ICES Journal of Marine Science, 62: 131−143 (2005)
doi:10.1016/j.icesjms.2004.10.006

Provision of catch advice taking account of non-stationarity in productivity of Atlantic salmon (*Salmo salar* L.) in the Northwest Atlantic

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Chaput, G., Legault, C. M., Reddin, D. G., Caron, F., and Amiro, P. G. 2005. Provision of catch advice taking account of non-stationarity in productivity of Atlantic salmon (*Salmo salar* L.) in the Northwest Atlantic. − ICES Journal of Marine Science, 62: 131−143.

The paper presents the data, the models, and the approach for the provision of management advice for a high seas mixed stock fishery on Atlantic salmon (*Salmo salar* L.). The approach incorporates observation errors, model uncertainty, and considers a possible shift in the productivity of Atlantic salmon. The risk analysis framework further incorporates uncertainty in the fishery harvest characteristics and presents the catch advice as probabilities of meeting or exceeding the conservation objectives relative to catch options. There is very strong evidence from the analyses that there has been a phase shift in productivity of Atlantic salmon of North American origin in the Northwest Atlantic. The change in productivity likely resulted from a change in marine survival which occurred in the early 1990s and has persisted to date. When the uncertainties in the input data are considered, the most parsimonious models suggest that there has been a shift in absolute abundance independent of variations in the spawner index contributing to the recruitment. There continues to be a large amount of uncertainty in the measures of abundance and population dynamics of Atlantic salmon. Uncertainty in the understanding of population dynamics does not necessarily equate to uncertainty in management advice. If model results suggest that spawning objectives are unattainable even when harvest rates are zero, then any harvest level will either accelerate the rate of decline if the model prediction is correct or diminish the probability of recovery if the model prediction is wrong.

Keywords: Atlantic salmon, non-stationarity, productivity, risk analysis.

Received 25 November 2003; accepted 28 October 2004.

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Introduction

Prior to the 1950s, little was known about the migrations and distribution of Atlantic salmon (*Salmo salar* L.) in the ocean. Atlantic salmon were fished by the local population in Greenland for decades prior to the development of the offshore driftnet fishery in the 1960s (Dunbar and Thomson, 1979; Horsted, 1988). The offshore driftnet fishery developed quickly with a peak catch in 1971 of just under 2700 t (Horsted, 1988). The capture in the Greenland fishery in 1956 of a tagged salmon originating from a river in Scotland followed by the recapture of salmon originating from the Miramichi River (Canada) in 1961 and subsequently recaptures of tagged fish from numerous rivers provided the direct evidence that substantial numbers of salmon from both continents undertook feeding migrations to the Northwest Atlantic and were being harvested in the fishery at Greenland (Paloheimo and Elson, 1974; Horsted, 1988). This mixed stock high seas fishery was of sufficient concern that an international body (the North Atlantic Salmon Conservation Organization (NASCO)) was formed in 1982 and a treaty subsequently signed by participating

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countries to manage the marine fisheries on Atlantic salmon (Windsor and Hutchinson, 1994). The annual stock status reports developed by the Working Group North Atlantic Salmon (WGNAS) and the subsequent advice provided by the International Council for the Exploration of the Sea (ICES) have formed the basis for the negotiations and subsequent management of these fisheries.

The robustness of a management system based on a forecast of abundance depends in large part on the relative stability of the system being controlled or an understanding and preferably control of the mechanisms which cause the system to drift from its average state. Stability does not infer a lack of variability but rather variability around an average state over time. There is no reason to expect Atlantic salmon abundance and productivity to have been on average constant over time. Dunbar and Thomson (1979) describe variations in the rudimentary reports of salmon abundance in the Northwest Atlantic going back almost five centuries and the variations in the climate and oceanographic regime to which salmon would have been exposed. The concept of regime shift has been discussed relative to trends in Pacific salmon production (Beamish *et al.*, 1999). A regime shift refers to a large and sudden change in abundance which in the case of managing fisheries, may be unrelated to fishing effects (Beamish *et al.*, 1999). The occurrence of rapid or even slower but persistent directional changes has also been referred to as the problem of non-stationarity in which past observations may not be a good predictor of current outcomes (Walters and Korman, 2001). For the management of Atlantic salmon, the issue is how we manage for the current state and account for the uncertainties.

As in homewater Atlantic salmon fisheries of North America, NASCO has adopted a fixed escapement management strategy (Potter, 2001). In doing so, NASCO and ICES recognize the importance of spawning stock on recruitment. Consequently, the spawner requirements for those rivers contributing salmon to the Greenland fishery must be defined. Management advice, in a currency of harvest tonnage, is then predicated on a forecast of salmon abundance prior to the fishery at Greenland and the management of the harvests with the objective of achieving the spawner requirements for the contributing stocks (Potter, 2001). The challenge to the members of the WGNAS was the definition of the spawning objectives, the development of a measure of abundance prior to the fishery (pre-fishery abundance − PFA), a measure of spawning stock contributing to the PFA, a model to forecast the PFA, and the development of a risk analysis framework.

