Modélisation et prédiction de l'abondance des saumons atlantiques dans l'Atlantique Nord

Une approche Bayesienne

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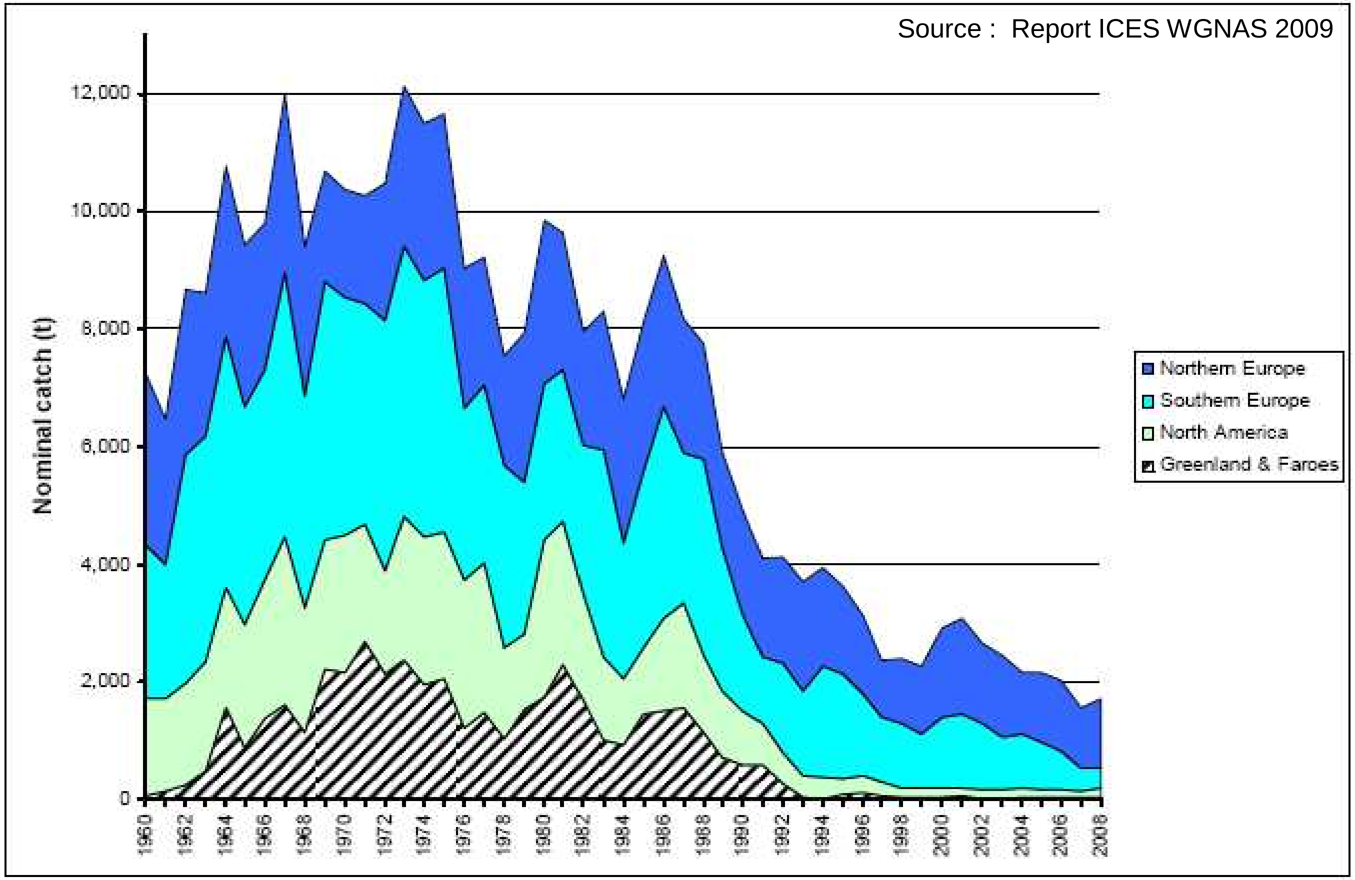
Séminaire Amedee, 23 Novembre 2009, Rennes

Management framework for salmon in the North Atlantic

A. salmon (wild) stocks are decreasing worldwide



Source : Report ICES WGNAS 2009

Figure 2.1.1.1 Reported total nominal catch of salmon (tonnes round fresh weight) in four North Atlantic regions, 1960–2008.

Worldwide production of farmed Atlantic salmon in 2008 was estimated at > 1.48 Million Tons (= over 870 times the reported nominal catch of Atlantic salmon in the North Atlantic)

Management framework for salmon in the North Atlantic

- **NASCO : North Atlantic Salmon Conservation Organisation**

  International convention 1984

- **Receives scientific advices**

  ICES : WGNAS, WGBS

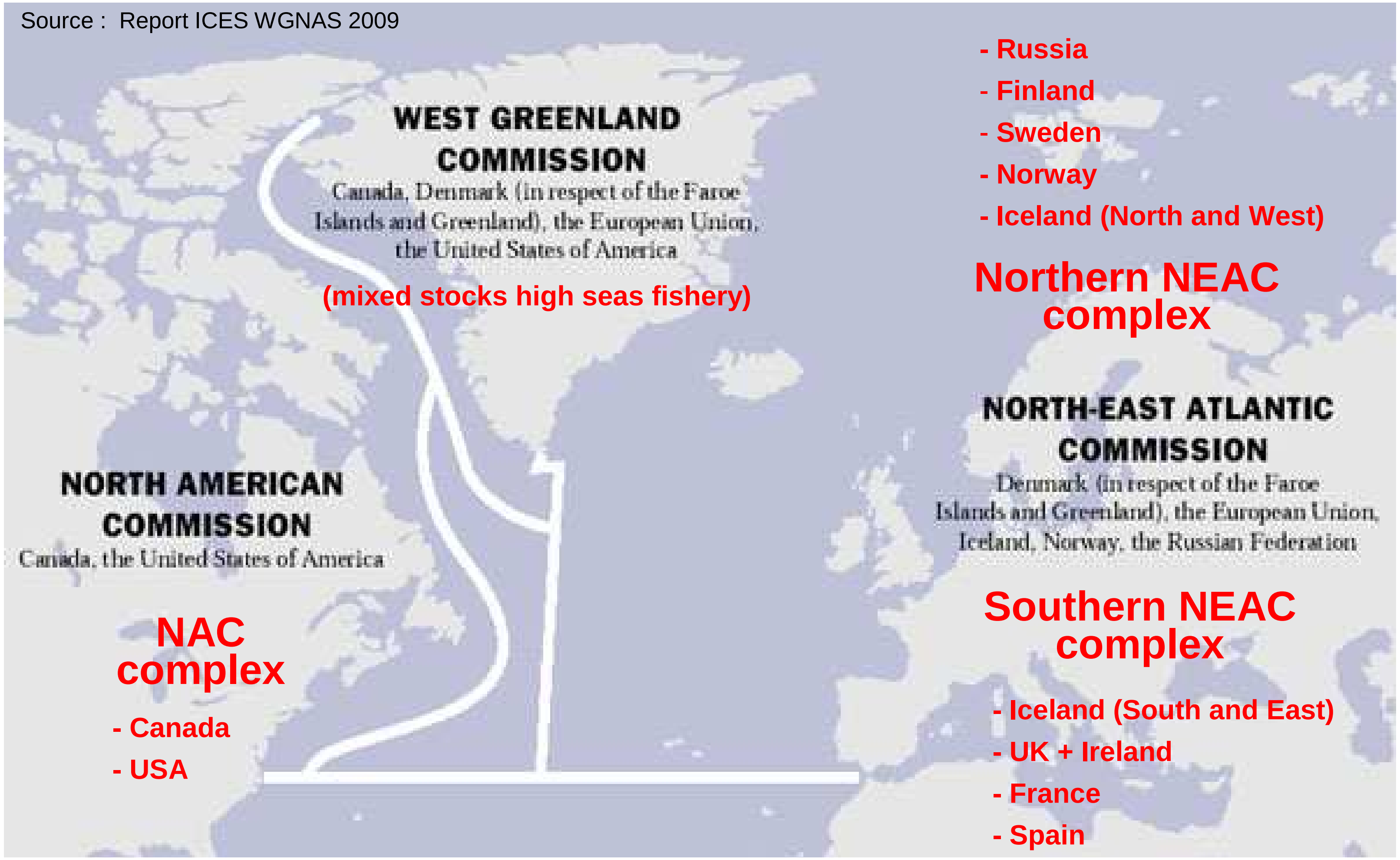
- **3 commissions area**

- **Management of distant water salmon fisheries**

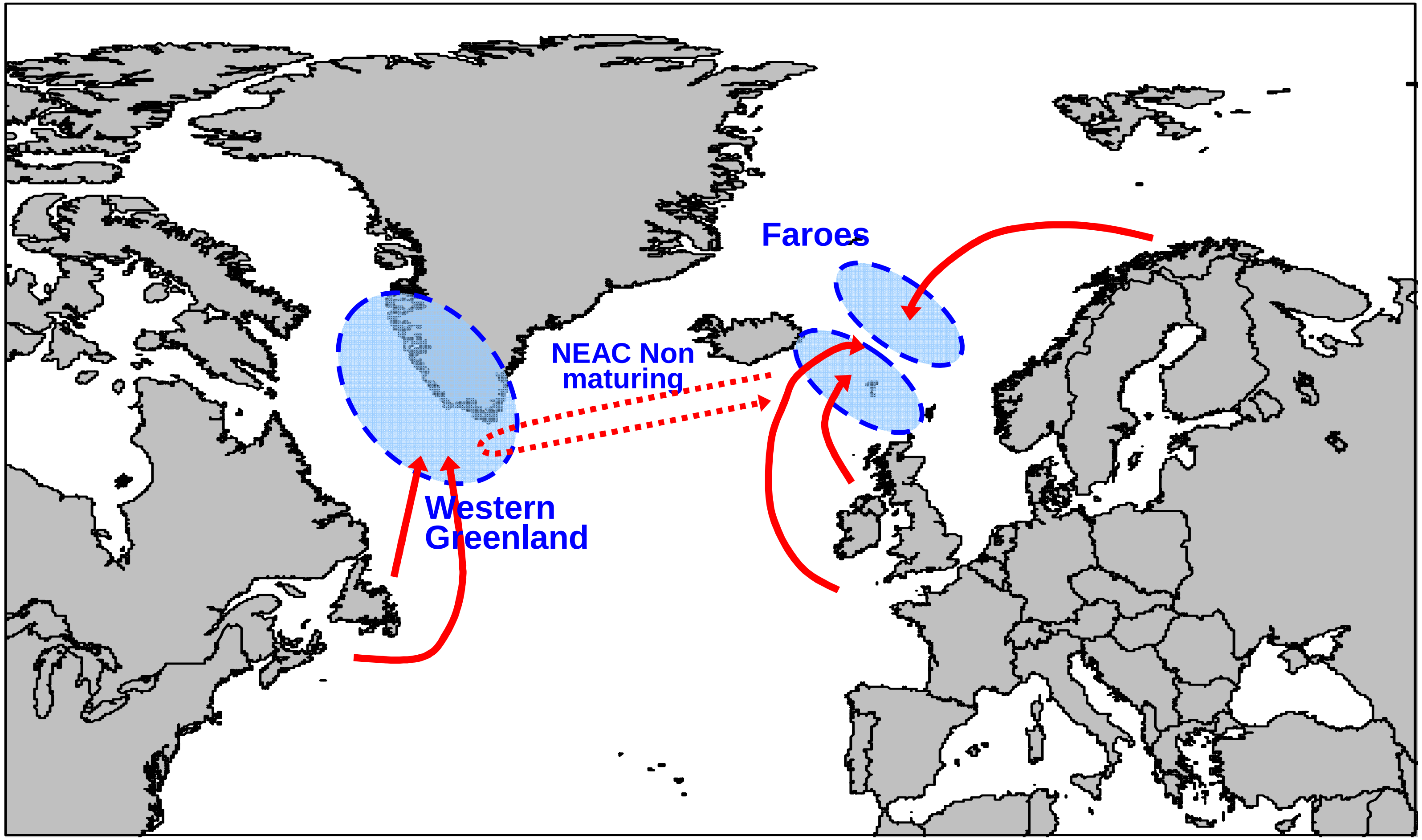
  West Greenland and Faroes

  (Coastal + Freshwater: in charge of contributed stocks-countries)

NASCO - 3 Commission areas



A. salmon (wild) feeding migrations and (mixed stocks) high-seas fisheries



High-seas fisheries management

- **Fixed escapement management strategies**
  - Ensure spawning escapement is reached in each contributed stocks
  - Based on an estimation of the Pre-Fishery Abundance (PFA)
- **Faroes**
  - Complexes concerned: Southern + Northern NEAC
  - Qualitative advice
- **West Greenland**
  - Complexes concerned: Southern NEAC non maturing
NAC
  - Quantitative advice

A. salmon (wild) stocks are decreasing worldwide

Executive summary

Report ICES WGNAS 2009

- **Marine survival indices remain low**
- **North West**

  The North American Commission 2SW stock complex is suffering reduced reproductive capacity. Factors other than fisheries (marine mortality, fish passage, water quality) are contributing to continued low adult abundance

- **North East**

  Northern NorthEast Atlantic Commission stock complexes (1SW and MSW) are at full reproductive capacity prior to the commencement of distant water fisheries

  Southern NorthEast Atlantic Commission stock complexes (1SW and MSW) are at risk of suffering reduced reproductive capacity prior to the commencement of distant water fisheries

- **High-seas mixed stock fisheries**

  There are no catch options for the fishery at the West Greenland (2009-2011) that would meet precautionary management objectives

ICES Study Group on Salmon Stock Assessment and Forecasting [ICES SGSSAFE]

- **2007: DFO funded research Program**

  International Governance of High Seas Fisheries

  Conservation Strategies Component

  Formulating Multi-year Catch Advice in a Mixed-Stock Fishery Context

  Workshop Nov. 2007 (Moncton, NB, Canada)

- **2009: ICES Study Group on Salmon Stock Assessment and Forecasting [ICES SGSSAFE]**

