAC complex, only the random walk model was tested).

Random walk (RW)

In the first hypothesis, the productivity parameters are supposed to vary by time following a simple random walk with a flat prior on the first value of the time series :

(6a) *Initialization* $$\alpha_{m,1} \sim N(0, V = 1000)$$

$$t = 1,\ldots,n-1 \qquad \alpha_{m,t+1} = \alpha_{m,t} + \omega_t \qquad with \quad \omega_t \overset{i.i.d}{\sim} N(0, \sigma^2_{\alpha})$$

with non informative prior on the precision

(6b) $$1/\sigma^2_{\alpha} \sim Gamma(0.01, 0.01)$$

The model can be used both for retrospective analysis and forecasts. Indeed, provided the variance σ^2_{α} is large enough, the random walk structure will enable us to capture any kind of change in the productivity along the time series of historical data. Equation 6 shows that persistence (memory) and possibility of variation will be accounted for at any time in the forecasts. Indeed, if the productivity level is α at time $t = n$, then the forecasted productivity at time $t = n+1$ is random and normally distributed around the previous level of productivity.

Shifting level model (SL)

The shifting level model (*Fortin et al. 2004.*) is an interesting alternative to the simple random walk model. By contrast with the RW model that assumes that the productivity may change each year, the SL model supposes that the level of productivity remains constant for epochs, with abrupt shift in the levels between epochs (7). However, the model is highly flexible because both the number of epochs, their duration and the corresponding levels of productivity are unknowns a priori and do not need to be specified a priori.

(7a) *Initialization* $$\alpha_1 \sim N(\mu_{\alpha}, \sigma^2_{\alpha})$$

$$t = 1,\ldots,n-1 \qquad \alpha_{t+1} = \begin{cases} \alpha_t & \text{with proba } (1-p_{shift}) \\ \alpha_t^{new} \sim N(\alpha_t, \sigma_\alpha^2) & \text{with proba } (p_{shift}) \end{cases}$$

with non informative prior

(7b)
$$p_{shift} \sim Beta(1,1)$$
$$1/\sigma^2_\alpha \sim Gamma(0.01, 0.01)$$

The model can be used both for retrospective analysis and forecasts. Retrospective analysis enable us to infer *a posteriori* the phase(s) (levels, shifting points and duration) in the historical series of data. The probability of seeing a shift at any time *t* is also estimated, and can then be used for forecasting. Equation (7c) shows that both persistence (memory) and possibility of a shift will be accounted for at any time in the forecasts. Indeed, if the productivity level is α at time *t* = *n*, then the forecasted productivity at time *t* = *n+1* is defined as :

(7c)
$$\alpha_{n+1} \begin{cases} = \alpha & \text{with probability } (1-p_{shift}) \\ = \alpha + \omega & \text{where } \omega \sim N(0, \sigma_\alpha{}^2) \quad \text{with probability } p_{shift} \end{cases}$$

PFAm / PFAnm → Returns

Maturing PFA → Returns as 1SW

Survival of maturing up to Faroes catches (0-1 months after reference time) is modelled through a Binomial distribution:

(8a)
$$N_{1,m}(t) \sim Binomial(PFA_m(t), s_{1.1}(t))$$
$$s_{1.1}(t) = \exp(-M_1 \cdot time_{1.1})$$
$$M_1 \sim N(0.03, \sigma^2{}_M)$$
$$time_{1.1} = 0.5$$

The natural mortality is constant between years, and considered as uncertain. Uncertainty is modelled as a Normal distribution with mean 0.03 (instantaneous rate of mortality per month) and standard deviation ensuring that 95% of the probability is between 0.02 and 0.04.

Catches of maturing 1SW salmon at Faroes are introduced as covariates (subscript "•" in the catches stands for the region North or South, depending upon the model under concern). Uncertainty about catches are introduced (see below).

(8b)
$$N_{1,1}(t) = N_{1,m}(t) - CF1_{\bullet,m}(t)$$

Survival up to Returns as 1SW (7-9 months after reference time).

(8c)
$$R_1(t) \sim Binomial(N_{1,1}(t), s_{1.2}(t))$$
$$s_{1,2}(t) = \exp(-M_1 \cdot time_{1.2})$$
$$time_{1.2} = 7.5$$

Non-Maturing PFA → Returns as MSW

Survival of non maturing (0-1 months)

(8d)
$$N_{1,nm}(t) \sim Binomial(PFA_{mnm}(t), s_{1.1}(t))$$
$$s_{1.1}(t) = \exp(-M_1 \cdot time_{2.1})$$
$$time_{2.1} = 0.5$$

Catches of non maturing 1SW salmon at Faroes are introduced as covariates. Uncertainty about catches are introduced (see below).

(8e)
$$N_{2,0}(t) = N_{1,nm}(t) - CF1_{\bullet,nm}(t)$$

Survival up to the Greenland fishery (8-10 months from the reference time)

(8f)
$$N_{2,1}(t) \sim Binomial(N_{2,0}(t), s_{2.1}(t))$$
$$s_{2.1}(t) = \exp(-M_2 \cdot time_{2.2})$$
$$M_2 \sim N(0.03, \sigma^2{}_M)$$
$$time_{2.2} = 8.5$$

Catches of MSW at West Greenland are introduced as covariates. Uncertainty about catches are introduced (see below).

(8g)
$$N_{2,2}(t) = N_{2,1}(t) - CG2_{\bullet}(t)$$

Survival up to the Faroes fishery 2SW (13-14 months from the reference time)

(8h)
$$N_{2,3}(t+1) \sim Binomial(N_{2,2}(t), s_{2.2}(t+1))$$
$$s_{2.2}(t+1) = \exp(-M_2 \cdot time_{2.3})$$
$$tme_{2.3} = 5$$

Catches of MSW at Faroes are introduced as covariates. Uncertainty about catches are introduced (see below).

(8i)
$$N_{2,4}(t+1) = N_{2,2}(t+1) - CF2_{\bullet}(t+1)$$

Survival up to returns as 2SW (16-19 months from the reference time)

(8j)
$$R_2(t+1) \sim Binomial(N_{2,4}(t+1), s_{2.3}(t+1))$$
$$s_{2.3}(t+1) = \exp(-M_2 \cdot time_{2.4})$$
$$time_{2.4} = 3.5$$

2. Incorporating uncertainty about lagged eggs, returns and catches

Lagged eggs

Uncertainty was accounted for in the lagged eggs. Lagged eggs of 1SW and MSW fish were both considered distributed as Normal distributions with median and standard deviation issued from Monte-Carlo run reconstruction at the scale of the stock complex (Southern and Northern NEAC) (Table 1).

(9)
$$LE1_t \sim Normal(LE1.med_t, \sigma^2_{LE1,t})$$
$$LE2_t \sim Normal(LE2.med_t, \sigma^2_{LE2,t})$$

Returns

The model is designed to account for the uncertainty about the returns through the pseudo-observation method proposed by Michielsens et al. (2008).

(10)
$$R1.med_t \sim Normal(R1_t, \sigma^2_{R1,t})$$
$$R2.med_t \sim Normal(R2_t, \sigma^2_{R2,t})$$

where R1.med, R2.med and σ_{R1}, σ_{R2} are respectively the medians and the standard deviations of the estimated returns issued from Monte-Carlo run reconstruction at the scale of the stock complex (Southern and Northern NEAC) (Table 4).

However, at present, the uncertainty in the returns was not accounted for. The model was run with σ_{R1}=1 and $\sigma_{R2=1,}$; this corresponds to virtually no observation errors on returns.

Catches

1SW Faroes catches

Estimation of true catches of 1SW fish (*C*) are derived from the declared captures (C^{dec}) and assumptions made on the corresponding discarded rate (*unr*). The assumption is that 80% of the total (1SW+MSW) discarded catches die. Because the discarded rate *unr* is given for total cactches :

(11)
$$CF1_t = CF1^{dec}{}_t + 0.8 \cdot (CF1^{dec}{}_t + CF2^{dec}{}_t) \cdot \frac{unr_t}{(1 - unr_t)}$$

Source of Uncertainty: Discard rate $unr_t \sim Unif()$ (bounds depend upon time).

Distinction is then made between mature (that will return as 1SW grilse) and non mature (that will return as MSW fish) 1SW fish.

1SW Faroes catches - Maturing

A correction factor is applied to $CF1_t$ to account for the proportion of mature fish, prop. of catches attributed to Southern NEAC, and the prop. of wild fish :

(11a)
$$CF1_{s,m_t} = \left[pm_{F1t} \cdot p_{wt} \cdot p_{S,F1m}\right] \cdot CF1_t$$
$$CF1_{n,m_t} = \left[pm_{F1t} \cdot p_{wt} \cdot (1 - p_{S,F1m})\right] \cdot CF1_t$$

Source of Uncertainty: - Proportion of mature 1SW $pm_{F1_t} \sim Unif(0.73, 0.83)$

Fixed coef: - Proportion wild fish $p_{wt} =$ fixed value but depends upon time

- Proportion Southern NEAC $p_{S,F1m} = 0.5$ (constant over time)

1SW Faroes catches – Non Maturing

A correction factor is applied to $CF1^{true}{}_t$ to account for the proportion of non mature fish, prop. of catches attributed to Southern NEAC and the prop. of wild fish :

(11b)
$$CF1_{s,nm_t} = \left[(1-pm_{F1t})\cdot p_{wt}\cdot p_{S,F1nm}\right]\cdot CF1_t$$
$$CF1_{n,nm_t} = \left[(1-pm_{F1t})\cdot p_{wt}\cdot (1-p_{S,F1nm})\right]\cdot CF1_t$$

Source of Uncertainty: - Proportion of mature 1SW $pm_{F,1SW_t} \sim Unif(0.73, 0.83)$

Fixed coef: - Proportion wild fish p_{wt} fixed value (same as mature 1SW)

- Proportion Southern NEAC $p_{S,F1nm} = 0.275$ (constant over time)

MSW Faroes catches

Declaration rate is supposed to be =100%.