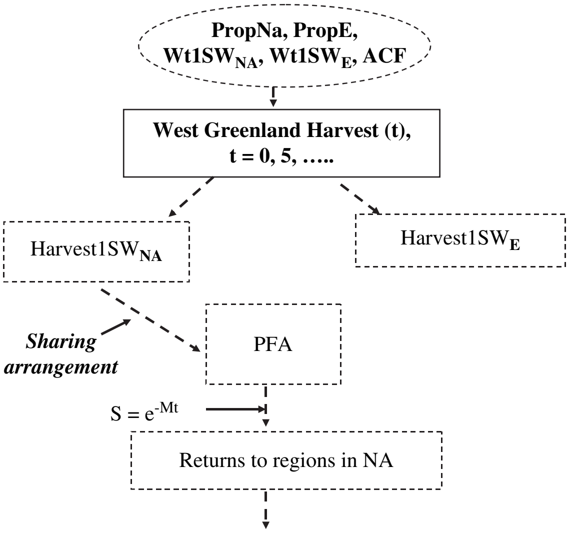
The paper presents the data, the model, and a new approach (for Atlantic salmon) for the provision of management advice which incorporates observation errors, model uncertainty, and considers a possible shift in the productivity of Atlantic salmon. We summarize and add to the methods developed over the last decade by the WGNAS for the provision of catch advice in a risk analysis framework.

Material and methods

The advice for the management of the Greenland Atlantic salmon fishery is presented in a risk analysis framework consisting of five components (Figure 1): (i) estimation of the abundance of salmon prior to the fishery at Greenland, pre-fishery abundance (PFA), (ii) estimation of the spawning stock which would have contributed to the PFA, (iii) the definition of the spawning requirements for the stocks of eastern North America, (iv) the development of a model to forecast abundance of PFA in the year of interest, and (v) consequences to spawning escapement objectives of catch options at Greenland.

Estimation of pre-fishery abundance (PFA)

The Atlantic salmon fishery at West Greenland harvests fish originating from eastern North America and Europe (Reddin, 1986; Reddin and Friedland, 1999; ICES, 2003). The proportions of the fishery harvests of North American origin have varied between 0.40 and 0.90 from 1978 to



Probability (%) of meeting or exceeding objective		
Tons	**Four northern regions**	**Two southern regions**
0	**1.2**	**77.2**
5	**1.1**	**76.2**
10	**1.1**	**75.1**
15	**1.0**	**74.1**
20	**1.0**	**73.4**
25	**1.0**	**72.7**
30	**0.9**	**72.1**
35	**0.9**	**71.6**
40	**0.8**	**71.1**
45	**0.8**	**70.2**
50	**0.7**	**69.5**

Figure 1. Flowchart of risk analysis of catch options at West Greenland. Inputs with solid borders are considered known without error. Inputs with dashed borders are estimated and contain observation error which is incorporated in the analysis. Solid arrows are functions which introduce or transfer without error whereas dashed arrows transfer errors through the components.

2002 (ICES, 2003). The majority (>95%) of the salmon in the catches are one-sea-winter (1SW) non-maturing salmon, fish which are on a feeding migration and would be destined to return primarily as two-sea-winter (2SW) salmon to the rivers of eastern North America and Europe. The remaining fish represent 2SW and older non-maturing salmon and previous spawners (ICES, 2003). It is because the fishery harvests primarily 1SW non-maturing salmon that the WGNAS developed a model to estimate the abundance of this age group prior to the fishery at Greenland.

The run-reconstruction model developed by Rago *et al.* (1993) has been used to estimate the PFA of non-maturing 1SW salmon of North American origin (PFA) for the 1971 to 2001 PFA years (year of abundance of fish at Greenland):

$$\mathrm{PFA}_{\mathrm{year(i)}} = \left[\mathrm{NR2}_{\mathrm{year(i+1)}} \times e^{M\times 1} + \mathrm{NC2}_{\mathrm{year(i+1)}}\right] \times e^{M\times 10} + \mathrm{NC1}_{\mathrm{year(i)}} + \mathrm{NG1}_{\mathrm{year(i)}} \qquad (1)$$

where $\mathrm{NR2}_{\mathrm{year(i+1)}}$ is the sum of 2SW returns to six regions of North America in year i + 1, $\mathrm{NC2}_{\mathrm{year(i+1)}}$ is the catch of 2SW salmon in Newfoundland and Labrador commercial fisheries in year i + 1, $\mathrm{NC1}_{\mathrm{year(i)}}$ is the catch of 1SW non-maturing salmon in Newfoundland and Labrador commercial fisheries in year i, $\mathrm{NG1}_{\mathrm{year(i)}}$ is the catch of 1SW non-maturing salmon of North American origin in the Greenland fishery in year i, and M is the monthly instantaneous natural mortality of 0.03.