  March 2009, Copenhagen

  DFO, Canada

  Marine Institute, Ireland

  CEFAS, UK

  VNIRO, Russia

  INRA, Agrocampus, Fr

ICES Working Group on North Atlantic Salmon

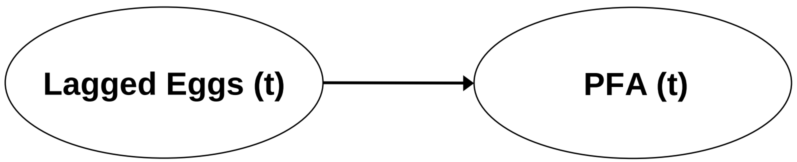
Working Papers 2008, 2009

Pre-Fishery abundance and forecasting

Pre Fishery Abundance forecasting models

■ Lagged-eggs (spawners) - PFA

A “stock-recruitment” relationship
Focus on the survival during the 1st winter at sea



Spawning contribution to PFA (t)

Abundance of 1SW after the first winter at sea, before the high-seas fisheries

$$PFA_t = e^{\alpha_t} \cdot LE_t \cdot e^{\varepsilon_t} \quad with \quad \varepsilon_t \sim N(0,\sigma^2)$$

Running method : 3 steps

- **Independent estimates of LE(t) and PFA(t)**

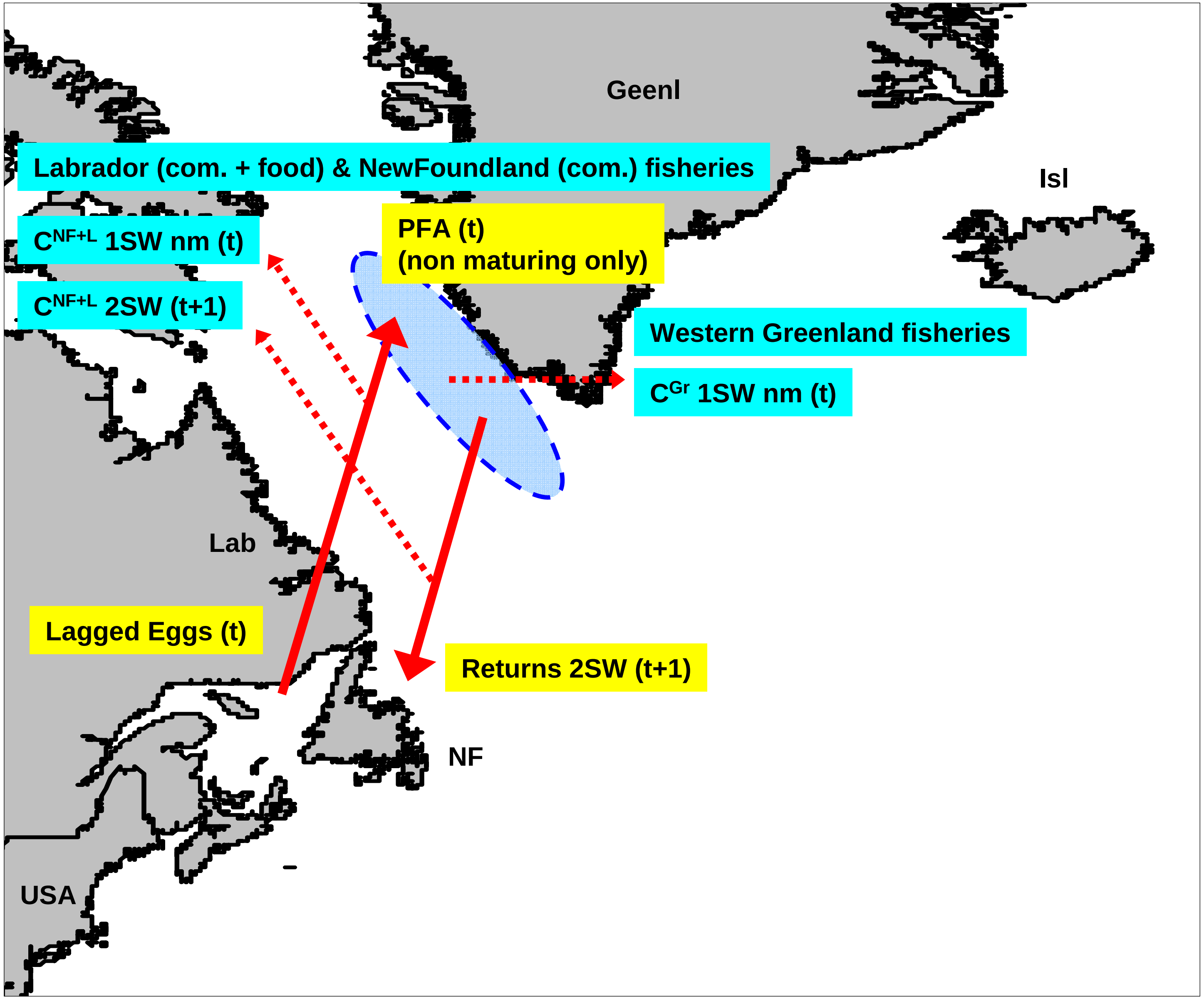
  PFA : **Run reconstruction**

  LE : **Returns + Smolts contribution**

- **Incorporate uncertainty**

- **Fit LE-PFA models and use it for forecasting**

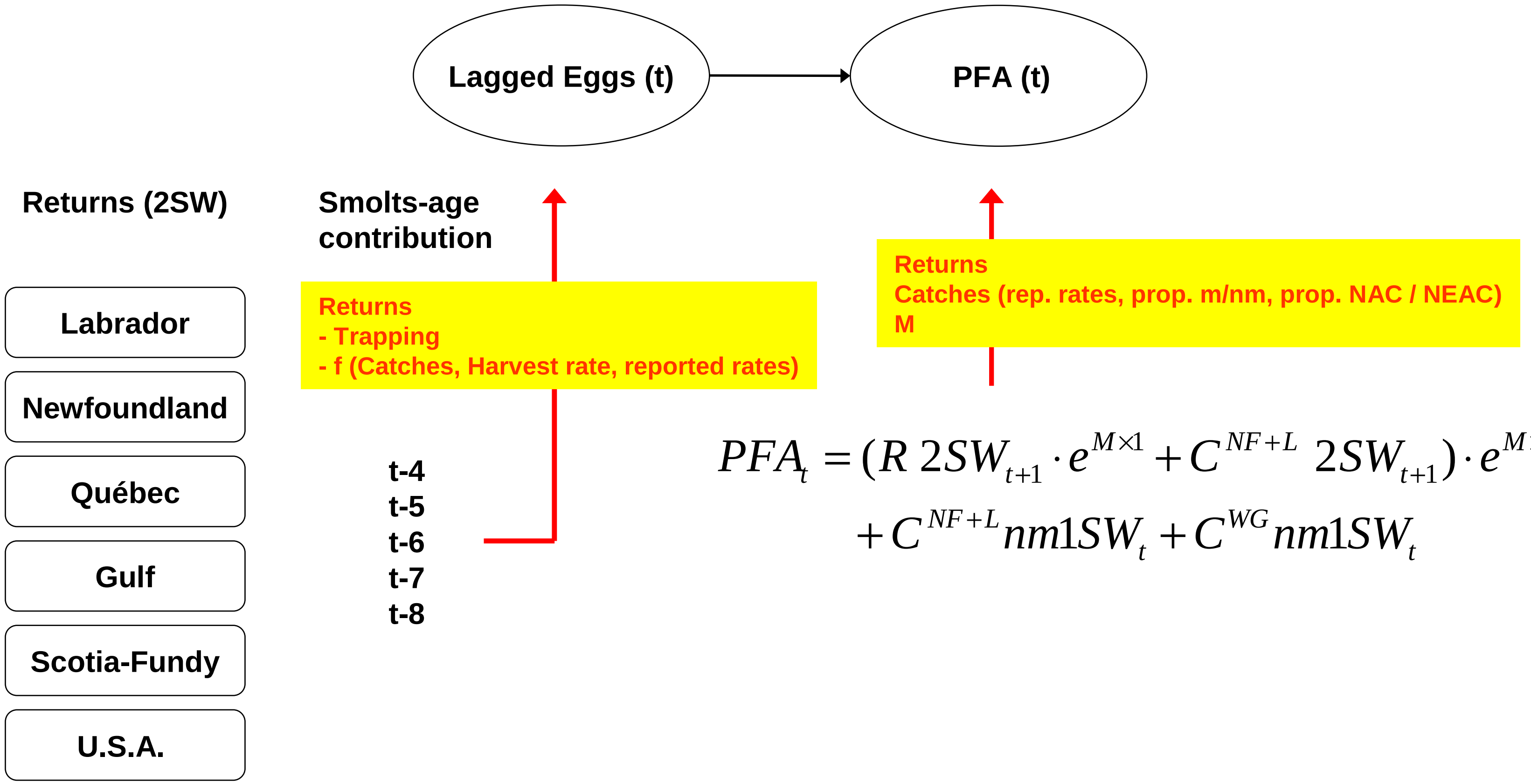
Example - NAC complex



Example - NAC complex

Lagged eggs reconstruction

Run reconstruction



$$PFA_t = (R\,2SW_{t+1} \cdot e^{M\times1} + C^{NF+L}\,2SW_{t+1}) \cdot e^{M\times10} + C^{NF+L}\,nm1SW_t + C^{WG}\,nm1SW_t$$

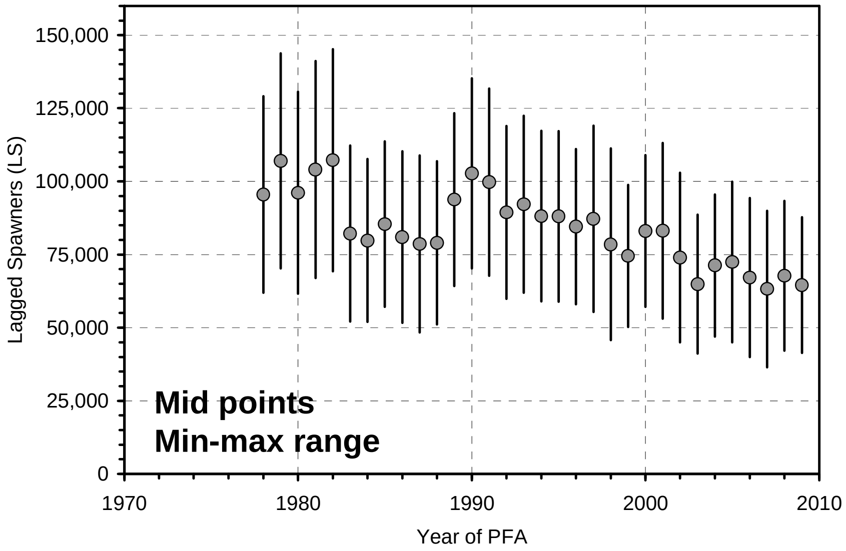
Example - NAC complex

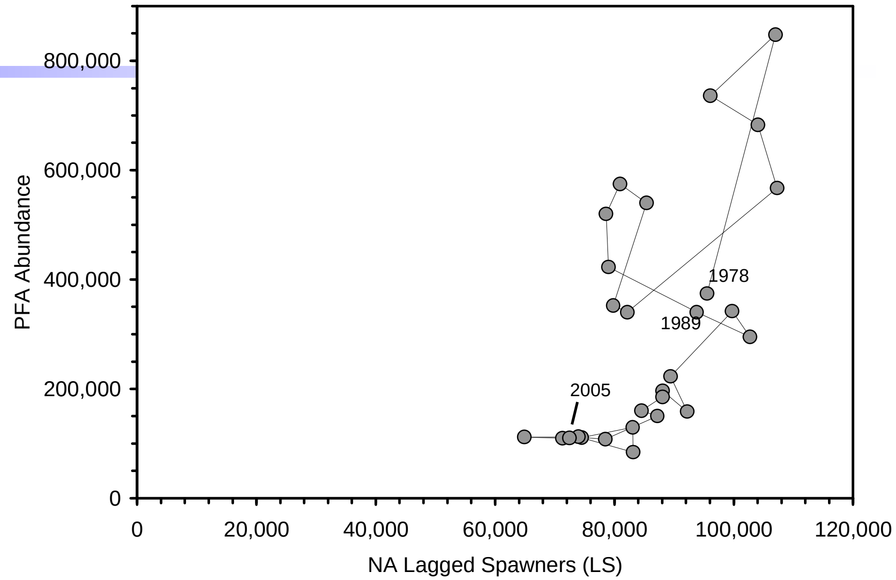
Calculation of Lagged Eggs

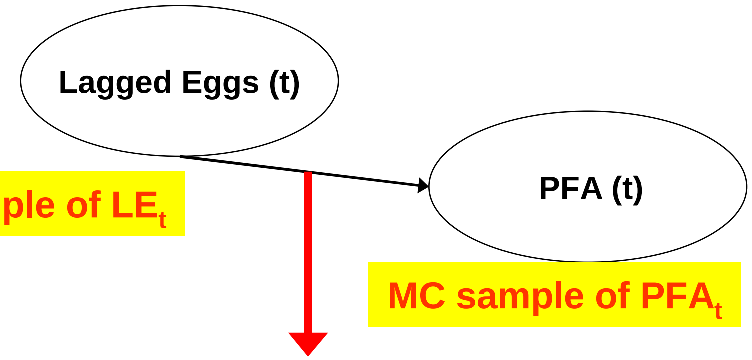
		Smolt age							
		1	2	3	4	5	6		
	Spawners	Proportion at smolt age							Lagged
Year	in year	0	0.0577	0.4644	0.3783	0.0892	0.0104	PFA year	spawner
1995	22575	0						1995	
1996	19010	0						1996	
1997	15531	0						1997	
1998	14240	0						1998	
1999	17250	0	1303					1999	
2000	16128	0	1097	10484				2000	
2001	16696	0	896	8828	8540			2001	
2002	12467	0	822	7213	7192	2014		2002	
2003	20738	0	995	6613	5875	1696	235	2003	15414
2004	17462	0	931	8011	5387	1385	198	2004	15912
2005	17529	0	963	7490	6526	1270	162	2005	16411
2006	16211	0	719	7754	6101	1539	148	2006	16261