A correction factor is applied to $CF2^{true}{}_t$ to account for the prop. of catches attributed to Southern NEAC and the prop. of wild fish :

(12)
$$CF2_{st} = \left[p_{S,F2}\cdot p_{wt}\right]\cdot CF2^{dec}{}_t$$
$$CF2_{nt} = \left[(1-p_{S,F2})\cdot p_{wild\,t}\right]\cdot CF2^{dec}{}_t$$

Source of uncertainty : - None

Fixed coef: - Proportion Southern NEAC $p_{S,F2} = 0.5$

- Proportion wild fish p_{wt} =fixed value but depends upon time (same as 1SW)

West Greenland MSW catches

The declaration rate is supposed to be 100%, i.e. there are estimates of unreported catch from the fishery which are added to the declared catches from 1993 to 2007.

A correction factor is then applied to account for the proportion of catches attributed to southern NEAC and the proportion of wild fish in these catches :

(13)
$$CG2_{S_t} = \left[p_{NEAC\,t}\cdot p_{St}\cdot p_{wt}\right]\cdot CG2^{dec}{}_t$$
$$CG2_{nt} = \left[p_{NEAC\,t}\cdot (1-p_{St})\cdot p_{wt}\right]\cdot CG2^{dec}{}_t$$

Source of uncertainty: - Proportion NEAC $p_{NEAC\,t}$ (random – Method depends upon the year)

Fixed coef: - Proportion southern NEAC p_s = 0.969 (constant over time)

3. Fitting and forecasting

3.1. Fitting

For the Southern NEAC model, the model was fitted to an historical data series of 29 years, lagged eggs starting from 1978 to 2006, and returns starting from 1978 to 2007 (last year for MSW returns issuing from lagged eggs of year 2006). Indeed, although the return estimates to southern NEAC begin in 1971, the lagged eggs are only available from 1978 due to the smolt age distributions (1 to 5 years) (Tables 1 and 2).

For the Nouthern NEAC model, the model was fitted to an historical data series of 16 years, lagged eggs starting from 1991 to 2006, and returns starting from 1991 to 2007 (last year for MSW returns issuing from lagged eggs of year 2006). Indeed, return estimates begin in 1983 but due to the smolt age distributions (1 to 6 years),the lagged eggs are only available from 1991 onward (Tables 1 and 2).

All models were fitted in a Bayesian framework under the OpenBUGS 3.0.3 software (http://mathstat.helsinki.fi/openbugs/ ; Lunn et al. 2000).

3.2. Forecasting

Fitting and forecastings were derived in a single consistent Bayesian framework.

For both Southern and Northern NEAC complexes, forecastings were derived for 4 years, for lagged eggs starting from 2007 to 2010.

As first illustration, forecastings were performed under the scenario of null exploitation rates (all sea catches =0)

3.3. Estimated risks

Risks are defined each year as the posterior probability that the PFA stands below the SER levels.
SER levels are defined as follow :

Southern complex	Maturing PFA	SER = 842396 fish
	Non maturing PFA	SER = 498216 fish
Northern complex	Maturing PFA	SER = 306318 fish
	Non maturing PFA	SER = 213495 fish

4. Results

The trends in lagged eggs are shown in Figure 2 and the trends is returns of 1SW and MSW to the southern NEAC and northern NEAC stock complexes is shown in Figure 3.

<u>Southern NEAC</u>

The total PFA (mature and non-maturing 1SW salmon at Jan. 1 of the first winter at sea) ranged between 3 million and 4 million fish between 1978 and 1989 and declined rapidly to just over 2 million fish in 1990 (Figure 4). Further declines occurred since then to its lowest level of just over one million fish in 2006 (Figure 4). The non-maturing 1SW PFA fell below the spawning escapement reserve (SER) for southern NEAC in 2006 (842396 fish) whereas the maturing 1SW PFA remained above the maturing 1SW SER (498216) but reached its lowest level as well in 2006 (Figure 4).

Over the entire time series, the maturing proportions averaged about 0.6 with the lowest proportion in 1980 and the highest proportion in 1998 (Figure 4). There is an increasing trend in the proportion maturing (8 of 13 values below the average during 1978 to 1990 compared with 3 of 16 values between 1991 and 2006) (Figure 4).

Based on this model, the overall PFA is expected to be about the levels observed in 2005 and 2006 but with increasing uncertainty from 2007 to 2010 (Figure 4). The 25th percentiles of the maturing 1SW non-maturing PFAs are expected to fall below SER during that time (Figure 4).

The productivity parameters for the maturing and non-maturing components are linked, peaked in 1985 and 1986, and reached the lowest values in 1997 (Figure 5).

Northern NEAC

The series of lagged eggs and returns for the northern NEAC complex is shorter than for the southern NEAC complex, beginning in 1991. Peak PFA abundance was estimated at about 2 million fish in year 2000 with the lowest value of the series in 2004 at over 1 million fish (Figure 6). The proportion maturing has varied around 0.5 over the time series (Figure 6). The maturing PFA abundance has generally been under one million fish whereas non-maturing PFA has been about 500 thousand fish (Figure 6).

The productivity parameter is higher on maturing 1SW salmon than on the non-maturing component (Figure 7).

Based on this model, the overall PFA and the maturing and non-maturing components are expected to decline into 2010 (Figure 8).

Comparison of southern and northern NEAC complexes

There has been a more important decline in total PFA in southern NEAC compared to northern NEAC with the most important change in the non-maturing 1SW salmon (Figure 9). Whereas 1SW non-maturing salmon of the southern NEAC complex were more abundant than the northern NEAC complex prior to 1996, these fish are now more abundant in the northern NEAC complex (Figure 9). The 1SW maturing component remains more abundant in the southern NEAC complex, the difference between the northern and southern areas is getting smaller (Figure 9). Projected median abundances of maturing and non-maturing 1SW salmon are expected to decline further in the northern area relative to the southern area (Figure 9). The northern NEAC has higher productivity parameters than southern NEAC, and particularly for the non-maturing 1SW component (Figure 10).

Comparison of random walk versus shifting level models of the productivity parameter for southern NEAC

As mentioned previously, the shifting level (SL) model is an interesting alternative to the simple random walk model (Fortin et al. 2004). The SL model supposes that the level of productivity remains relatively constant for periods but can be subjected to abrupt shift in the levels. Under the SL model, the number of periods, their duration and the corresponding levels of productivity are unknown and need not be specified a priori.

The southern NEAC time series of lagged spawners and returns suggest that there has been an abrupt shift in productivity between the 1989 and 1990 PFA years (Figure 10). Productivity was almost halved and rather abruptly. There was a secondary higher level of probability of a shift in level in 1981 to 1982 although the probability of a shift was less than 50% (Figure 10).

The PFA estimates are similar between the models but the forecast variance is smaller (at least within the interquartile range) for the shift model compared to the random walk model. The productivity parameter estimates are less variable post-1990 for the shift level model compared to the random walk model (Figure 12). The shift level model has fewer parameters to estimate and is considered a more parsimonious model than the random walk model (although this has not been formally tested).

Estimated risks

Figure 13 shows that for the Southern NEAC complex, the estimated risks are rather high for both the maturing and non maturing component, even in the absence of catches.

The estimated risks are very low for the Northern NEAC complex.

Figure 13 also highlights that for the Southern NEAC complex, the estimated risks for the 4 forecasting are lower for the shifting level model than for the random walk model. this is due to the lower prediction variance that is estimated in the shifting level, thus emphasizing the interest of that model for prediction purpose.

Discussion

Further work to be done :

- incorporating observation errors on returns via the pseudo-observation method of Michielsens (2008)

- posterior checks on model assumptions

- …

Suggest using the random walk model now for southern and northern NEAC as a start.

References

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Table 1. Lagged eggs input data from 1SW and MSW salmon for southern NEAC and northern NEAC stock complexes.