The reconstruction begins with the estimation of returns of 2SW salmon in year i + 1 to six regions in eastern North America: Labrador, Newfoundland, Québec, Gulf, Scotia-Fundy, and USA (Figure 2). For the four southern regions, the regional returns include the harvest in the coastal commercial fisheries but this is not the case for Newfoundland and Labrador. For Labrador, the returns to rivers are estimated from the commercial harvest factored by an exploitation rate. The harvest of 2SW salmon in the Newfoundland and Labrador mixed stock fisheries in year i + 1 is added to the sum of the returns to the six regions (prorated backward for one month of natural mortality − equates to 1 June of year i + 1) to produce the returns to North America. Finally, the harvests of North American origin salmon in the Greenland fisheries in year i and the harvest of non-maturing 1SW salmon in the Newfoundland and Labrador commercial fisheries in year i are added to the prorated returns to North America (10 months between abundance at Greenland on 1 August year i and North America on 1 June year i + 1) to produce the pre-fishery abundance of non-maturing 1SW salmon of North American origin (Figure 3). An instantaneous natural mortality rate of 0.03 per month is assumed for salmon in the second year at sea for all years (ICES, 2002). Adjustments to the input data resulting from reductions and subsequent closures of commercial fisheries in North America are summarized by Friedland *et al.* (2003).

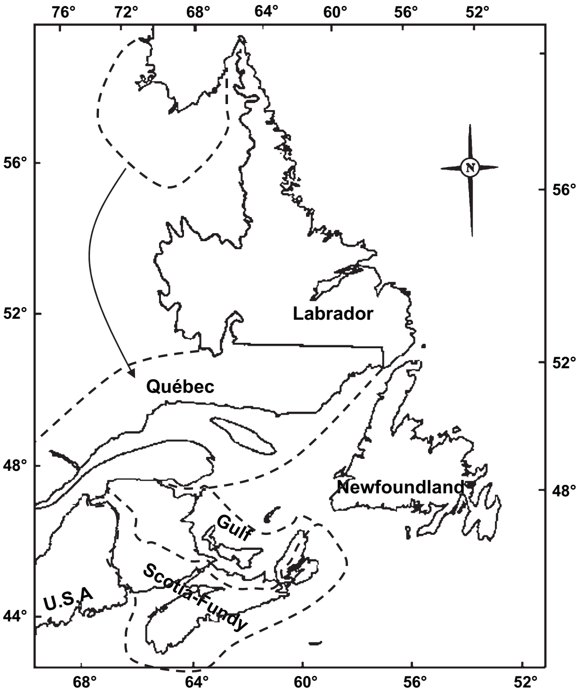


Figure 2. Geographic areas of North America used to structure the run reconstruction of Atlantic salmon abundance.

The returns to each region are estimates with the uncertainty defined by a range of minimum and maximum values based on the best information available for each region (ICES, 2003).

Estimation of spawners

Estimates of the spawning escapement to North America are obtained for the same six regions used in the development of the PFA estimates. The escapements are defined in terms of only the 2SW salmon to each region because the PFA recruitment age group of interest is the 2SW maiden component. This makes the broad assumption that the recruitment of 2SW salmon is conditioned primarily by the 2SW salmon escapement. The uncertainty in the spawning escapement is characterized by an annual range of minimum and maximum estimates for each region. The spawning stock of 2SW salmon contributing to the PFA recruitment of the year of interest is calculated by lagging forward the spawners (lagged spawners) based on the smolt age distributions in each region (Rago, 2001) (Figures 3 and 4; Table 1). 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). The annual spawning escapement is lagged forward in proportion to the smolt age distribution, the latter was assumed constant for each region for the entire time-series.

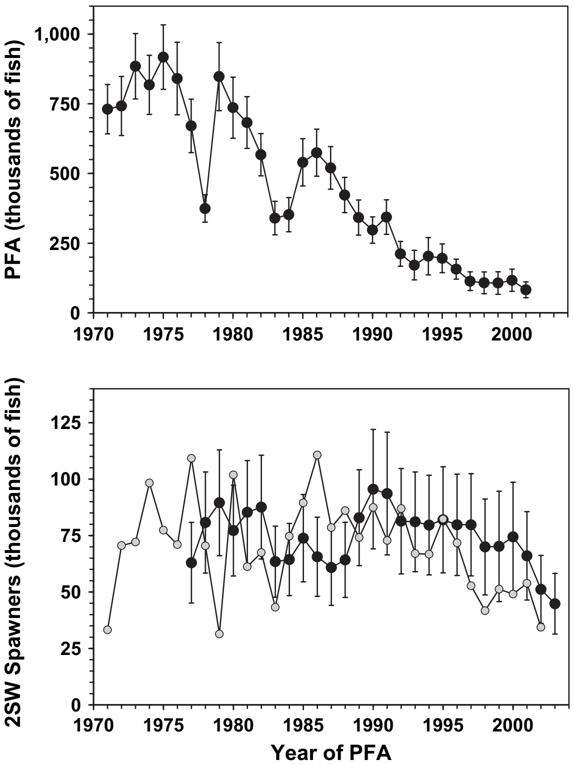


Figure 3. Midpoint and corresponding minimum and maximum range of the annual estimates of pre-fishery abundance (PFA) of 1SW non-maturing salmon (upper panel) and estimates of 2SW Atlantic salmon spawners (annual spawners in grey symbol; lagged spawner index to North America in black symbol) (lower panel) for the year of the PFA estimate.