Example - NAC complex

Lagged spawners (2SW only)







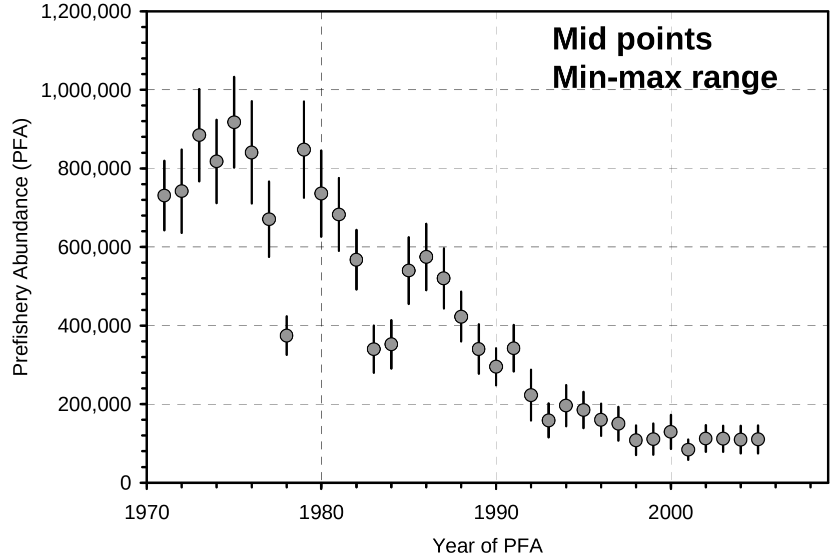
MC sample of LE_t

MC sample of PFA_t

$$PFA_t = e^{\alpha_t} \cdot LE_t \cdot e^{\varepsilon_t}$$

MC sample of MLE for α_t

PFA (non maturing 1SW)



Objectives (terms of reference of the ICES SGSSAFE)

- **Update and further develop stock and/or catch forecast models for salmon stocks in the NASCO NC and NEAC**
- **Evaluate methods for incorporating uncertainty in the assessments and forecasting (catch advices)**
- **Evaluate options for developing forecast models which include all sea-age classes**

“ PFA modelling and forecasting could advantageously be embedded within a Bayesian framework ”

Use DAG and conditional reasonning

DAG and conditional modeling

- **Directed Acyclic Graphs**

  Graphical representation of conditional modeling

- **Conditional reasoning**

  Modeling cause-to-effect relationships with uncertainty

  Probabilistic influence relationships between variables, parameters …

Baby example

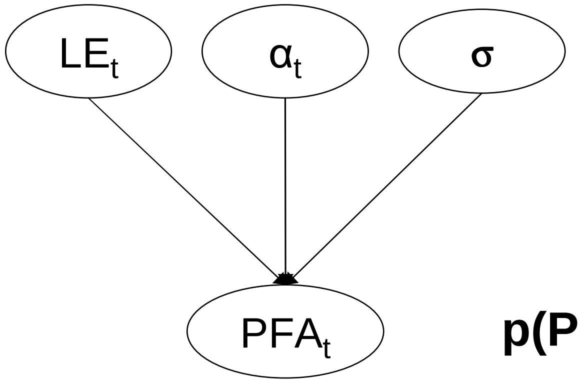
$$LE_t \rightarrow PFA_t \rightarrow Maturing\ Salmons_t \begin{cases} \rightarrow\ Catches_{t+1} \\ \rightarrow\ \mathrm{Re}\,turns_{t+1} \end{cases}$$

(1) Set a prior structure for the model

$$\begin{cases} PFA_t = e^{\alpha_t} \cdot LE_t \cdot e^{\varepsilon_t} \quad with \quad \varepsilon_t \sim N(0,\sigma^2) \\ Maturing\ salmons_t = PFA_t \cdot e^{-M_t} \cdot e^{\omega_t} \quad with \quad \omega_t \sim N(0,\tau^2) \\ \mathrm{Re}\,turns_{t+1} = Maturing\ salmons_t - Catches_{t+1} \end{cases}$$

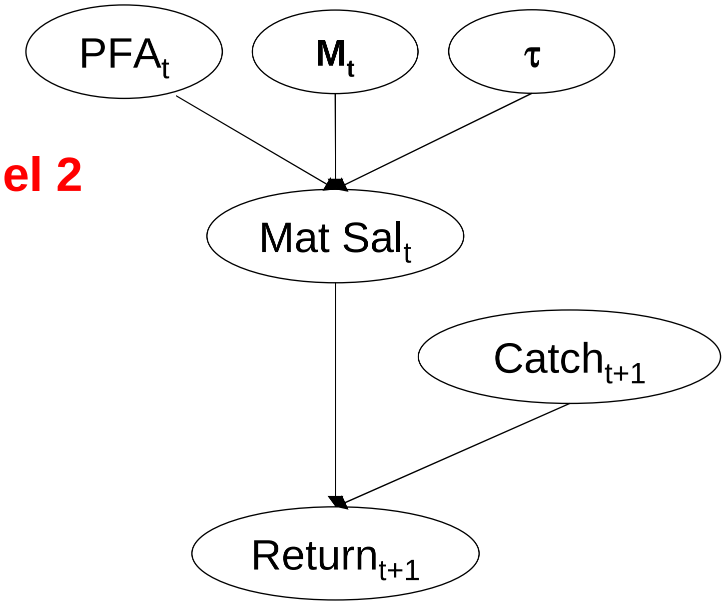
(2) DAG

Sub-model 1



$p(PFA_t \mid LE_t, \alpha_t, \sigma)$

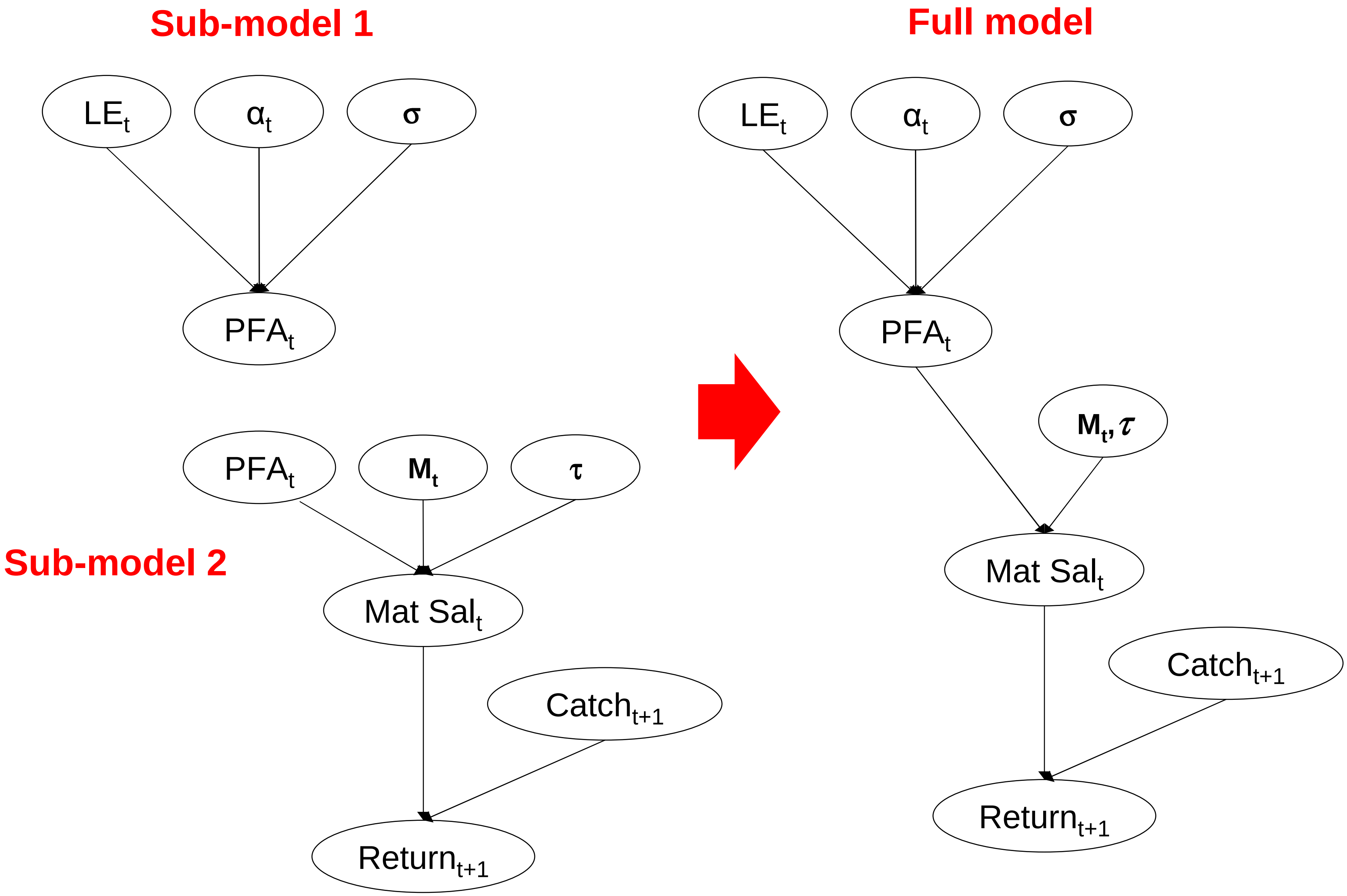
Sub-model 2



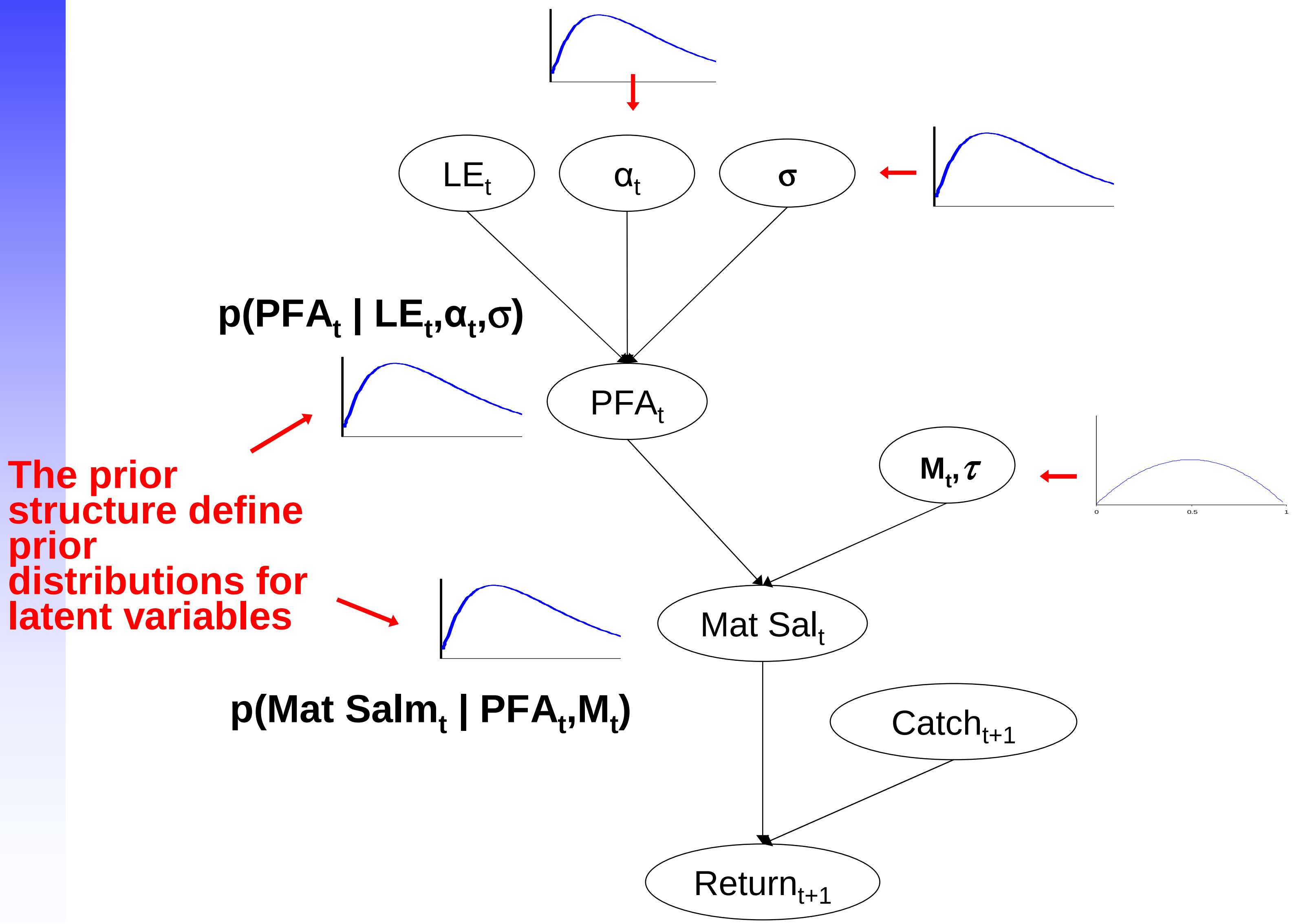
$p(\text{Mat Salm}_t \mid PFA_t, M_t, \tau)$