		Lagged Eggs (x1000)							
		Southern complex				**Northern complex**			
Program		**1SW**		**MSW**		**1SW**		**MSW**	
index	**Year**	**LE1.s.med**	**LE1.s.sd**	**LE2.s.med**	**LE2.s.sd**	**LE1.n.med**	**LE1.n.sd**	**LE2.n.med**	**LE2.n.sd**
	1971								
	1972								
	1973								
	1974								
	1975								
	1976								
	1977								
1	**1978**	1871509	277790	3475852	295669				
2	**1979**	1881394	302265	3168537	282182				
3	**1980**	1534913	216004	2599006	226919				
4	**1981**	1363470	184325	2269406	182603				
5	**1982**	1328201	163820	2326683	198887				
6	**1983**	1307350	152336	2208592	189956				
7	**1984**	1076089	120225	2329531	193730				
8	**1985**	756976	61638	2512784	203147				
9	**1986**	962300	95601	2291205	173391				
10	**1987**	1420642	160108	2519847	387863				
11	**1988**	1186171	99600	2256886	176568				
12	**1989**	1202829	141762	2430152	155656				
13	**1990**	1458483	173305	2802270	197814				
14	**1991**	1320526	118650	2879606	190784	417690	37972	1286570	112558
15	**1992**	1629752	144244	2982303	189084	389614	34702	1260003	112381
16	**1993**	1615033	119568	3058012	194143	358096	30693	1086365	90481
17	**1994**	1276725	82177	2617905	162673	376138	26756	969181	71120
18	**1995**	1013883	64754	2266488	135579	382404	24971	975463	66974
19	**1996**	1237046	87843	2194422	138061	373392	22321	1063820	69970
20	**1997**	1326386	78629	2318304	150329	393339	24085	1142413	76255
21	**1998**	1184101	77723	2332564	144594	415071	26578	1126249	73250
22	**1999**	1241069	85098	2396319	151514	451896	32078	1191307	83264
23	**2000**	1174179	79349	2038297	133310	427101	30366	1167153	79475
24	**2001**	1186221	78878	1674014	118537	410905	29209	1068526	71431
25	**2002**	1292868	84751	1388887	83780	467726	34870	974291	67774
26	**2003**	1102125	76038	1458156	123713	530917	38631	901706	65621
27	**2004**	1348298	100976	1625616	102708	537948	38613	981960	69071
28	**2005**	1325611	79836	1684037	113273	557687	37675	1184107	75400
29	**2006**	1166573	69473	1659622	107061	**613236**	**53065**	**1515791**	**102685**
30	**2007**	1183404	67028	1735708	113815	**626143**	**68767**	**1599622**	**103525**
31	**2008**	1152553	57854	1734499	109386	**595631**	**64571**	**1385847**	**87010**
32	**2009**	1196516	57425	1704986	109745	**496525**	**51636**	**1123482**	**71174**
33	**2010**	1150428	51848	1548066	109662	**455918**	**44702**	**920319**	**57121**
34	**2011**	1372989	140258	1481952	97791	**460127**	**49934**	**950932**	**64152**

Table 2. Returns of 1SW and MSW back to home countries for 1SW and MSW salmon for southern NEAC and northern NEAC stock complexes.

	Returns							
	Southern complex				Northern complex			
	1SW		MSW		1SW		MSW	
Year	R1.s.med	R1.s.sd	R2.s.med	R2.s.sd	R1.n.med	R1.n.sd	R2.n.med	R2.n.sd
1971	2124802	158370	933898	66789				
1972	2115219	167980	1188952	84775				
1973	2298831	183438	1221103	93848				
1974	2426801	202628	950703	71427				
1975	2476161	220981	1074012	81039				
1976	1780144	152791	670211	50401				
1977	1682015	133320	720974	52559				
1978	1699462	120137	798961	61769				
1979	1502051	109913	589042	48224				
1980	1186277	85510	795349	56149				
1981	962842	50292	841586	57486				
1982	1407414	80526	583898	43605				
1983	2000699	128931	759722	92173	906440	62282	604752	38942
1984	1413309	80381	563848	37924	951441	66603	612941	38751
1985	1666895	110609	677438	45427	1064461	67500	578778	35473
1986	1962665	130595	848671	61074	938888	58324	661316	42271
1987	1429811	105906	615318	41272	842174	49777	516987	32990
1988	1971442	125453	844358	59027	711759	42930	442681	26535
1989	1645632	96267	724701	49134	835762	52901	358983	20379
1990	1007255	58984	625188	41405	749343	46396	429484	24487
1991	831839	45365	460504	31382	682552	41072	392005	20970
1992	1190158	67354	556710	40679	686907	37600	411952	22379
1993	1151443	64155	494536	36465	633011	33672	436765	20067
1994	1225849	69532	593809	42160	726093	47533	403728	20586
1995	1223616	67994	563704	39973	559000	30633	415112	20736
1996	1006076	60860	434268	31010	551697	30051	383071	20023
1997	913648	58224	338272	25566	569702	32011	286900	14706
1998	1162574	66314	309272	21553	693164	39003	334480	16492
1999	796064	55239	322363	28764	631458	34243	333637	18594
2000	1202491	78154	385115	27688	886848	51612	513132	25181
2001	1031347	52731	370342	30284	821513	61192	541939	29275
2002	924097	46601	332864	26043	602286	49528	489343	26263
2003	884542	44673	369788	31169	682344	50213	401128	21518
2004	856633	40934	389141	31099	451738	32020	331548	19439
2005	904762	40237	337240	27408	611943	41476	322340	17607
2006	753498	37355	325124	29362	**608574**	**42919**	**389383**	**21166**
2007	805618	91031	275998	25259	**315398**	**22798**	**363299**	**17938**
2008	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
2009	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
2010	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
2011	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**

Table 3. Faroes fishery catches and input data for estimating catches of 1SW and MSW salmon from the southern NEAC and northern NEAC stock complexes.

Faroes Fishery
Reported catches

	1SW	MSW	Unreported catch rate				Prop. Mature in 1SW					
Year	CF1.dec	CF2.dec	p.unrep.F1.min	p.unrep.F1.max	p.unrep.F2.min	p.unrep.F2.max	p.m.F1.min	p.m.F1.max	p.wF	p.s.F1m	p.s.F1nm	p.s.F2
1971	2620	105796	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1972	2754	111187	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1973	3121	126012	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1974	2186	88276	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1975	2798	112984	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1976	1830	73900	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1977	1291	52112	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1978	974	39309	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1979	1736	70082	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1980	4523	182616	0.05	0.15	0.00	0.00	0.73	0.83	1.00	0.50	0.275	0.50
1981	7443	300542	0.05	0.15	0.00	0.00	0.73	0.83	0.98	0.50	0.275	0.50
1982	6859	276957	0.05	0.15	0.00	0.00	0.73	0.83	0.98	0.50	0.275	0.50
1983	15861	215349	0.05	0.15	0.00	0.00	0.73	0.83	0.98	0.50	0.275	0.50
1984	5534	138227	0.05	0.15	0.00	0.00	0.73	0.83	0.96	0.50	0.275	0.50
1985	378	158103	0.05	0.15	0.00	0.00	0.73	0.83	0.92	0.50	0.275	0.50
1986	1979	180934	0.05	0.15	0.00	0.00	0.73	0.83	0.96	0.50	0.275	0.50
1987	90	166244	0.05	0.15	0.00	0.00	0.73	0.83	0.97	0.50	0.275	0.50
1988	8637	87629	0.05	0.15	0.00	0.00	0.73	0.83	0.92	0.50	0.275	0.50
1989	1788	121965	0.05	0.15	0.00	0.00	0.73	0.83	0.82	0.50	0.275	0.50
1990	1989	140054	0.05	0.15	0.00	0.00	0.73	0.83	0.54	0.50	0.275	0.50
1991	943	84935	0.05	0.15	0.00	0.00	0.73	0.83	0.54	0.50	0.275	0.50
1992	68	35700	0.05	0.15	0.00	0.00	0.73	0.83	0.62	0.50	0.275	0.50
1993	6	30023	0.05	0.15	0.00	0.00	0.73	0.83	0.69	0.50	0.275	0.50
1994	15	31672	0.05	0.15	0.00	0.00	0.73	0.83	0.72	0.50	0.275	0.50
1995	18	34662	0.05	0.15	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
1996	101	28381	0.05	0.15	0.00	0.00	0.73	0.83	0.75	0.50	0.275	0.50
1997	0	0	0.10	0.20	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
1998	339	1424	0.10	0.20	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
1999	0	0	0.10	0.20	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2000	225	1765	0.10	0.20	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2001	0	0	0.10	0.20	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2002	0	0	0.00	0.00	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2003	0	0	0.00	0.00	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2004	0	0	0.00	0.00	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2005	0	0	0.00	0.00	0.00	0.00	0.73	0.83	0.80	0.50	0.275	0.50
2006	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**
2007	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**
2008	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**
2009	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**
2010	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**
2011	**0**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.83**	**0.80**	**0.50**	**0.275**	**0.50**

Table 4. West Greenland fishery catches and input data for estimating catches of MSW salmon from the southern NEAC and northern NEAC stock complexes.

	Greenland Fishery MSW only Catches MSW total (declared		Proportion for NEAC				% South Neac
Year	CG2	p.NEAC.G.method	GSampleNAC	GSampleNEAC	GPropNACMin	GPropNACMax	p.sNEAC.G
1971	856369	2	1	1	0.28	0.40	0.97
1972	614244	2	1	1	0.34	0.37	0.97
1973	560048	2	1	1	0.39	0.59	0.97
1974	535475	2	1	1	0.39	0.46	0.97
1975	650641	2	1	1	0.40	0.48	0.97
1976	386513	2	1	1	0.38	0.48	0.97
1977	442023	2	1	1	0.38	0.57	0.97
1978	293731	2	1	1	0.47	0.57	0.97
1979	417665	2	1	1	0.48	0.52	0.97
1980	370807	2	1	1	0.45	0.51	0.97
1981	398738	2	1	1	0.58	0.61	0.97
1982	346302	2	1	1	0.60	0.64	0.97
1983	100000	2	1	1	0.38	0.41	0.97
1984	95498	2	1	1	0.47	0.53	0.97
1985	301045	2	1	1	0.46	0.53	0.97
1986	316832	2	1	1	0.48	0.66	0.97
1987	305696	2	1	1	0.54	0.63	0.97
1988	280818	2	1	1	0.38	0.49	0.97
1989	117422	2	1	1	0.52	0.60	0.97
1990	101859	2	1	1	0.70	0.79	0.97
1991	178113	2	1	1	0.61	0.69	0.97
1992	84342	2	1	1	0.50	0.57	0.97
1993	4404	2	1	1	0.50	0.76	0.97
1994	4404	2	1	1	0.50	0.76	0.97
1995	40234	2	1	1	0.65	0.72	0.97
1996	38889	2	1	1	0.71	0.76	0.97
1997	23247	2	1	1	0.75	0.84	0.97
1998	7914	2	1	1	0.73	0.84	0.97
1999	10227	2	1	1	0.84	0.97	0.97
2000	12062	1	344	146	0	0	0.97
2001	17667	2	1	1	0.67	0.71	0.97
2002	6552	1	341	160	0	0.00	0.97
2003	6250	1	1089	512	0	0.00	0.97
2004	7862	1	1232	456	0	0.00	0.97
2005	7553	1	583	184	0	0.00	0.97
2006	**9877**	1	859	334	0	0.00	**0.97**
2007	**11745**	1	921	202	0	0.00	**0.97**
2008	**0**	1	1	1	0.00	1.00	**0.97**
2009	**0**	1	1	1	0.00	1.00	**0.97**
2010	**0**	1	1	1	0.00	1.00	**0.97**
2011	**0**	1	1	1	0.00	1.00	**0.97**

Figure 1. Directed Acyclical Graph (DAG) of the proposed structure of the Southern and Northern NEAC PFA models.