Spawning requirement for North America

O'Connell *et al.* (1997) document the methods and the values used to derive egg and spawner conservation limits for Atlantic Canada. The conservation limits were generally derived using freshwater production dynamics translated to adult returns to estimate the spawning stock for maximum sustainable yield. Data were available on a limited number of stocks and the values were transported to the remaining rivers where only habitat area and spawner demographics were available. The conservation limits for USA rivers were determined using a similar procedure as those of Atlantic Canada (ICES, 1995). Adult to adult stock-recruitment relationships for six rivers were used to define the conservation limits for rivers in the Québec region (Caron *et al.*, 1999). The total 2SW salmon requirement for North America, calculated from the adult age structure within the regions, equals 152 548 fish (Table 1) (ICES, 2003).

Model for forecasting PFA abundance

Ideally, the lagged spawner variable would be the sum of the lagged spawners in all regions of North America. In terms of assessing population dynamics or relative recruits per spawner, a relative (time) index of spawners is sufficient. After the closure of the Labrador commercial salmon fishery in 1999, the spawner estimate for Labrador could not be derived because the returns and spawner estimates for Labrador were derived from the commercial harvest of Labrador origin fish adjusted for an exploitation rate in this fishery (ICES, 2003). The lagged spawner index without Labrador is highly correlated with the sum of lagged spawners for all of North America ($r = 0.86$) in the years when these data were available. The variation in Labrador spawners has been much greater than the variation of the sum of the other regions (Figure 4). The lagged spawners in the other regions declined from 1978 to 1988 and rose rapidly in 1989, directly as a response to the management plan of 1984 which imposed the closure of the commercial fishery and the mandatory release of large salmon in the Maritimes – the stepped increase in 1989 was driven by the Gulf stock (Figures 3 and 4). Subsequent to 1989, lagged spawners have declined almost continually and most rapidly into 1992.

A preliminary plot of the annual midpoint estimates (range/2) of PFA relative to the lagged spawner (LS) index suggested two periods of productivity: a high productivity period during 1977 to 1988 and a low productivity period during 1990 to 2001 with intermediate productivity in 1978 and 1989 (Figures 5 and 6). Initial analyses of the lagged spawner index with a phase shift variable and a previously used habitat index variable (Friedland and Reddin, 1993) resulted in the habitat index variable being of minimal explanatory power ($P > 0.10$) and it was excluded from all further analyses.

Subsequently, we fitted a series of models relating PFA to LS and to assess the presence of two phases of productivity. The general model was of the form:

$$\mathrm{PFA} = e^{(\alpha+\beta\times \mathrm{Ph})}\mathrm{LS}^{(\gamma+\delta\times \mathrm{Ph})}e^{\xi}$$

where PFA is the pre-fishery abundance estimate of 1SW non-maturing salmon of North American origin, LS is the lagged spawner index of 2SW salmon excluding Labrador (1977–2001), Ph is the phase indicator variable representing two time periods, α, β, γ, δ are the coefficients of the slope and intercept variables, and e^{ξ} is the lognormal residual error.

The PFA and LS variables were natural log transformed before analysis and the linearized form of the model was:

$$\mathrm{Ln(PFA)} = \alpha + \beta \times \mathrm{Ph} + (\gamma + \delta \times \mathrm{Ph}) \times \mathrm{Ln(LS)} + \xi$$

Six nested models (parameters = P) were evaluated.

(0) Null model ($P = 2$) $\mathrm{Ln(PFA)} = \alpha + \xi$
(1) No phase shift ($P = 3$) $\mathrm{Ln(PFA)} = \alpha + \gamma \times \mathrm{Ln(LS)} + \xi$
(2) Only phase shift ($P = 3$) $\mathrm{Ln(PFA)} = \alpha + \beta \times \mathrm{Ph} + \xi$