$p(\text{Return}_{t+1} \mid \text{Mat Salm}_t, \text{Catch}_{t+1})$

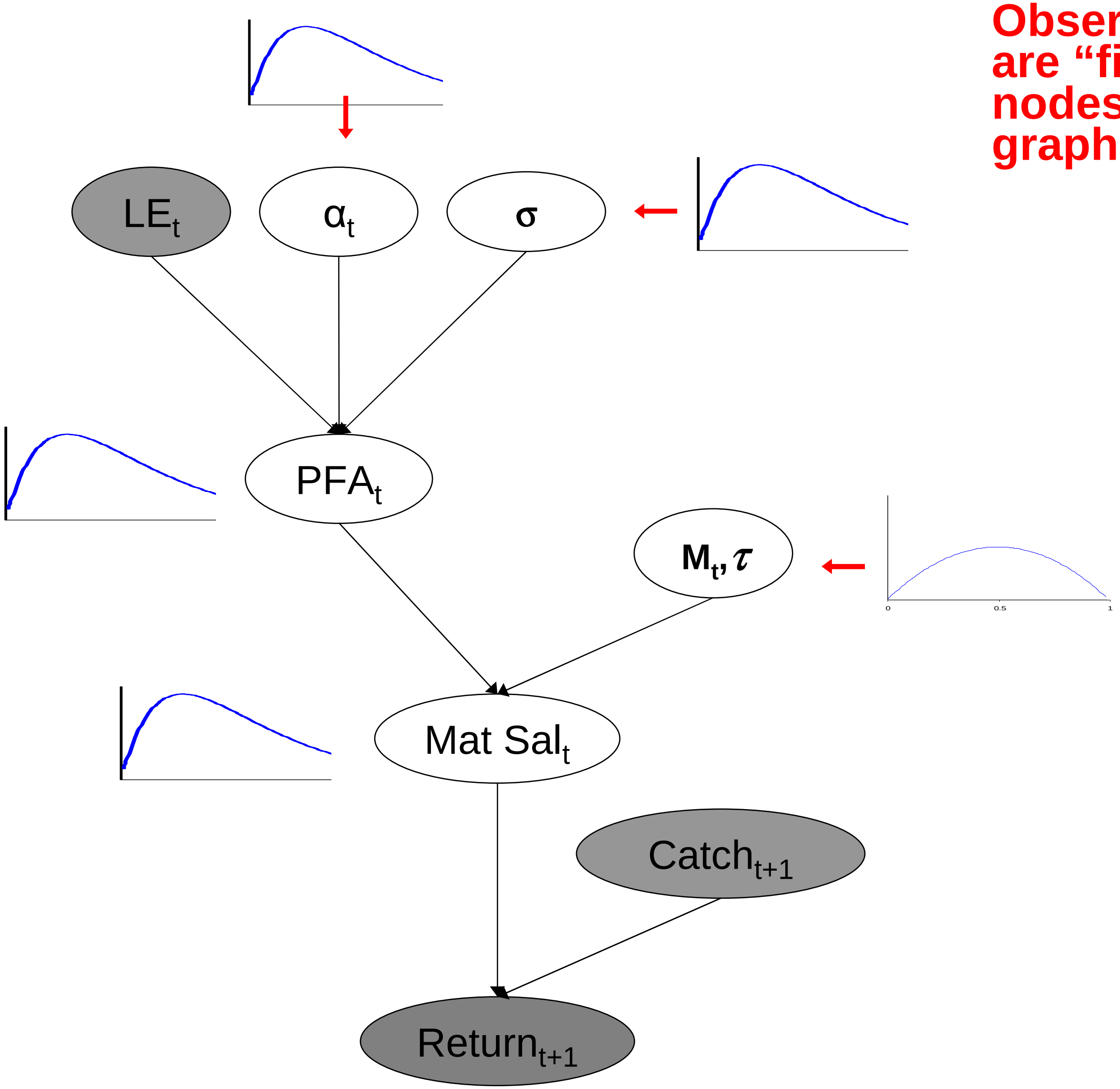
(2) DAG


Sub-model 1
LEt
αt
σ
PFAt
Sub-model 2
PFAt
Mt
τ
Mat Salt
Catcht+1
Returnt+1
Full model
LEt
αt
σ
PFAt
Mt, τ
Mat Salt
Catcht+1
Returnt+1

(3^{bis}) Integrate prior information



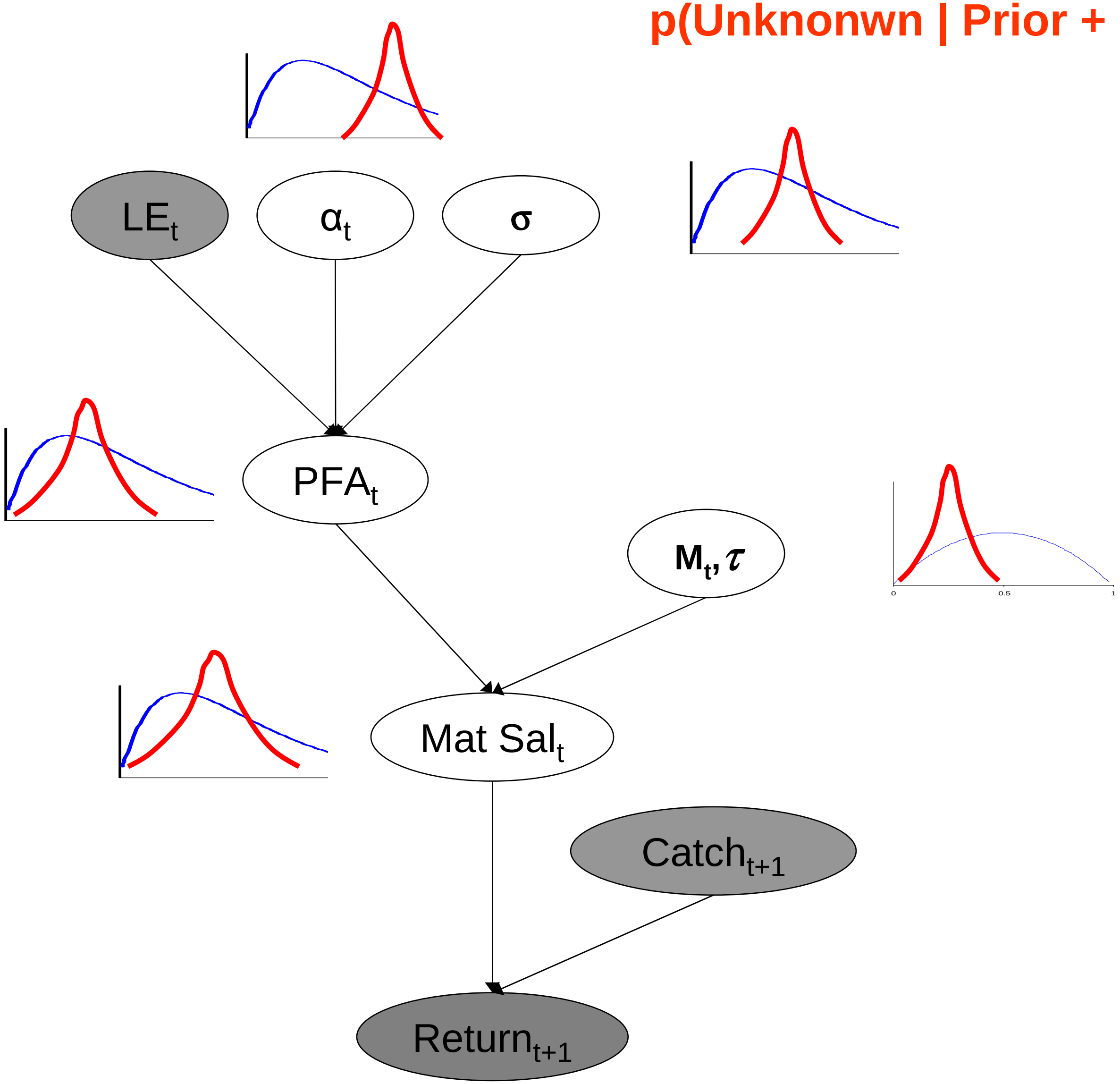
(4) Introduce "observations"



Observations are "fixed nodes" in the graph

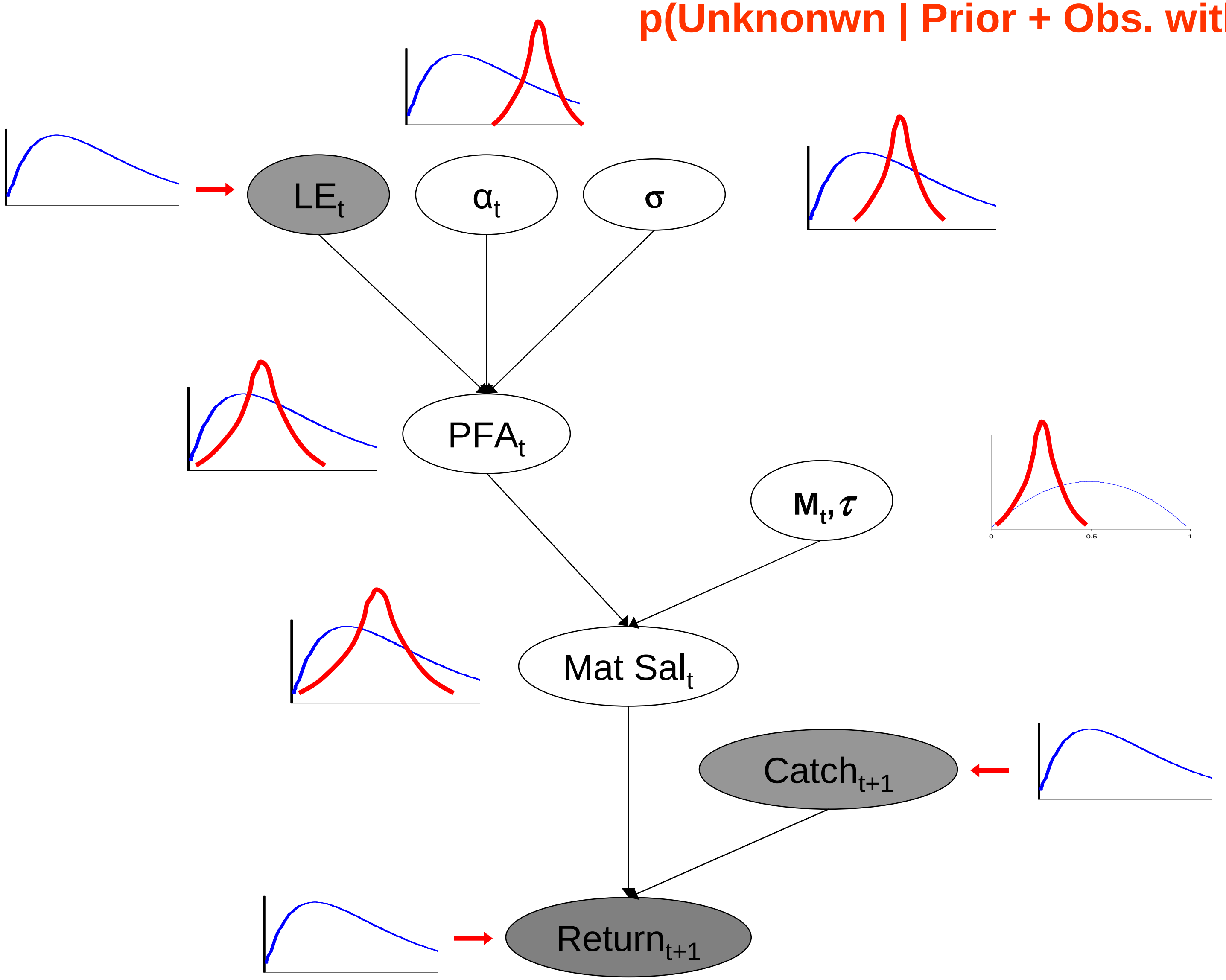
(5) Derive Bayesian inference

p(Unknonwn | Prior + Obs.)

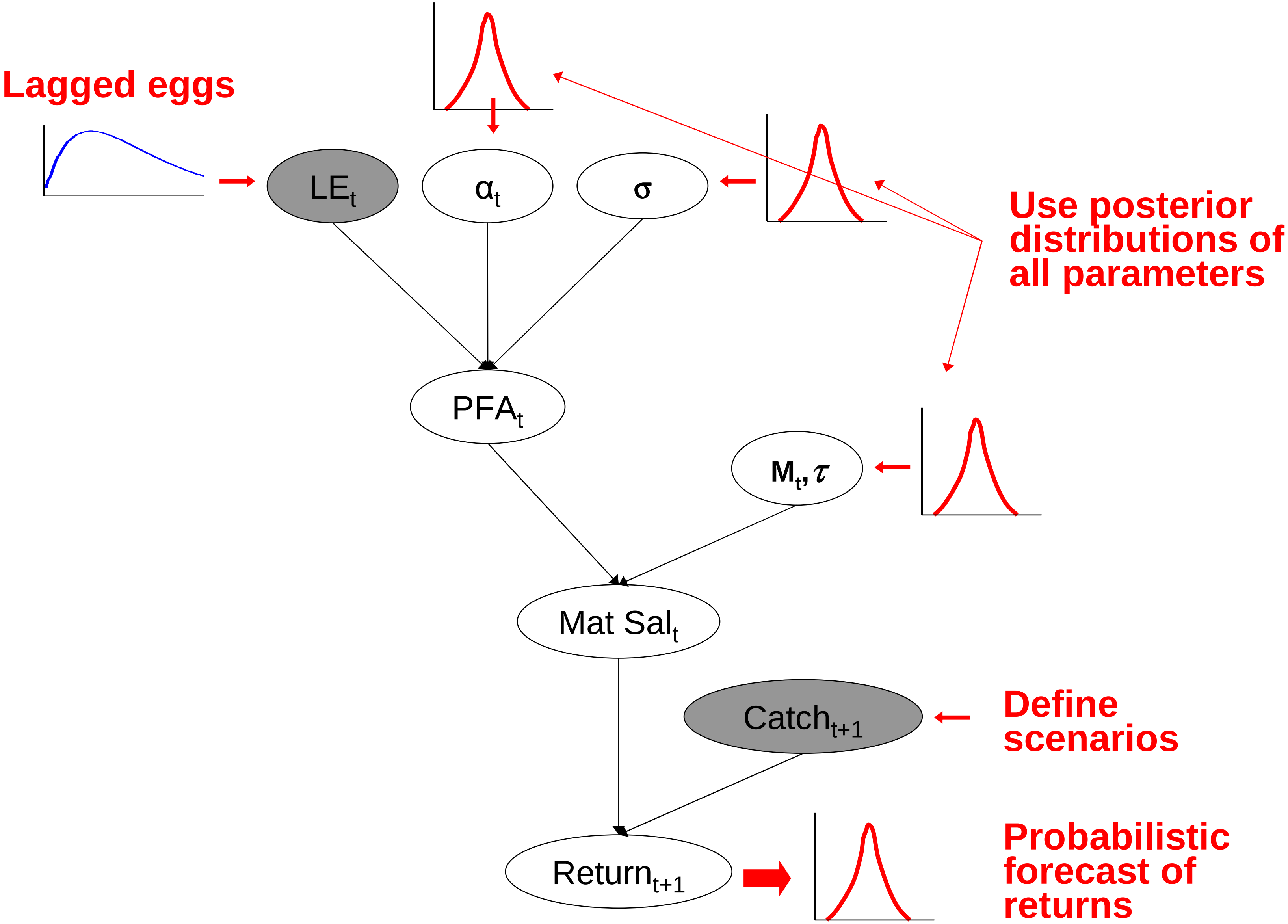


(5bis) Derive Bayesian inference with obs. errors

p(Unknonwn | Prior + Obs. with errors)