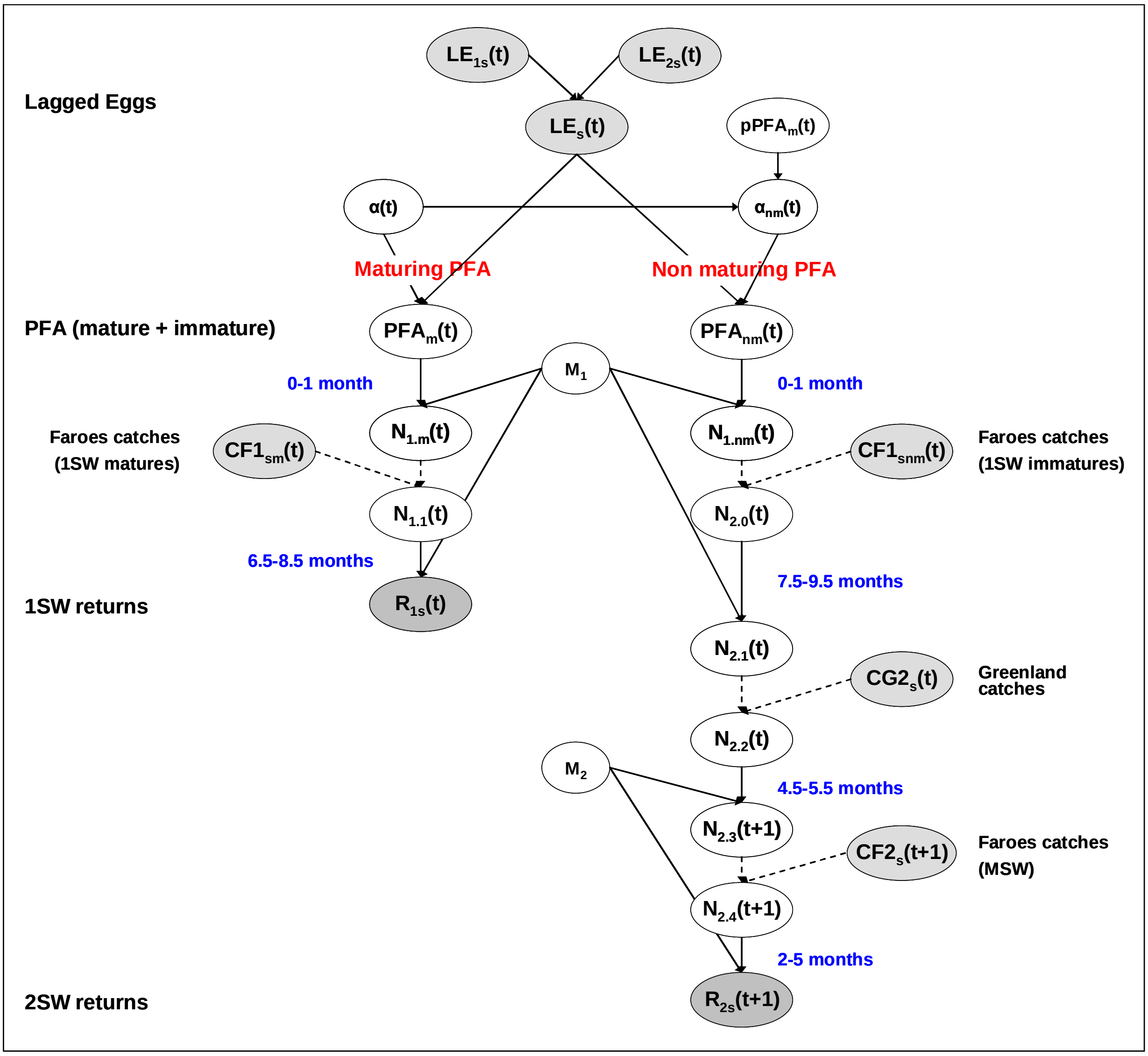


Figure 2. Midpoint trend in lagged eggs (X1000) for 1SW and MSW salmon from the southern NEAC and northern NEAC stock complexes. The year shown is for the PFA year.

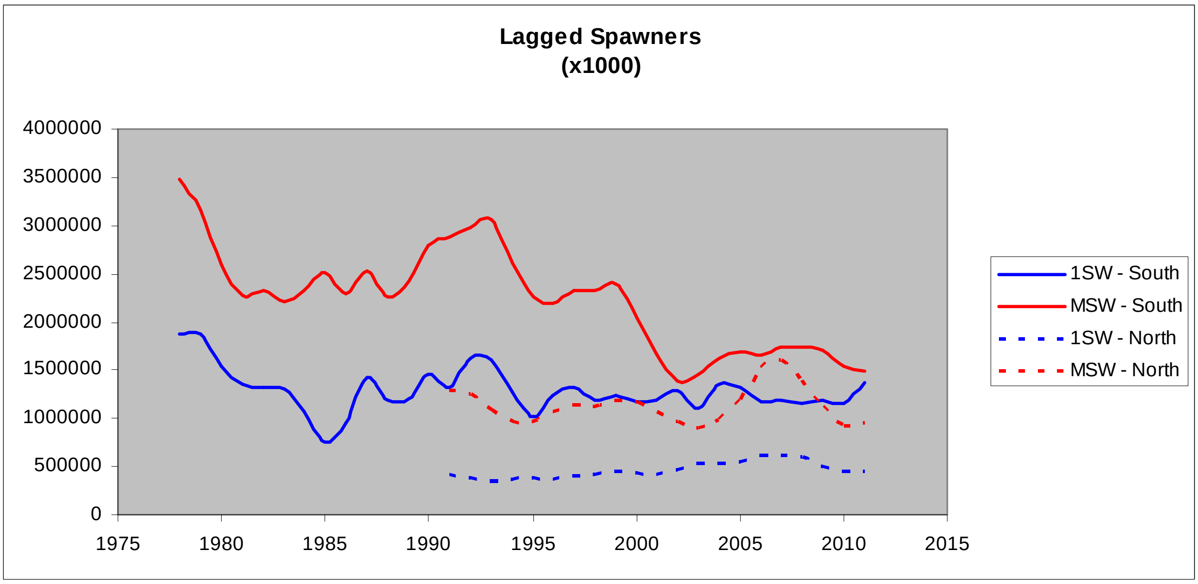


Figure 3. Midpoint of returns of 1SW and MSW salmon to the southern NEAC and northern NEAC stock complexes. Year shown is for the corresponding year of return.

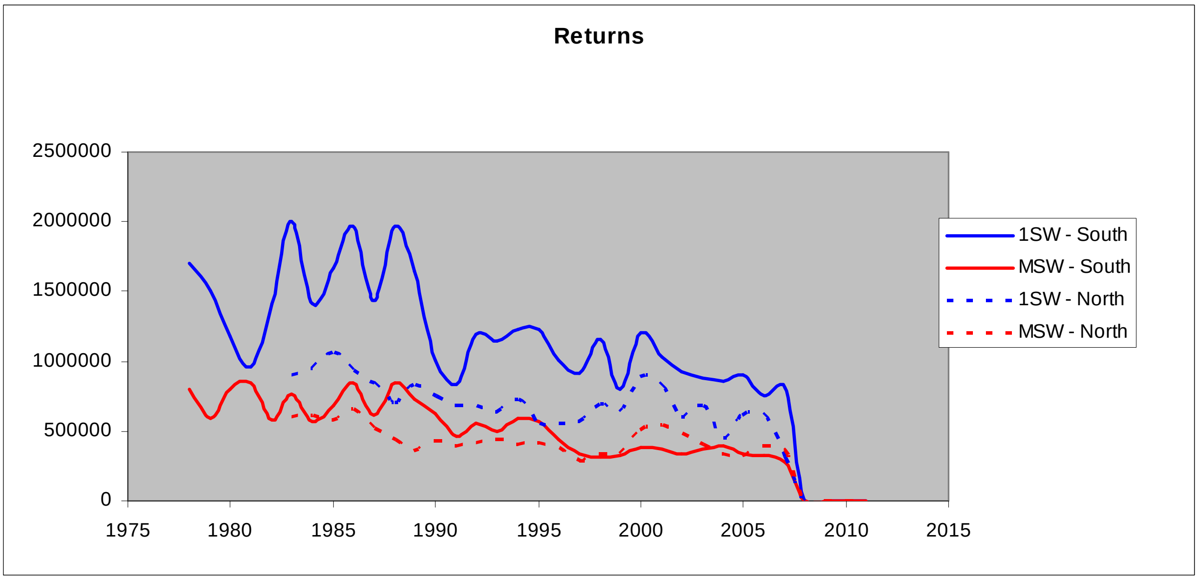


Figure 4. Posterior distributions of total PFA for the southern NEAC stock complex (top left), proportion of PFA maturing (top right), maturing PFA (bottom left) and non-maturing PFA (bottom right) based on the random walk productivity dynamic. Dashed red line : mean proportion of maturing PFA (top right); SER of maturing (842396) and non maturing PFA (498216).