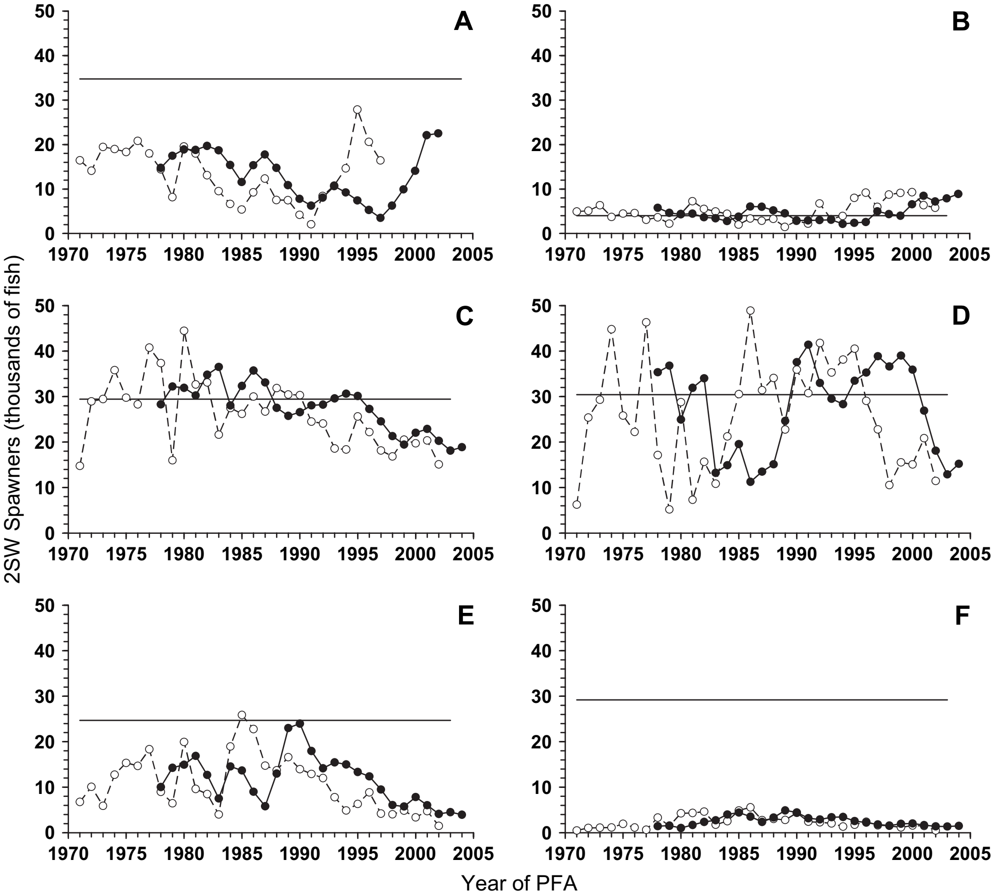


Figure 4. Midpoint of estimated 2SW spawners (open symbols) for 1971 to 2002 and lagged spawners (solid symbols) for 1977 to 2001 in the six regions of eastern North America. The solid horizontal line represents the 2SW spawner requirement for each region. Regions are: A — Labrador, B — Newfoundland, C — Québec, D — Gulf, E — Scotia-Fundy, F — USA (see Figure 2).

(3) Shifted intercept ($P = 4$) $\mathrm{Ln(PFA)} = \alpha + \beta \times \mathrm{Ph} + \gamma \times \mathrm{Ln(LS)} + \xi$

(4) Shifted slope ($P = 4$) $\mathrm{Ln(PFA)} = \alpha + (\gamma + \delta \times \mathrm{Ph}) \times \mathrm{Ln(LS)} + \xi$

(5) Full model ($P = 5$) $\mathrm{Ln(PFA)} = \alpha + \beta \times \mathrm{Ph} + (\gamma + \delta \times \mathrm{Ph}) \times \mathrm{Ln(LS)} + \xi$

Phase shift years were explored starting with 1985 (i.e. 1977–1985; 1986–2001) sequentially through time to 1993 (i.e. 1977–1993; 1994–2001). All models were adjusted to the data sets of sliding breakpoints and the parsimonious model and breakpoint year was determined using the Akaike information criterion (AIC) (Hilborn and Mangel, 1997):

$$\mathrm{AIC} = \mathrm{L(Y|m)} + 2\mathrm{p}$$

where L(Y|m) is the negative log likelihood of the data given the model $(\frac{n}{2}\log_e 2\pi + \frac{n}{2}\log_e \sigma^2 + \frac{1}{2\sigma^2}\sum (\mathrm{Y_{obs}} - \mathrm{Y_{pred}})^2)$ and P is the number of parameters in model m.

The effect of uncertainty in PFA and LS on the selection of the most parsimonious model and the detection of a phase shift was examined by Monte Carlo simulation. PFA was estimated by non-correlated random draws from a uniform distribution within the minimum and maximum range of the source data (from Equation (1)). The uncertainty in LS was characterized by non-correlated random draws from a uniform distribution within the minimum and maximum range of the regional estimates prior to summation. In all, 10 000 data sets of annual values (1977–2001) of PFA and LS were generated. The model and phase shift period combination resulting in the minimum AIC criterion was retained for each simulation.

Predicting PFA for the year of the Greenland fishery

The potential presence of a phase shift in marine productivity presents the additional uncertainty of knowing which phase of marine productivity best describes the year of interest. When sequential observations are autocorrelated,

Table 1. Smolt age distribution (proportion by region) and 2SW salmon spawning requirements (number of fish) for six regions of North America (ICES, 2003).