(6) Derive probabilistic forecasting



… Sum up

- **Conditional reasoning and DAG help to built complex models**

  - several bricks can be built independently and plugged together

  - take advantages of latent variables

- **Bayesian framework offers a consistent framework for**

  - drawing inferences on all unknown quantities (including latent variables such as PFA)

  by integrating uncertainties on all "inputs" (M, LE, LS, Catches, returns) (from expertise or from observations)

  - deriving probabilistic forecasting in a consistent framework

- **Offers some flexibility in the modelling (regime shifts …)**

Chart flow of the method

Prior distributions

LE, catches, returns

→

Bayesian inference on all unknown, (including latent variables (PFA))

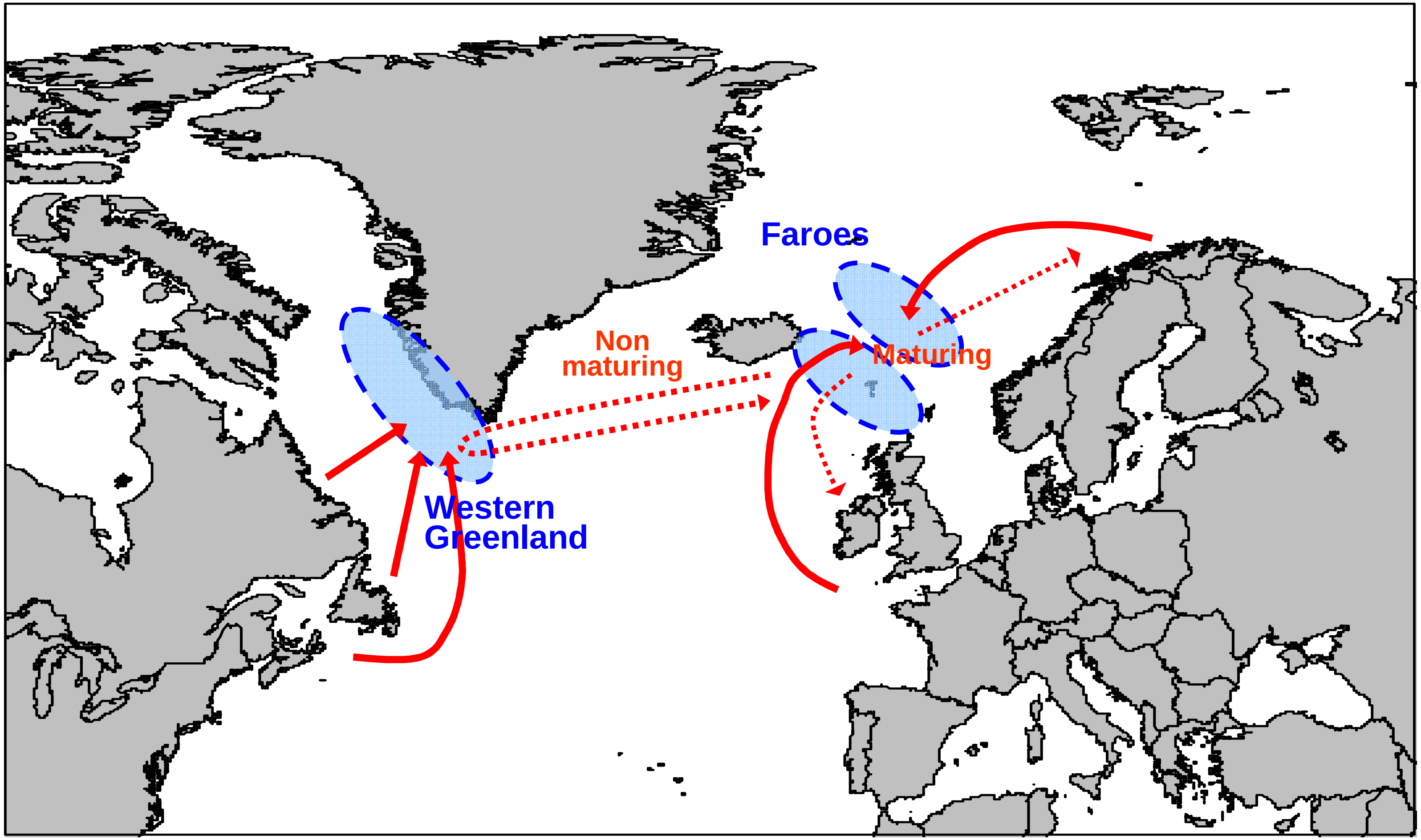
→

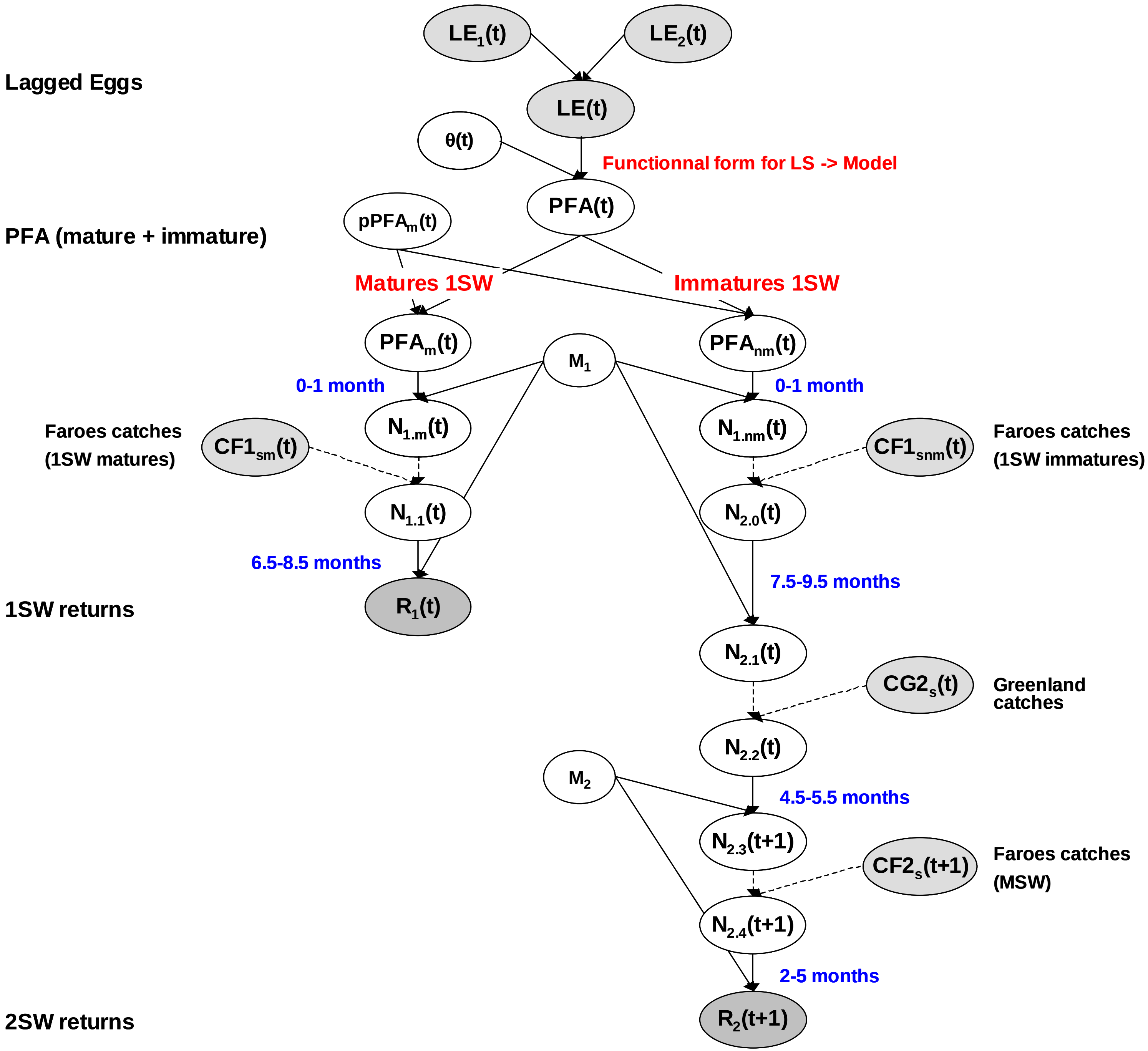
Probabilistic forecasting

Cristal Ball

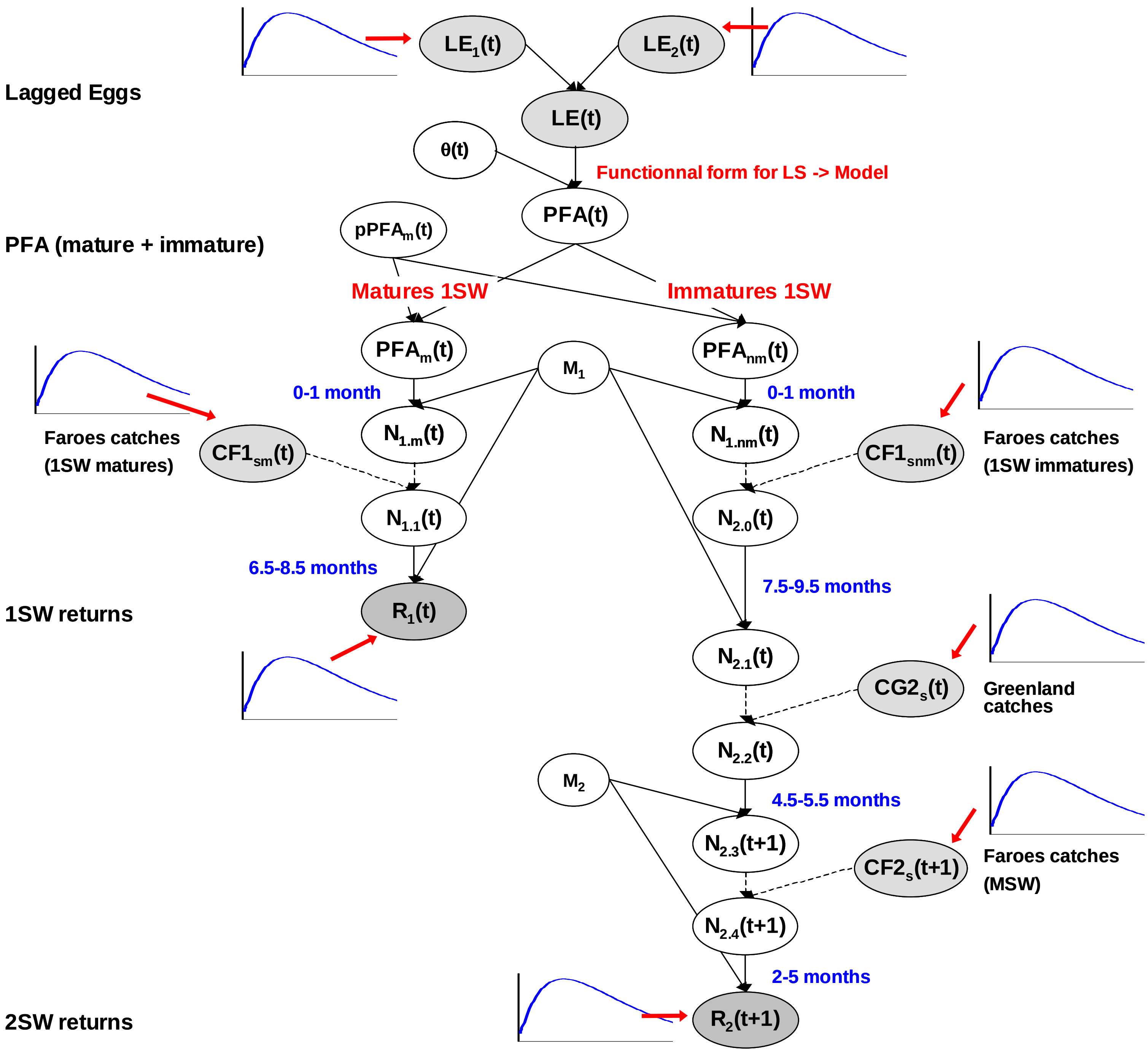
Bayesian model for the Southern NEAC complex

A. salmon (wild) feeding migrations and (mixed stocks) high-seas fisheries





LE1(t)
LE2(t)
Lagged Eggs
LE(t)
θ(t)
Functionnal form for LS -> Model
PFA(t)
pPFAm(t)
PFA (mature + immature)
Matures 1SW
Immatures 1SW
PFAm(t)
PFAnm(t)
M1
0-1 month
0-1 month
N1.m(t)
N1.nm(t)
Faroes catches
(1SW matures)
CF1sm(t)
CF1snm(t)
Faroes catches
(1SW immatures)
N1.1(t)
N2.0(t)
6.5-8.5 months
7.5-9.5 months
1SW returns
R1(t)
N2.1(t)
CG2s(t)
Greenland catches
N2.2(t)
M2
4.5-5.5 months
N2.3(t+1)
CF2s(t+1)
Faroes catches
(MSW)
N2.4(t+1)
2-5 months
2SW returns
R2(t+1)