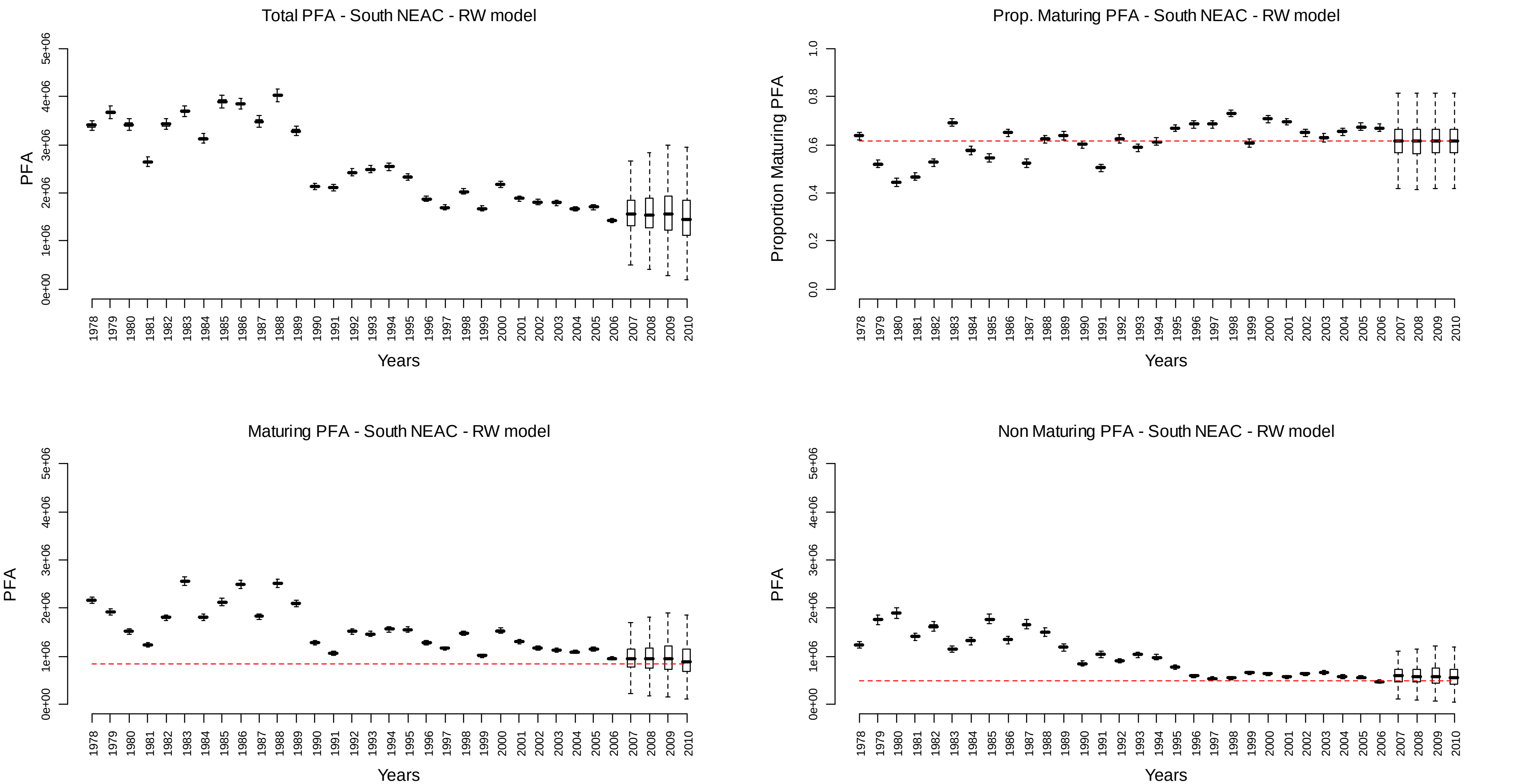
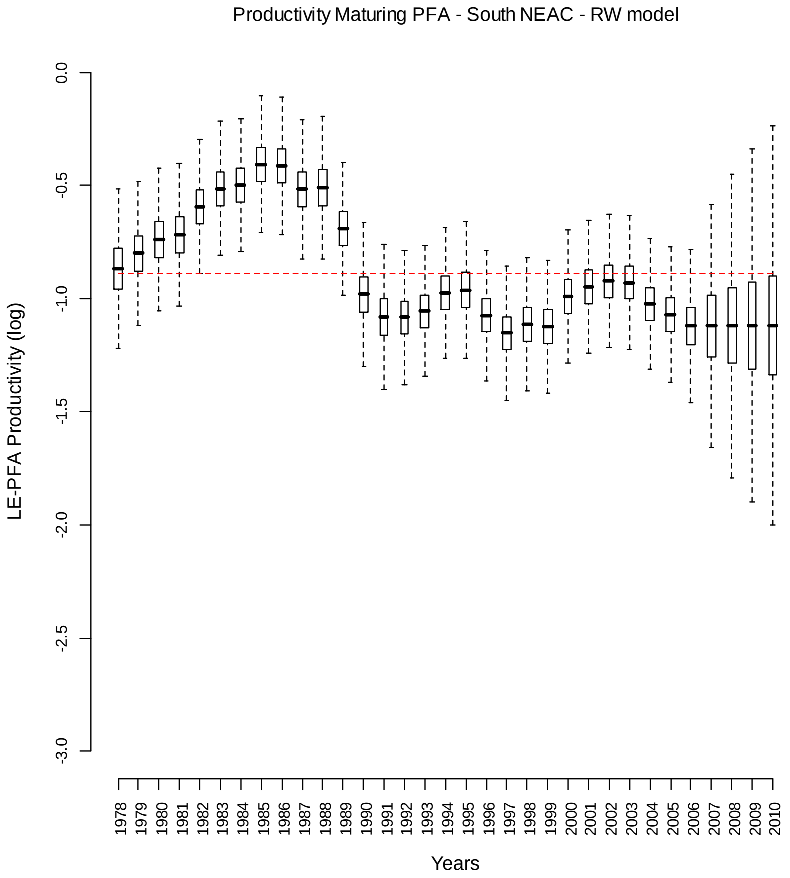


Figure 5. Posterior distributions of the annual productivity parameter for maturing PFA (left) and for non-maturing PFA (right) for the southern NEAC stock complex based on the random walk productivity dynamic. Dashed red line: mean productivity parameter.



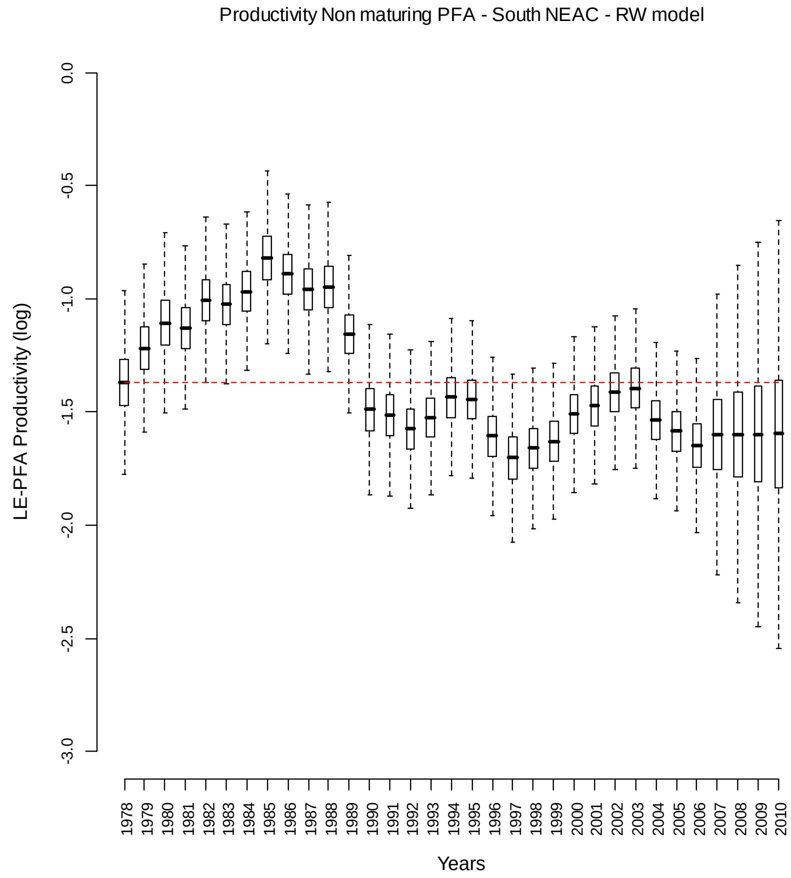


Figure 6. Posterior distributions of total PFA for the northern NEAC stock complex (top left), proportion of PFA maturing (top right), maturing PFA (bottom left) and non-maturing PFA (bottom right) based on the random walk productivity dynamic. Dashed red line : mean proportion of maturing PFA (top right); SER of maturing (306318) and non maturing PFA (213495).