Region	Smolt age 1	2	3	4	5	6	2SW spawning requirement
Labrador	0.0	0.0	0.077	0.542	0.341	0.040	34 746
Newfoundland	0.0	0.041	0.598	0.324	0.038	0.0	4 022
Québec	0.0	0.058	0.464	0.378	0.089	0.010	30 430
Gulf	0.0	0.398	0.573	0.029	0.0	0.0	29 446
Scotia-Fundy	0.0	0.600	0.394	0.006	0.0	0.0	24 705
USA	0.377	0.520	0.103	0.0	0.0	0.0	29 199
North America							152 548

previous states may provide a reasonable forecast of the immediate future. To forecast a PFA for 2003 in this example, a quantification of the probability of being in either phase is required. The approach taken to estimate this probability was to examine the historical changes in PFA from year t to year t + 2 which provides an indication of the likelihood of observing a change from the previously estimated PFA level sufficient to move the stock to an alternate state (Figure 6). The two-year lag is used because the previous year PFA estimate depends upon 2SW return estimates in the year of the high seas fishery on non-maturing 1SW salmon at West Greenland. There was no significant linear temporal trend ($p > 0.20$) in the relative change ratio but the ratio was more frequently less than unity since 1985 (Figure 6).

Application of these observed rates of change to the PFA two years before results in a distribution of potential PFA values for the forecast year. These values are not used for catch advice, but rather to determine the probability of being in each phase for each of the model and breakpoint combinations (note that model 1 and the null model are not relevant in this case because there is no phase shift component in its parameterization). The mean square error for a single predicted observation from the model fits is used to calculate the probability density of the PFA values for the parsimonious model and break year combination. Summing and standardizing these probabilities over all the potential PFA values for the model and break year combination produces the probability of being in either phase. These weights were used to subsequently assign 2003 to a phase based on a random draw from a uniform distribution.

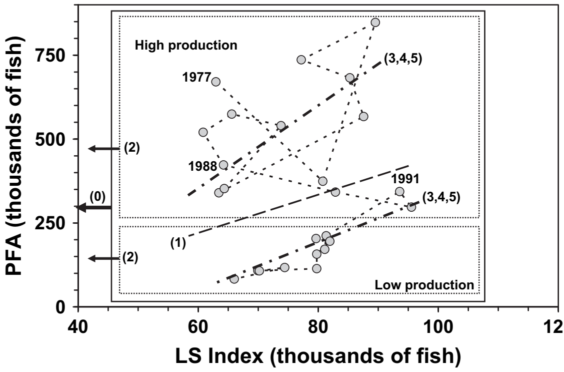


Figure 5. PFA and LS index relationship of Atlantic salmon abundance for North America. Numbers in parenthesis correspond to functional relationships of PFA and LS corresponding to the competing models examined.

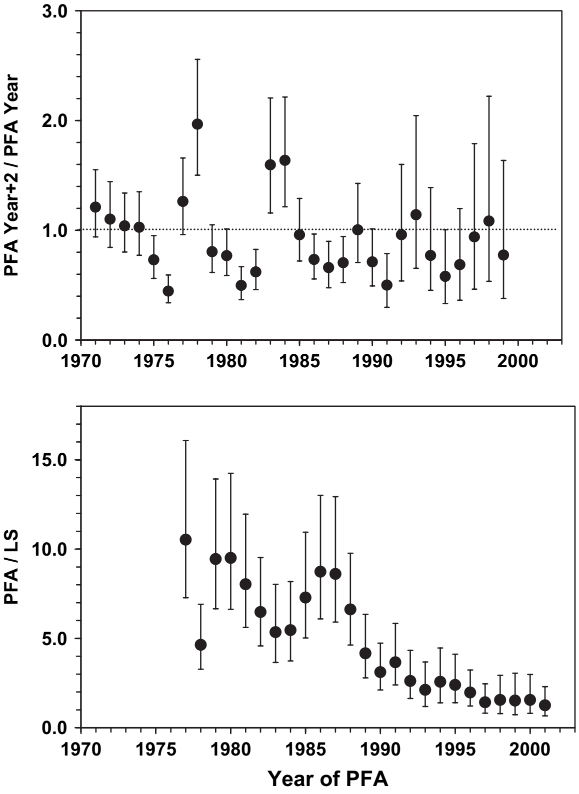


Figure 6. Temporal variation in PFA (year + 2)/PFA (year) (upper) and relative productivity (PFA/LS) (lower) by year of PFA.

For each simulated data series, a prediction for PFA in 2003 is obtained from the most parsimonious model/break year and an attributed productivity phase for the year 2003.

Risk analysis and catch advice

The risk analysis of catch options for Atlantic salmon from North America incorporates the following input parameter uncertainties: (i) the uncertainty in attaining the conservation requirements simultaneously in different regions, (ii) the uncertainty of the pre-fishery abundance forecast, and (iii) the uncertainty in the biological parameters used to translate catches (weight) into numbers of North American origin salmon.

The risk analysis proceeds as illustrated in the flowchart of Figure 1. The four inputs are the PFA forecast for the year of the fishery, the harvest level being considered (weight of salmon), the spawner requirements in the rivers of North America, and the post-fishery returns to each region. The uncertainty in the PFA is accounted for using the forecast approach described previously.