Lagged Eggs
LE1(t)
LE2(t)
LE(t)
θ(t)
Functionnal form for LS -> Model
PFA(t)
pPFAm(t)
PFA (mature + immature)
Matures 1SW
Immatures 1SW
PFAm(t)
PFAnm(t)
M1
0-1 month
0-1 month
N1.m(t)
N1.nm(t)
Faroes catches
(1SW matures)
CF1sm(t)
CF1snm(t)
Faroes catches
(1SW immatures)
N1.1(t)
N2.0(t)
6.5-8.5 months
7.5-9.5 months
1SW returns
R1(t)
N2.1(t)
CG2s(t)
Greenland
catches
N2.2(t)
M2
4.5-5.5 months
N2.3(t+1)
CF2s(t+1)
Faroes catches
(MSW)
N2.4(t+1)
2-5 months
2SW returns
R2(t+1)

Candidates models for *PFA$_t$ = f(LE$_t$)*

$$PFA_t = e^{\alpha_t} \cdot LE_t$$

- **Random walk (RW)**

  - Historical series: Autocorrelation (env. conditions) is captured

  - Forecasting: Persistence is accounted for

- **Shifting level (SL) models (*phase shift* models)**

  - Same advantages as RW

  +

  - Ecological significance

  *** Some have been identified/discussed in the literature (Beaugrand and Reid 2003)**

  *** Parcimonious modelling of change of productivity by time**

Candidates models for $PFA_t = f(LE_t)$

- **Random walk (RW)**

Model

$$\alpha_1 \sim N(0, V = 1000)$$

$$\alpha_{t+1} \sim N(\alpha_t, \sigma_\alpha^2)$$

$$(\alpha_{t+1} = \alpha_t + \varepsilon_t \sim N(0, \sigma_\alpha^2))$$

Priors

$$\sigma_\alpha^2 \sim \frac{1}{\sigma_\alpha^2}$$

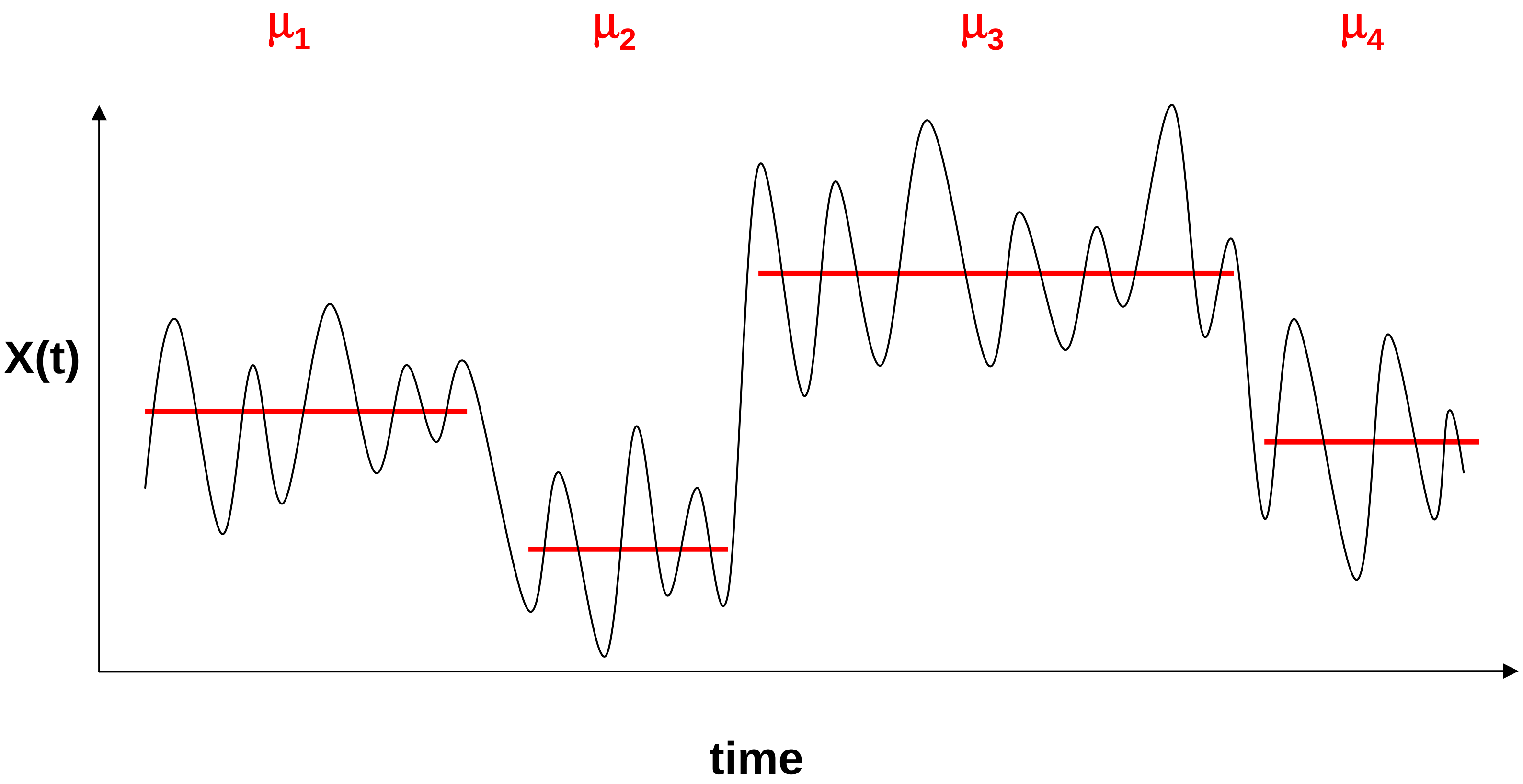
Forecasting

$$Mean \rightarrow \alpha_{last\ year}$$

Dispersion increase

Candidates models for $PFA_t = f(LE_t)$

- **Shifting Level (SL)**



Candidates models for $PFA_t = f(LE_t)$

- **Shifting Level (SL)**
  - **Enable us to infer the phase(s) (levels and duration) and the shifting point(s)**
  - **No need to specify a priori**

    - the number of realized phase during the series

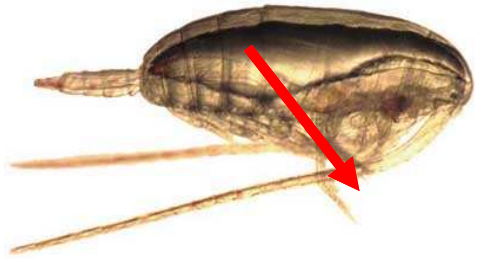
    - the level of each phase
  - **Persistence is accounted for**
  - **The model can be used both for**

    - retrospecive analysis (identify phases and shifts in historical series)

    - forecasting future putative phase shift

Regime shift in the North Atlantic

Beaugrand G. and Reid P. 2003. Long-term changes in phytoplankton, zooplankton and salmon related to climate. Global Change Biology, 9: 801-817.

NHT ↗ ➡  ➡ **Salmons** ↘

Calanus finmarchicus **(prey for post-smolts)**

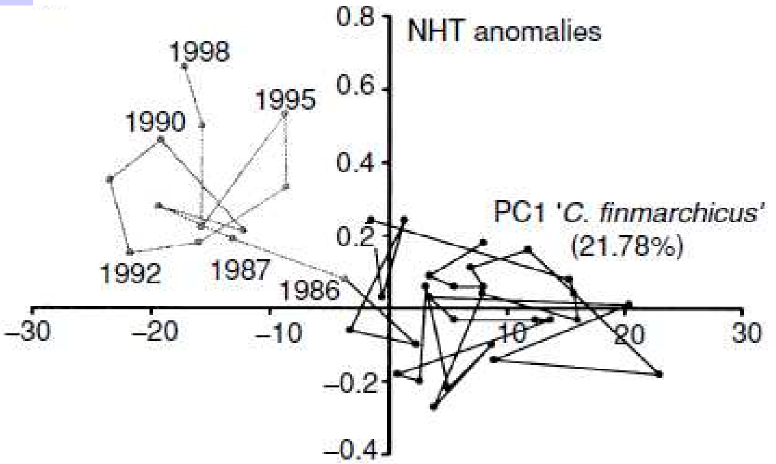


Fig. 5 in Beaugrand G. and Reid P. 2003.

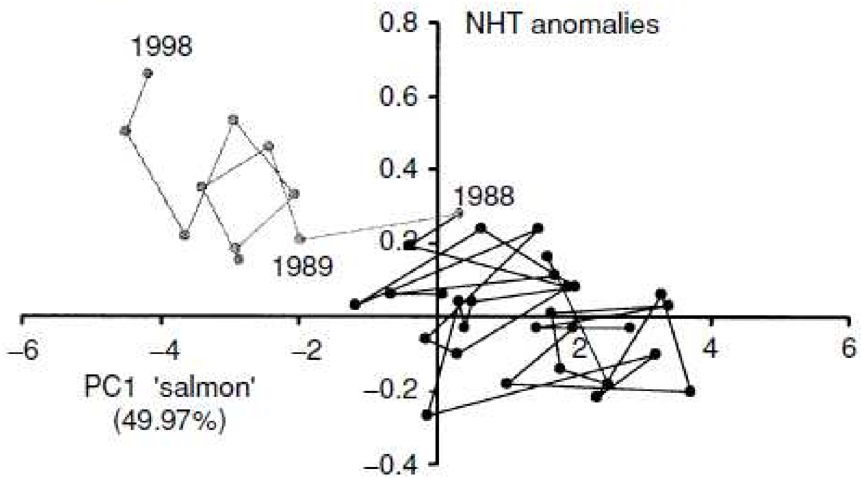


Fig. 5 in Beaugrand G. and Reid P. 2003.

Candidates models for $PFA_t = f(LE_t)$

- **Shifting Level (SL)**

  Based on a Hidden Markov Chain to represent multiple shifts in the production factor α

$\underline{Model}$

$$\alpha_1 \sim N(\mu_\alpha, \sigma_\alpha^2)$$

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

$\underline{Priors}$

$$\mu_\alpha \sim N(\mu = 0, V = 1000)$$

$$p_{shift} \sim Beta(1,1)$$

$$\sigma_\alpha^2 \sim \frac{1}{\sigma_\alpha^2}$$

$\underline{Forecasting}$

$$Mean \rightarrow \mu_\alpha$$

Fortin, V., L. Perreault, J.-C. Ondo and R.-C. Evra. 2002. Bayesian long-term forecasting of annual flows with a shifting-level model. *Proc. Symp. on Managing the Extremes*, Virginia, May 19-22, 2002.
Fortin, V., L. Perreault et J.D. Salas. 2004. Retrospective Analysis and Forecasting of Streamflows Using a Shifting Level Model, *Journal of Hydrology*, 296: 135-163, 2004.

Candidates models for *PFA$_t$ = f(LE$_t$)*

- **Shifting Level (SL) with persistence**

  Based on a Hidden Markov Chain to represent multiple shifts in the mean level of the production factor α

Model

$$\alpha_1 \sim N(\mu_\alpha, \sigma_\alpha^2)$$

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

Priors

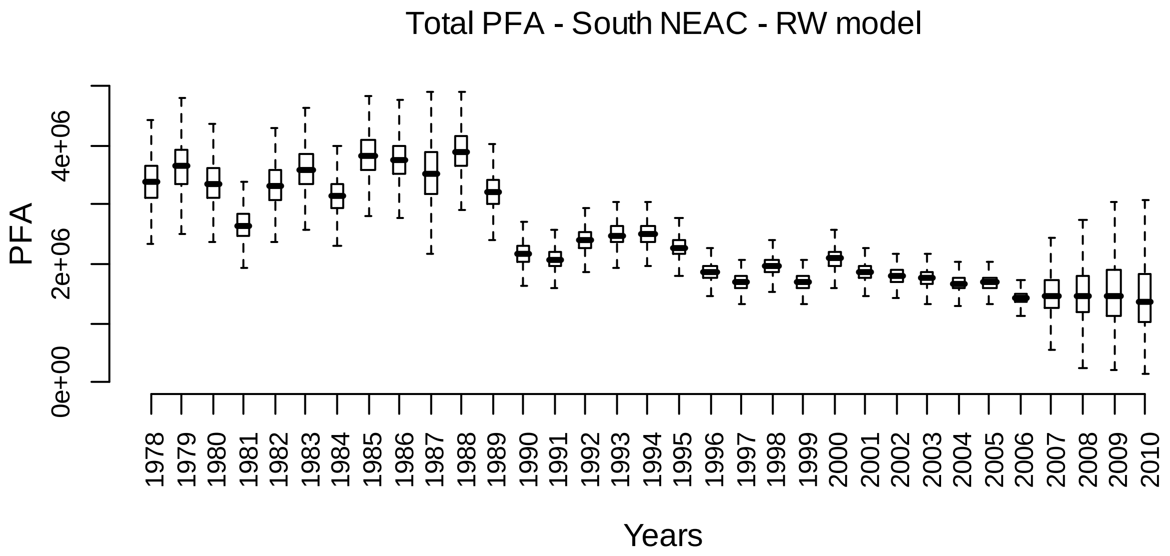
$$\mu_\alpha \sim N(\mu = 0, V = 1000)$$