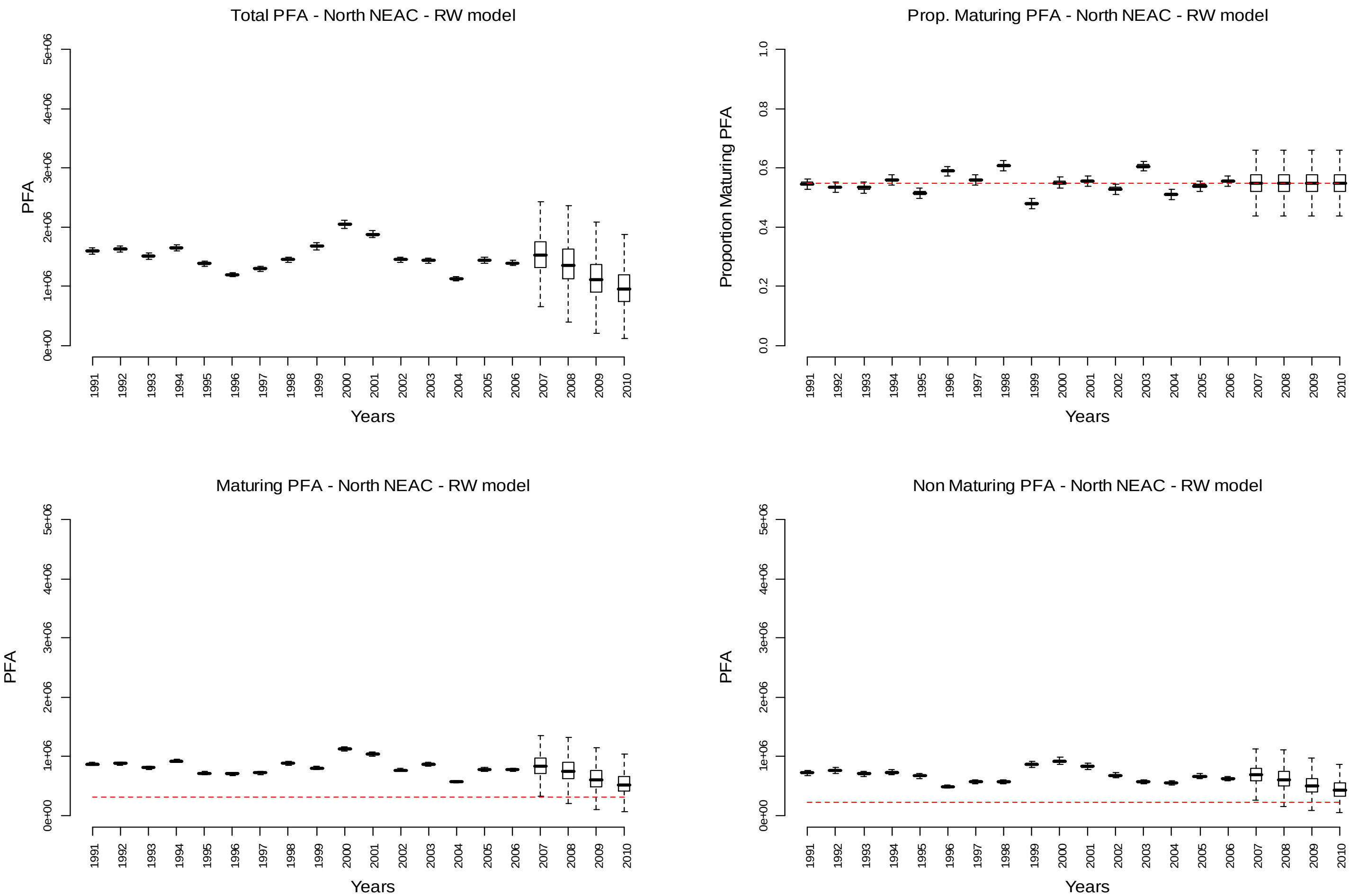


Figure 7. Posterior distributions of the annual productivity parameter for maturing PFA (left) and for non-maturing PFA (right) for the northern NEAC stock complex based on the random walk productivity dynamic. Dashed red line: mean production level.

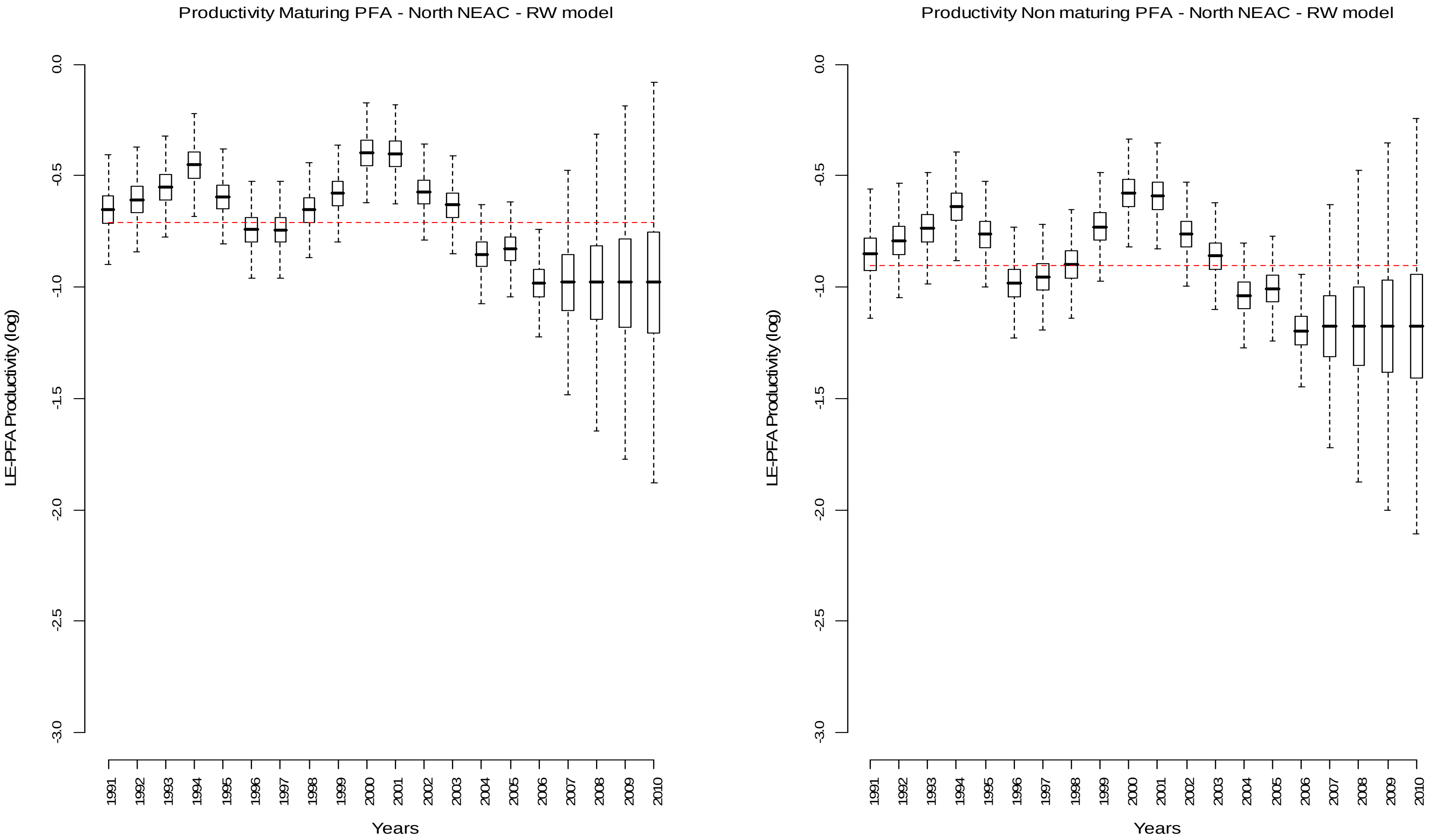


Figure 8. Comparisons of posterior distributions of total PFA (top left), proportion of PFA maturing (top right), maturing PFA (bottom left) and non-maturing PFA (bottom right) for southern NEAC and northern NEAC stock complexes, based on the random walk productivity dynamic.