The number of fish of North American and European origin in a given catch (t) is conditioned by the continent of origin of the fish, by the average weight of the fish in the fishery, and a correction factor by weight for the other age groups in the fishery. These parameters define how many fish originating from North America and Europe are expected in the fishery harvests. For a level of fishery under consideration, the weight of the catch is converted to number of fish of each continent's origin using the following equation:

$$C1SW_C = \frac{t \times propC}{ACF \times (propNA \times Wt1SW_{NA} + propE \times Wt1SW_E)}$$

where $C1SW_C$ is the catch (number of fish) of 1SW salmon originating from continent C (either North America or Europe), t is the fishery harvest at West Greenland in kg, propC is the proportion of the 1SW salmon harvest which originates from continent C, $Wt1SW_{NA}$ and $Wt1SW_E$ are the average weight (kg) in the fishery of a 1SW salmon of North American and European origin, respectively, and ACF is the age correction factor by weight for salmon in the fishery which are not at age 1SW.

Since these parameters for the year of interest are not known, they are borrowed from previous year values. The uncertainty in the parameters for 2003 is characterized by random draws from a uniform distribution described by the minimum and maximum range of values observed in the previous five years (Table 2).

The catch of 1SW salmon of North American origin is further discounted by the fixed sharing fraction (Fna) historically used in the negotiations of the West Greenland fishery, 40%:60% West Greenland:North America split. The total potential catch of 1SW salmon of North American origin in all the fisheries (t at West Greenland/0.4) is subtracted from one of the simulated forecast values of PFA. The fish which escape the fishery and return to home waters are discounted for natural mortality from the time they leave West Greenland to the time they return to rivers, a total of 11 months at a rate of M = 0.03 (equates to 28.1% mortality). The fish that survive to home waters are then distributed among the regions based on the regional proportions of lagged spawners for the PFA years 1998 to 2002, the last five years when estimates of spawners were available for all six regions (Table 3). The uncertainty in the regional proportions was characterized by drawing at random from a uniform distribution defined by the minimum and maximum regional ranges from the five years and calculating the average proportion for each of the six regions in North America.

Table 2. Risk analysis input parameters for calculating the number of 1SW salmon of North American origin per t of harvest at West Greenland.

Characteristic	Range of input values: Minimum	Maximum
Proportion North American origin (propNA)	0.65	0.91
Proportion European origin (propE)(calculated as 1 − propNA)	0.09	0.35
Average weight (kg) of 1SW salmon of North American origin (Wt1SWNA)	2.47	3.02
Average weight (kg) of 1SW salmon of European origin (Wt1SWE)	2.81	3.03
Age correction factor (ACF)	1.041	1.130

Estimated returns to each region are compared with the conservation objectives of Labrador, Newfoundland, Québec, and Gulf and to an alternate objective for the southern regions of achieving at least a 10% increase or a 25% increase relative to the average returns to the regions during a specified time period (for example 1998 to 2002) (Table 4). The advice to fisheries managers is presented as a probability plot (or table) of meeting or exceeding the objectives relative to increasing harvest levels at West Greenland.

Results

The estimated abundance of 2SW maiden salmon at the pre-fishery time period (1 August of the second year at sea) for eastern North America oscillated between 300 000 and 900 000 during 1971 to 1986 before declining continually to the lowest estimated level of record in 2001 at 83 000 fish (Figure 3). Estimates of overall 2SW spawners in North America have been less variable, ranging between 40 000 and 127 000 fish (Figure 3). The lagged spawner index (LS) peaked for the 1990 PFA year at about 96 000 fish and has declined continually to the lowest estimated level in 2003

Table 3. Minimum and maximum 2SW lagged spawner estimates (thousands of fish) for the six regions of North America, for the years 1998 to 2002, used to partition 2SW salmon returning to North America among the six regions. Data from ICES (2003).

		Year				
Region	Range	1998	1999	2000	2001	2002
Labrador	Min	1.6	3.1	5.1	9.2	9.8
	Max	11.0	16.8	23.1	35.1	35.2
Newfoundland	Min	2.0	1.8	3.0	4.0	4.0
	Max	6.8	6.2	10.2	13.0	10.4
Québec	Min	17.6	16.5	19.1	19.8	17.4
	Max	25.0	22.5	25.0	26.0	23.2
Gulf	Min	23.1	21.2	20.4	16.5	10.6
	Max	50.2	56.8	51.5	37.3	25.7
Scotia-Fundy	Min	4.5	4.3	5.8	4.4	2.7
	Max	7.7	7.2	9.9	7.7	5.6
USA		1.6	2.0	2.0	1.7	1.4

of less than 45 000 fish (Figure 3). The 2SW spawner requirement is the smallest for Newfoundland and of similar magnitude in the other five regions ranging from 24 000 for Scotia-Fundy to 34 000 for Labrador (Table 1; Figure 4). Only Newfoundland, Québec, and Gulf regions frequently achieved their spawner requirements but only Newfoundland region had 2SW spawners above the requirement in the last five years (Figure 4). Labrador and Newfoundland spawning escapement improved since the commercial fishery moratoria of 1992 and 1998.