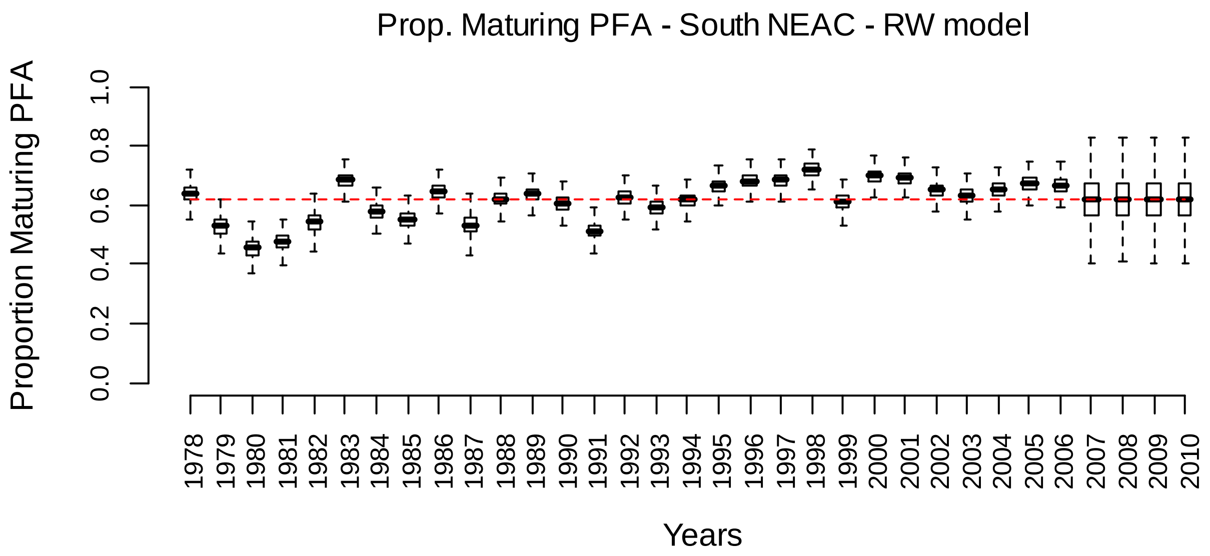
$$p_{shift} \sim Beta(1,1)$$

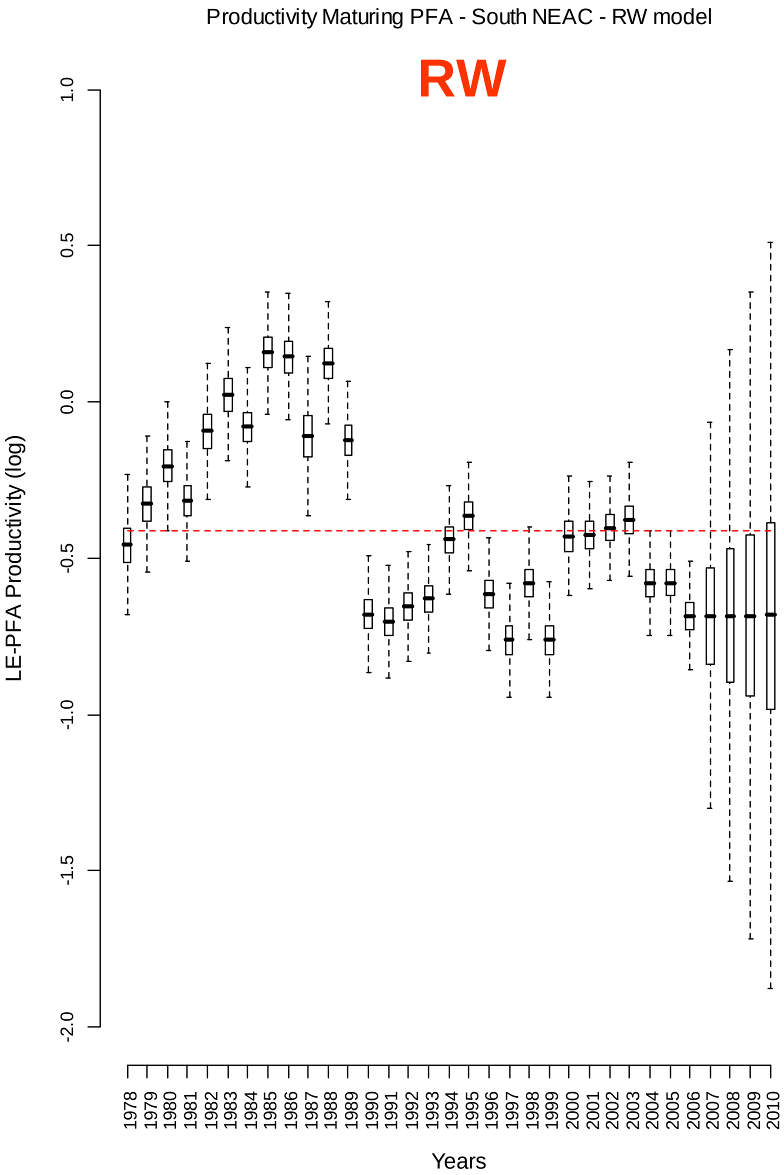
$$\sigma_\alpha^2 \sim \frac{1}{\sigma_\alpha^2}$$

Forecasting

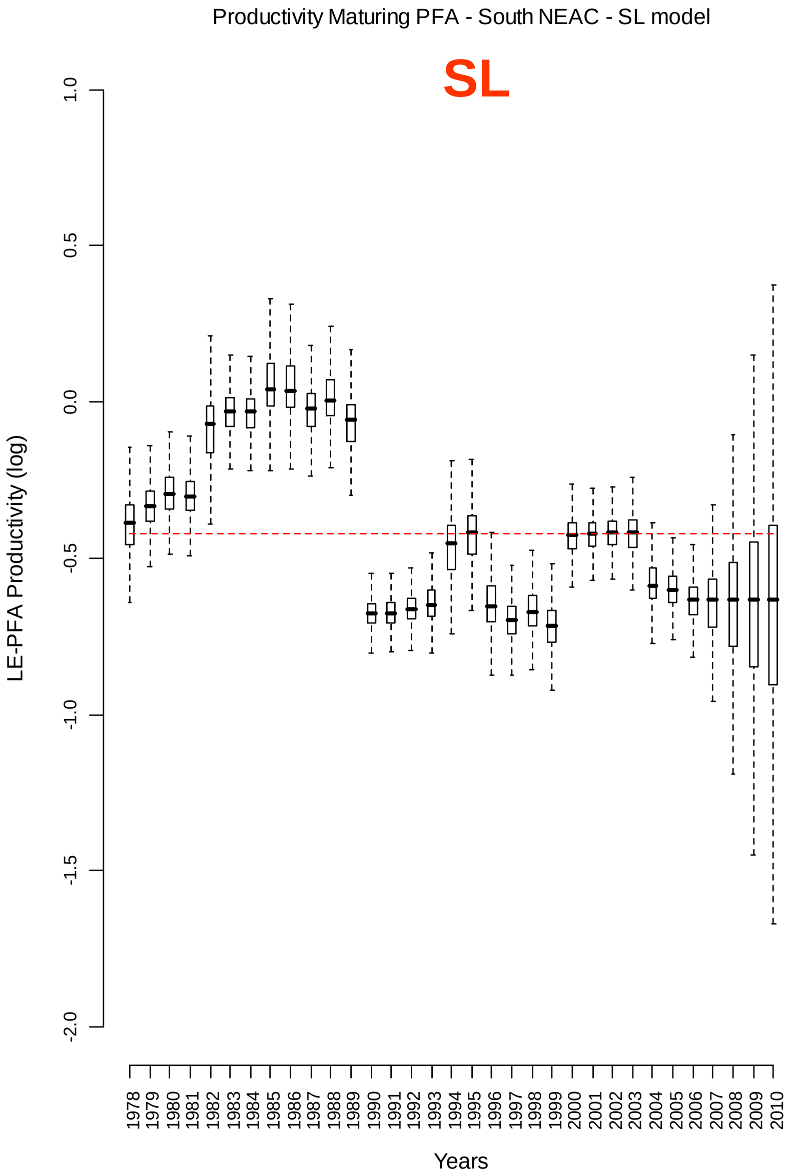
$$Mean \rightarrow \alpha_{last\ year}$$


Total PFA - South NEAC - RW model
PFA
0e+00
2e+06
4e+06
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Years

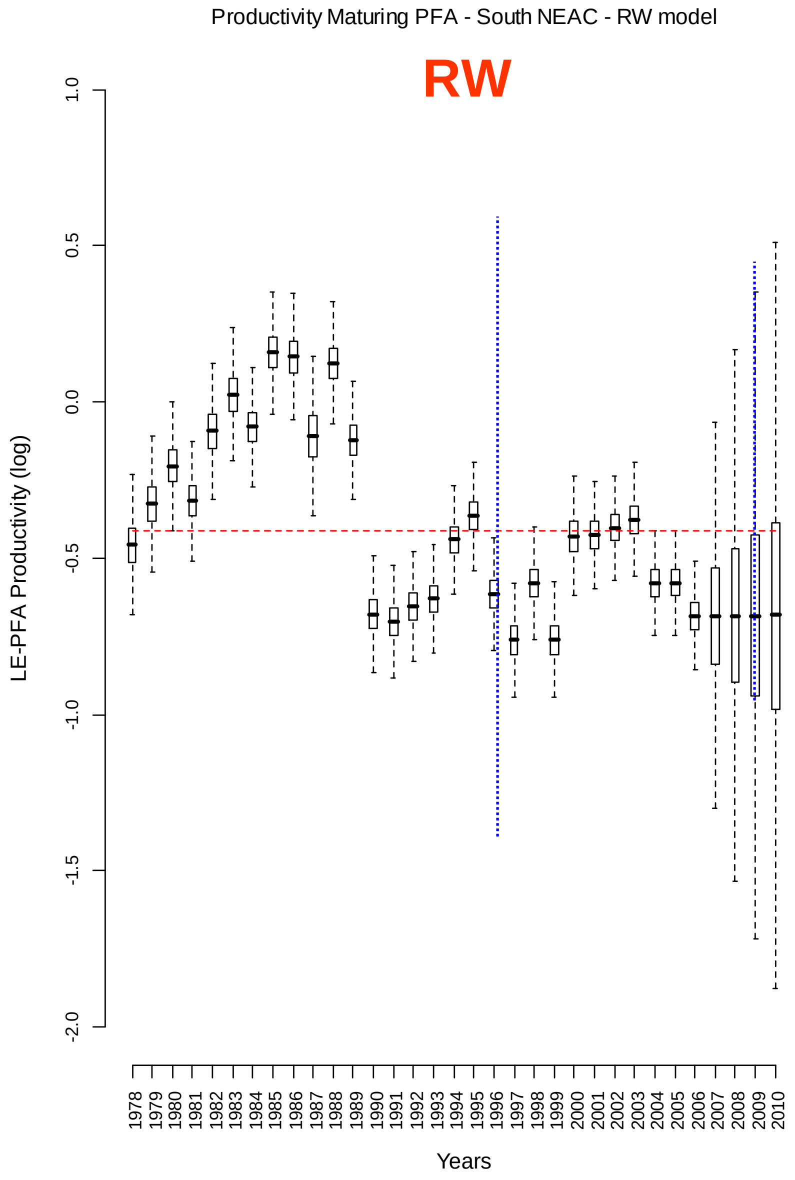

Prop. Maturing PFA - South NEAC - RW model
Proportion Maturing PFA
0.0
0.2
0.4
0.6
0.8
1.0
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Years



Productivity Maturing PFA - South NEAC - RW model
RW
LE-PFA Productivity (log)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Years



Productivity Maturing PFA - South NEAC - SL model
SL
LE-PFA Productivity (log)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Years


Productivity Maturing PFA - South NEAC - RW model
RW
LE-PFA Productivity (log)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1978
1979
1980
1981
1982
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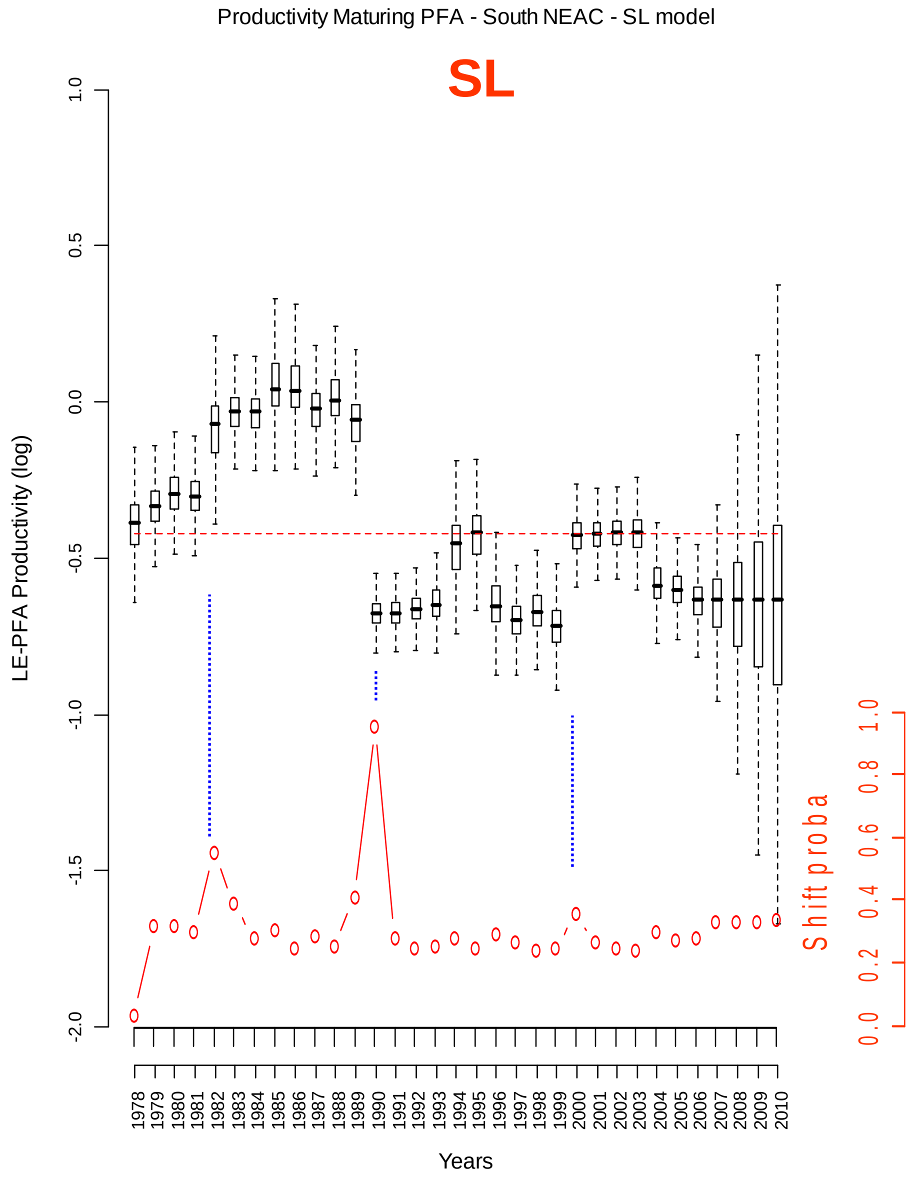
2006
2007
2008
2009
2010
Years