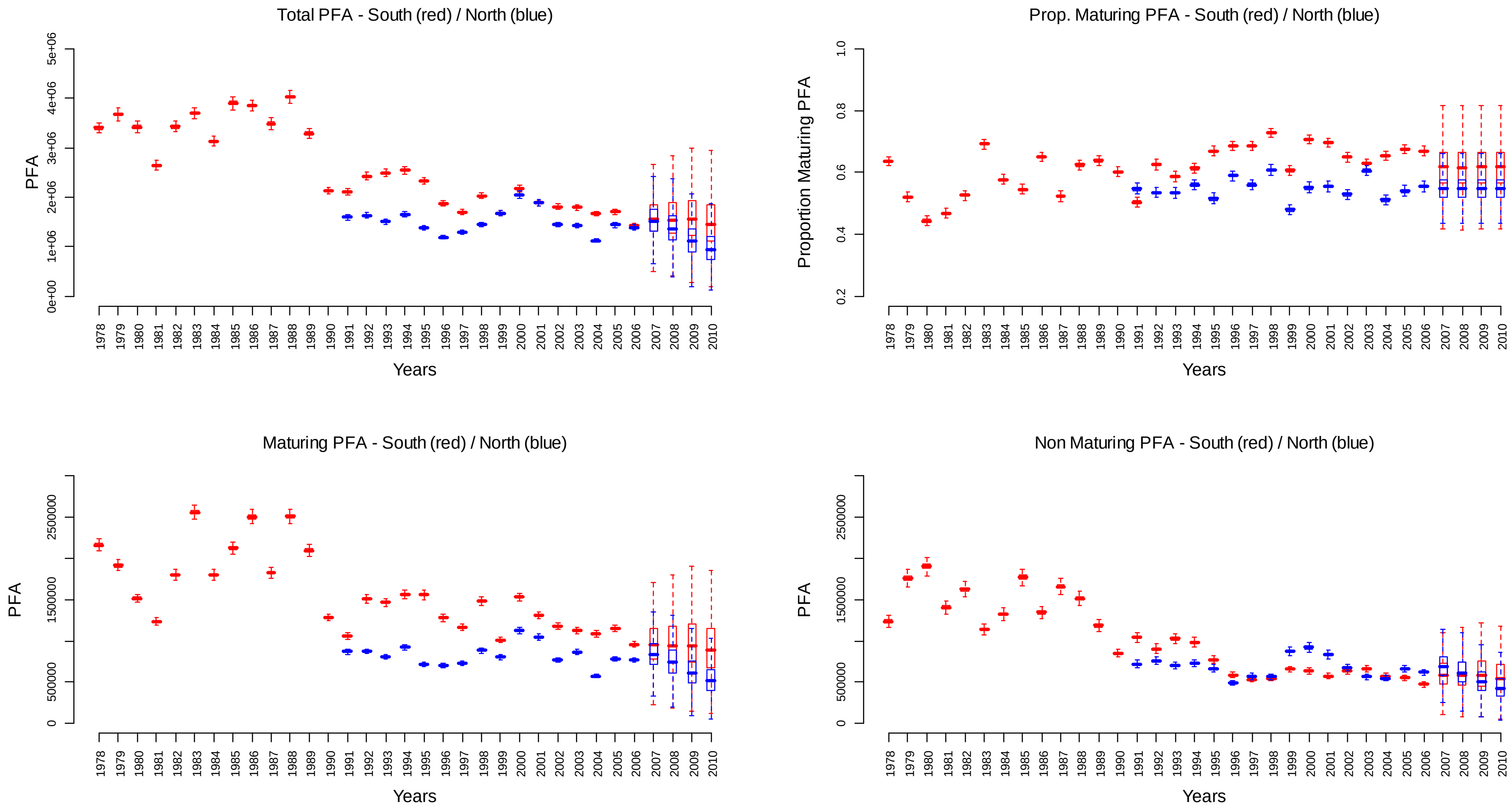


Figure 9. Comparison of posterior distributions of the annual productivity parameter for maturing PFA (left) and for non-maturing PFA (right) for the southern NEAC and northern NEAC stock complexes based on the random walk productivity dynamic.

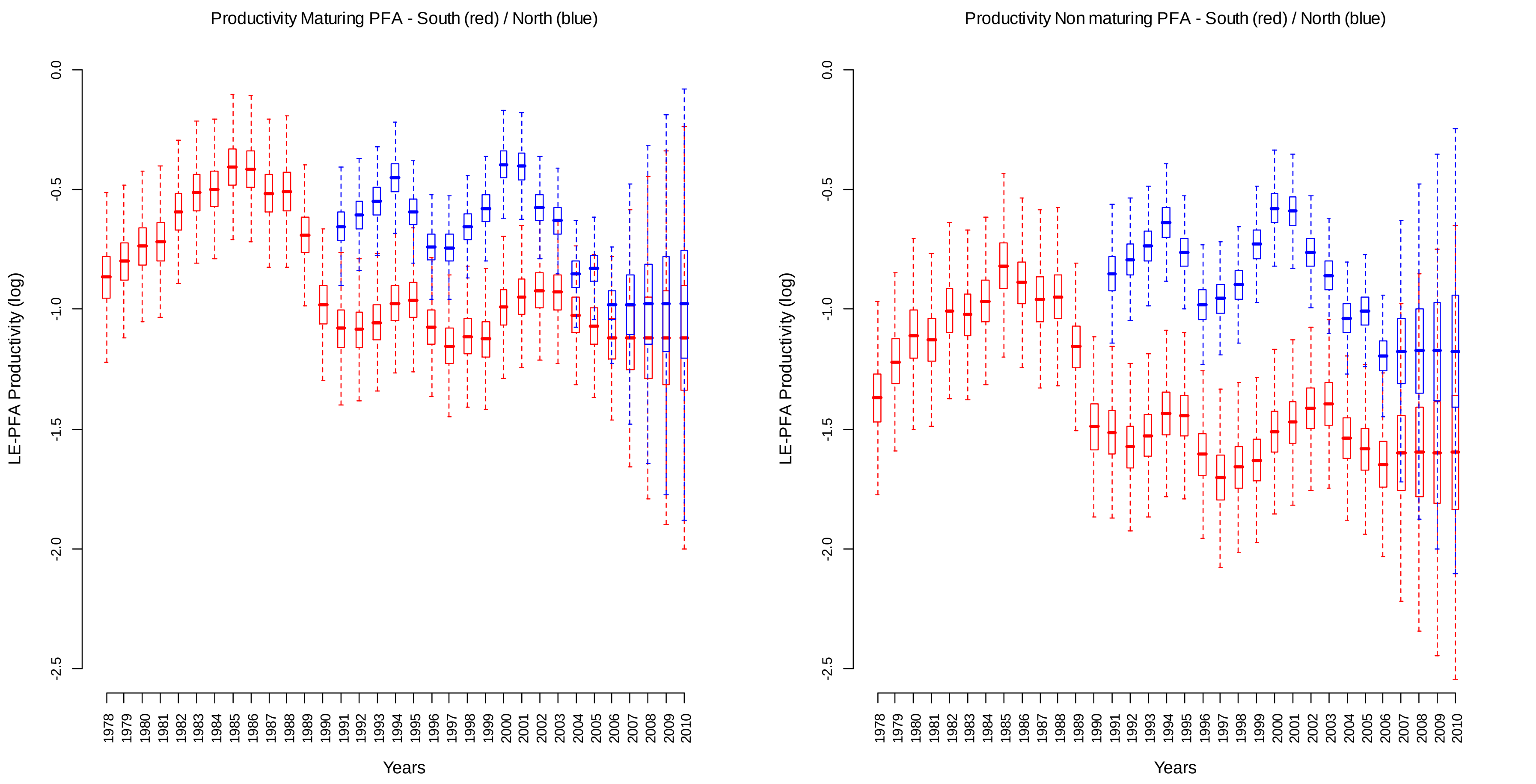


Figure 10. Posterior distributions of the productivity parameter (upper) for maturing 1SW salmon for southern NEAC and the probability of a shift in productivity level (lower) under the hypothesis of a shifting level model.

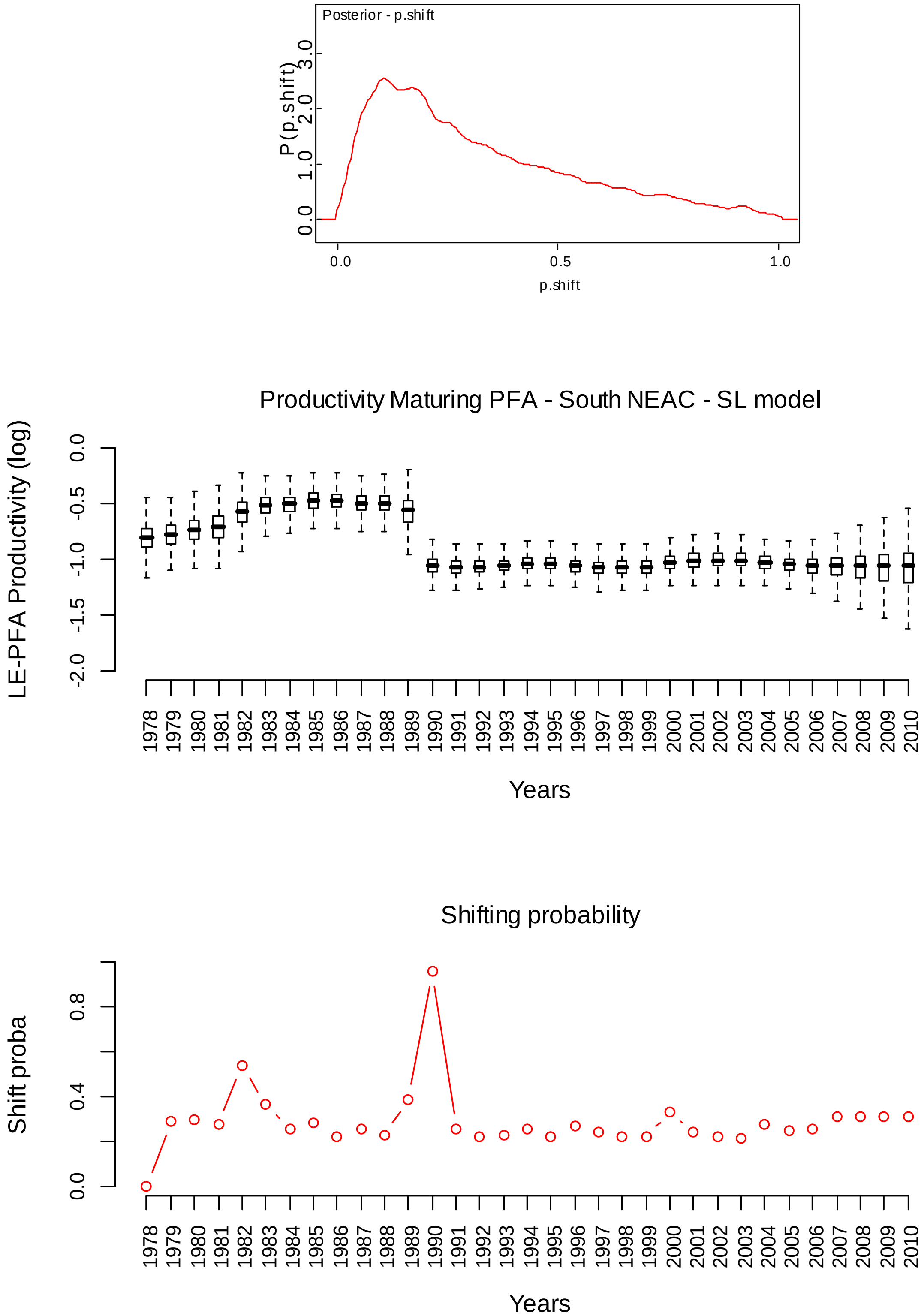


Figure 11. Comparison of posterior distributions of maturing PFA (top) and non-maturing PFA (bottom) from the random walk (left panels) and the shift level models (right) for southern NEAC stock complex. Dashed red line: SER of maturing (842396) and non maturing PFA (498216).