Productivity Maturing PFA - South NEAC - SL model
SL
LE-PFA Productivity (log)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Shift proba
0.0
0.2
0.4
0.6
0.8
1.0
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
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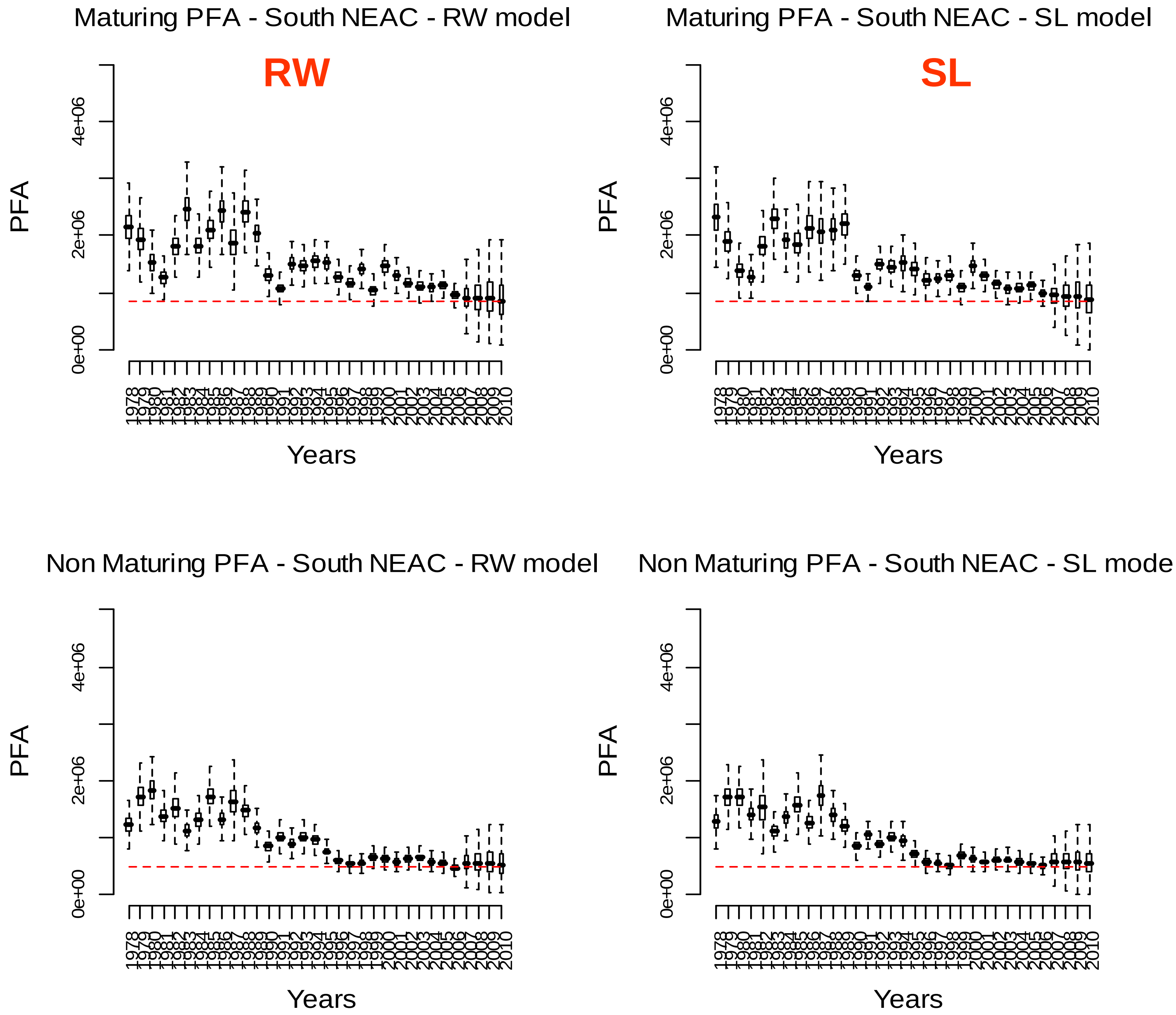
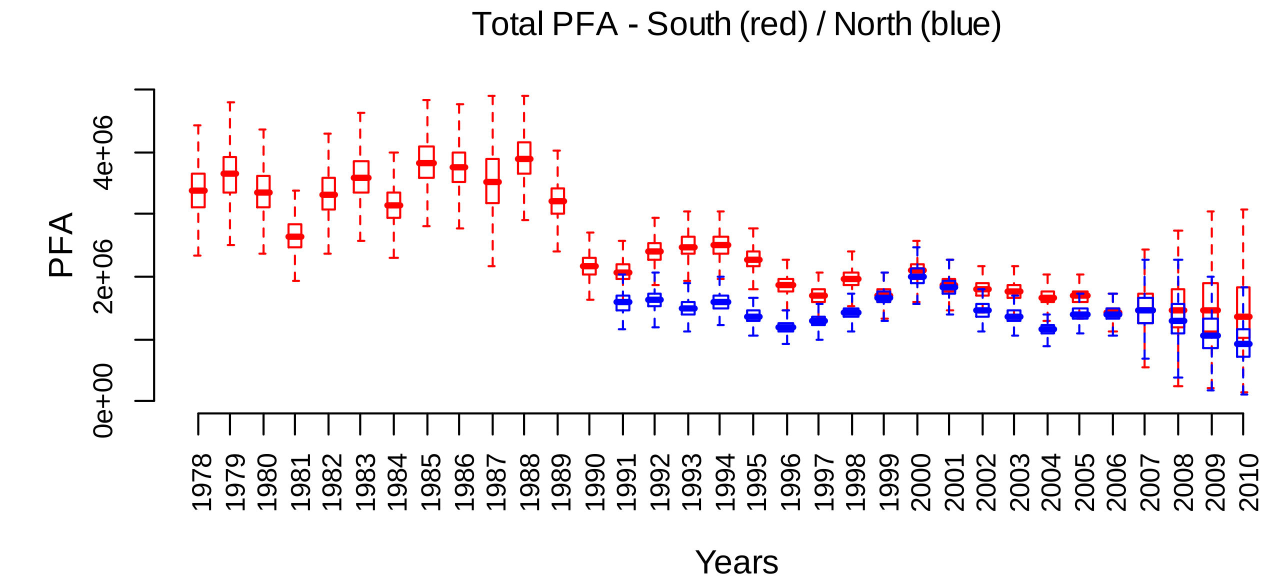
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years


Maturing PFA - South NEAC - RW model
RW
Maturing PFA - South NEAC - SL model
SL
Non Maturing PFA - South NEAC - RW model
Non Maturing PFA - South NEAC - SL mode
PFA
0e+00
2e+06
4e+06
Years
1978
2010

Comparing Northern / Southern NEAC dynamics


Total PFA - South (red) / North (blue)
PFA
0e+00
2e+06
4e+06
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
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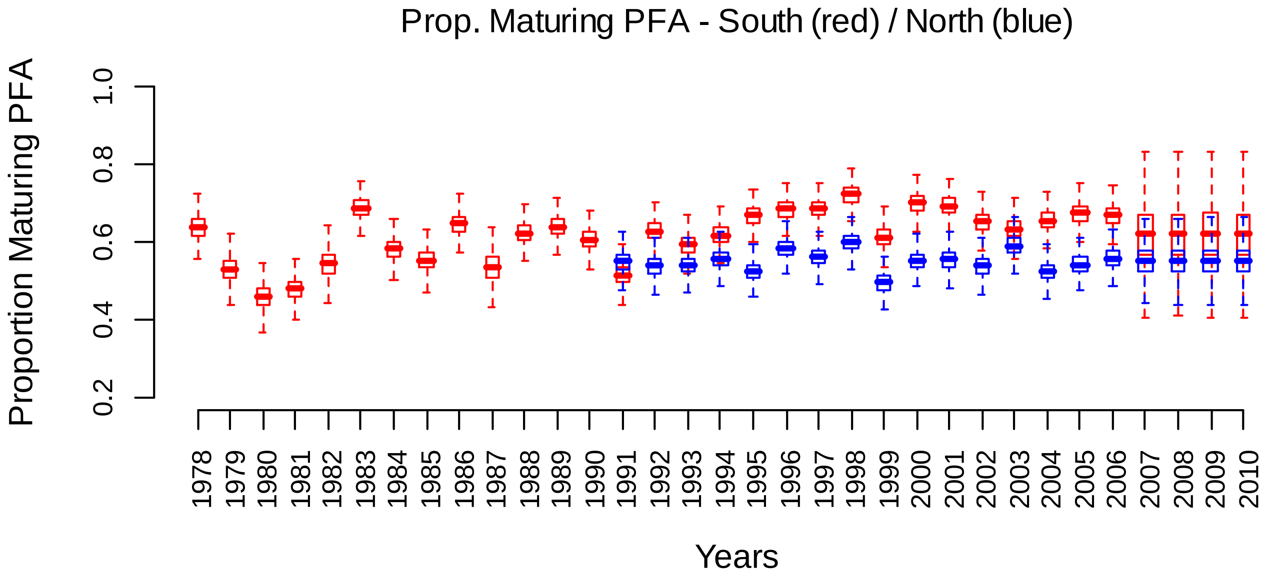
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years


Prop. Maturing PFA - South (red) / North (blue)
Proportion Maturing PFA
0.2
0.4
0.6
0.8
1.0
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
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1996
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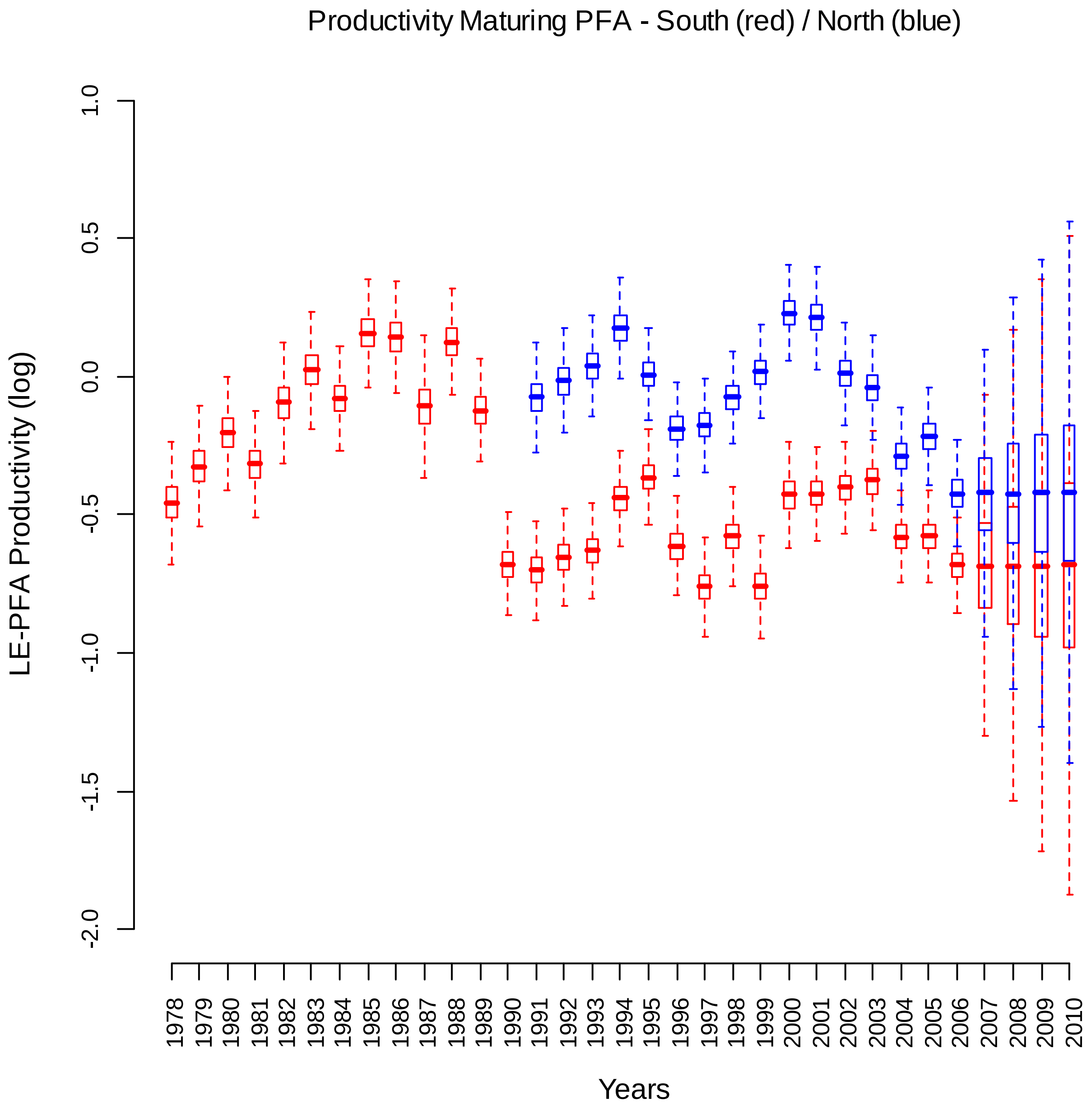
2007
2008
2009
2010
Years



Productivity Maturing PFA - South (red) / North (blue)
LE-PFA Productivity (log)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Years

The beginning of the story

- **2007: DFO funded research Program**
- **2009: ICES Study Group on Salmon Stock Assessment and Forecasting [ICES SGSSAFE]**

  March 2009, Copenhagen

  March 2010, ?
- **2010-2014**

  FP7 – ECOKNOWS
  "Effective use of ecosystem and biological knowledge in Fisheries"

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