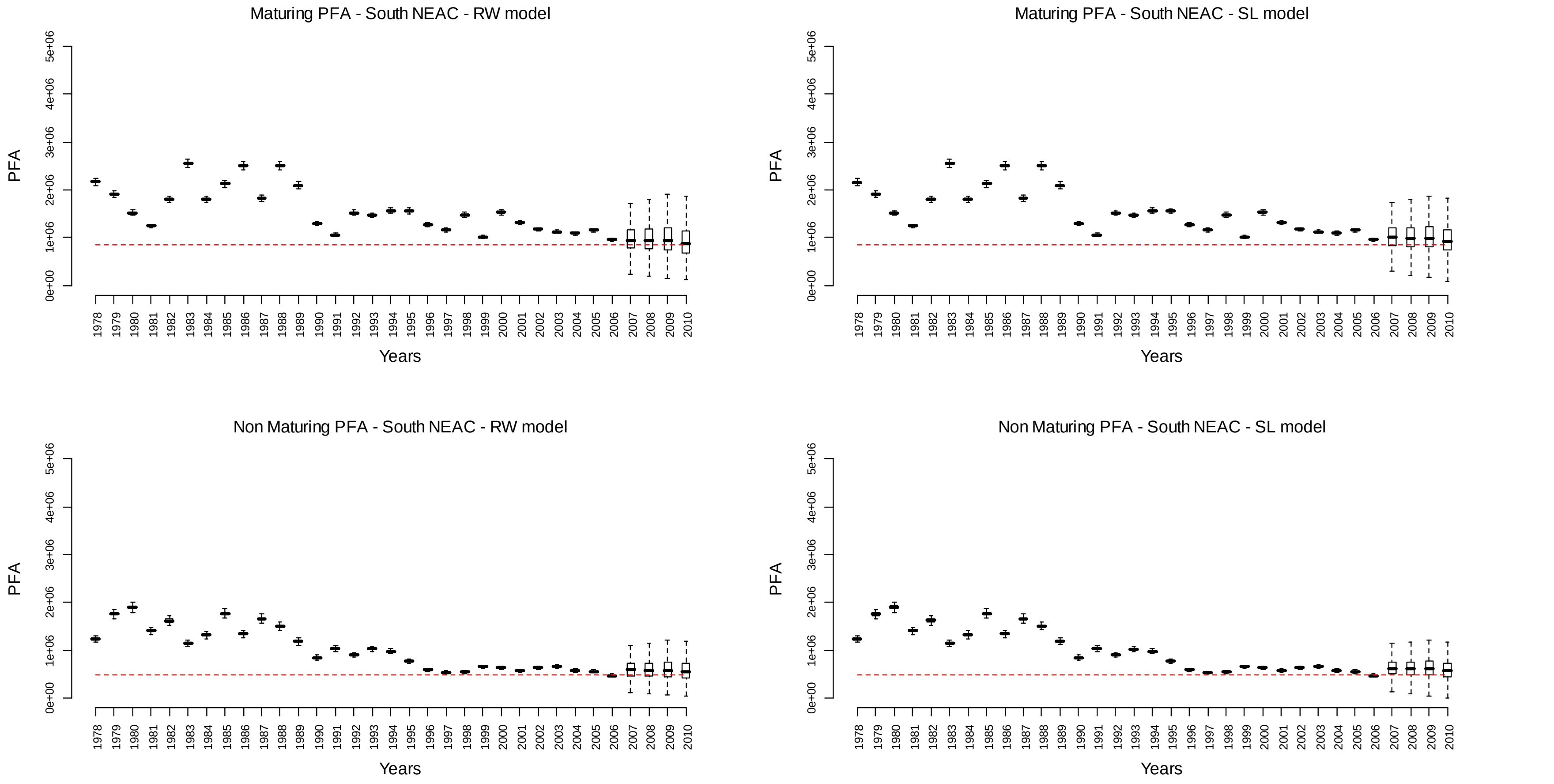


Figure 12. Comparison of posterior distributions of the productivity parameter for the maturing 1SW (top) and non-maturing 1SW (bottom) from the random walk (left) and the shift level models (right) for southern NEAC stock complex. Dashed red line: mean production level.

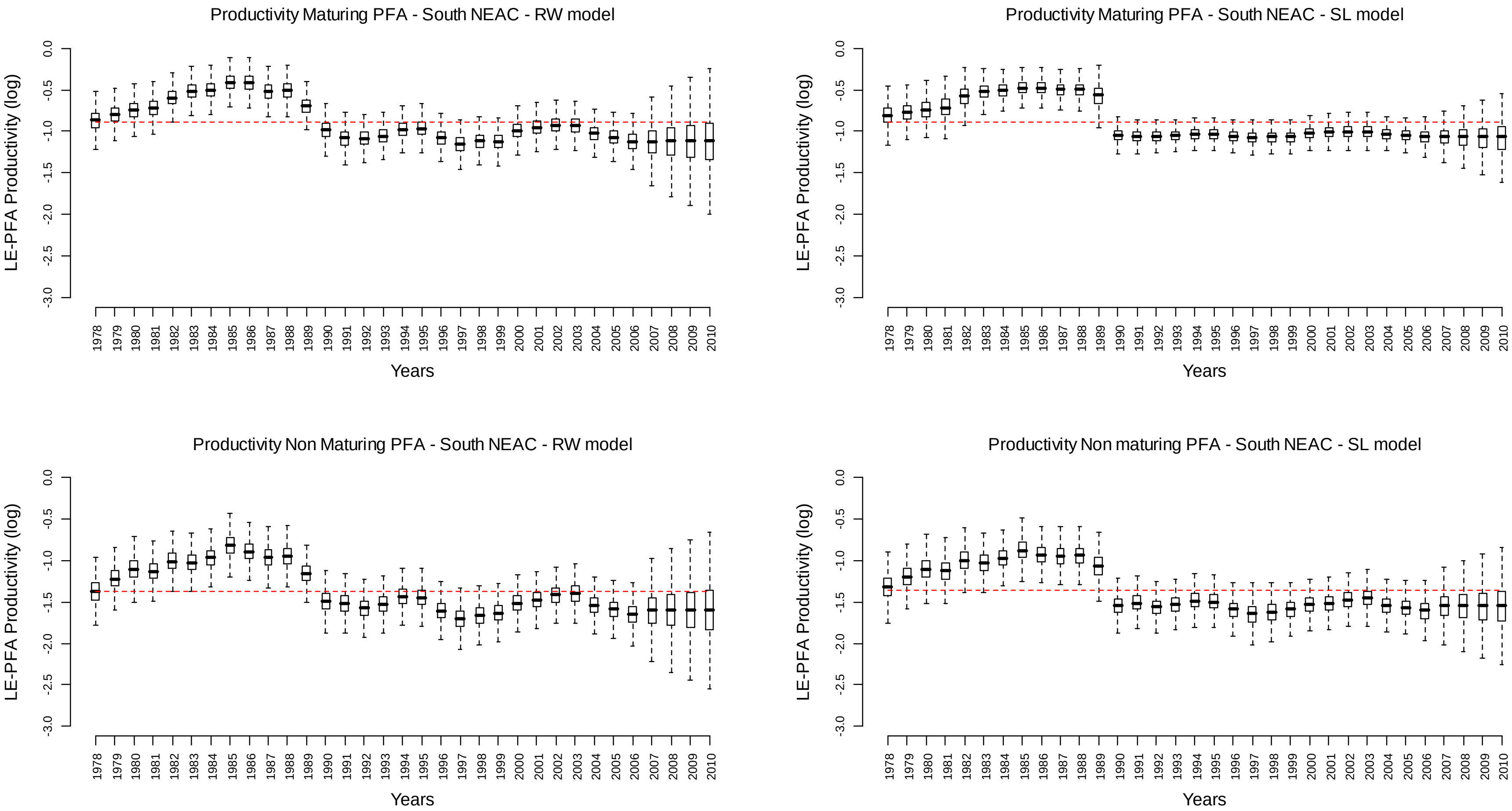


Figure 13. Estimated risks defined for each year as the posterior probability that the PFA falls below the SER level. (Southern NEAC: 842396 and 498216 for maturing and non maturing PFA respectively; Northern NEAC: 306318 and 213495 for maturing and non maturing PFA respectively. For the 4 years of forecasting (2007-210), PFA is forecasted under 0 exploitation rate (all catches =0)