When the midpoints (range/2) of the LS and PFA estimates are plotted, two productivity states become evident with a slide from the high state to the low state occurring during 1989 to 1991 (Figure 5). The ratio of the midpoints of PFA to LS ranged between 4.1 and 10.7 during 1977 to 1989 but decreased to between 1.2 and 3.7 during 1990 to 2001. When the midpoints of the recruitment and spawner index are fitted to the six competing models over the range 1985 to 1993 as the breakpoint year between two states, the most parsimonious model is the full model with a change in intercept and productivity rate (model 5) and breakpoint years 1988 or 1989 (i.e. those years in the high productivity state) (Table 5). This initial analysis indicated that the lagged spawner index had explanatory power when combined with a productivity phase variable.

When the uncertainty in the LS and PFA are considered, the importance of the spawning stock variable in explaining variation in PFA was diminished. In 68% of the cases, a simple average change model between two phases (model 2) was the most parsimonious model with the break year being 1991 (the last year of the high productivity state) (Table 6; Figures 5 and 6). In 32% of the data sets, the lagged spawner index was an important explanatory variable when included with a phase shift variable, the most commonly relevant models being models 3 and 5 which had the phase shift variable as an intercept change in absolute PFA abundance (Table 6). The model which excluded any consideration for a phase shift (model 1) was never selected. The importance of spawning stock in explaining variations in PFA corresponded to break years 1988 and 1989 (Table 6).

To provide a forecast of the PFA for 2003, the probability of 2003 being in either the low or high production phases needed to be quantified. The 2001 PFA estimate was 83 000 fish, ranging between 55 000 and 111 000 fish (Figure 3). The change in PFA in a given year relative to its level two years hence is relatively small, ranging from a halving to a doubling of PFA over two years (Figure 7). Simplistically, it seemed highly unlikely that the PFA abundance in 2003 would be greater than 200 000 fish. When the uncertainties in PFA are considered, there was a very small chance (3%) that the 2003 PFA would be in the high production state (Table 6).

The shape of the posterior predicted probability distribution of PFA for 2003 corresponds to the uncertainty in the dynamic and year of the phase shift (Figure 7). The

Table 4. Minimum and maximum 2SW salmon return estimates (thousands of fish) to the two southern regions of North America used to define the alternative objective for evaluating harvest levels of the West Greenland fishery. Data from ICES (2003).

	Scotia-Fundy		
Year	Min	Max	USA
1998	2.7	6.0	1.5
1999	3.5	7.1	1.2
2000	2.0	5.1	0.5
2001	3.1	6.9	0.8
2002	1.4	2.1	0.5
Mean	2.5	5.4	0.9

Table 5. AIC values for the six models and nine break year combinations based on the midpoint values of PFA and LS. Models are described in text. P = number of parameters in the model.

	Model					
Break year	0 P = 2	1 P = 3	2 P = 3	3 P = 4	4 P = 4	5 P = 5
1985	30.0	32.0	24.6	26.6	26.5	28.2
1986	30.0	32.0	22.3	23.8	23.8	25.8
1987	30.0	32.0	19.6	19.2	19.3	20.9
1988	30.0	32.0	17.4	12.2	12.6	8.9
1989	30.0	32.0	16.1	12.6	12.9	8.8
1990	30.0	32.0	15.6	15.9	16.2	12.0
1991	30.0	32.0	12.9	14.7	14.9	12.8
1992	30.0	32.0	14.9	16.9	17.1	16.3
1993	30.0	32.0	18.0	20.1	20.2	20.1

Table 6. The frequency, out of 10 000 Monte Carlo simulations, in which the model and break year combinations produced the most parsimonious model (minimum AIC) and the probability of 2003 PFA being in either the high production or low production phases when uncertainty in PFA and LS index were considered. Models are described in text.

Break year	Model 0	1	2	3	4	5	Overall	Percentage in low phase
1985							0	
1986							0	
1987							0	
1988				782	4	543	1 329	90.4
1989			2	885	5	765	1 657	92.9
1990				11		29	40	92.5
1991			6 530	70	1	112	6 713	99.8
1992			259	2			261	100.0
1993							0	
Overall	0	0	6 791	1 750	10	1 449	10 000	
Percentage in low phase			99.8	89.8	80.0	95.1	97.4	

most likely range of PFA in 2003 is between 130 000 and 140 000 fish, driven by the average shift model but values as low as 50 000 would not be unexpected arising from the spawning stock and phase shift dependent models (Figure 7).

The characteristics of the 1SW salmon in the West Greenland fishery have been variable over the recent five years (Table 2). A harvest of 50 t of salmon at West Greenland was estimated to represent about 12 900 1SW salmon of North American origin (90% C.I. 10 700 to 15 500). The 1SW salmon which escape the fishery were estimated to return to the individual regions of North America relative to the regional lagged spawner proportions of the past five years (1998−2002). The largest proportions of fish are expected to return to the Gulf region (38%) and Québec (26%) with proportionally fewer fish than expected (based on the 2SW spawner requirements of those regions within North America) returning to Labrador (18% vs. 23% expected), Scotia-Fundy (7% vs. 16%), and USA (2% vs. 19%) (Figure 8). Returns to Gulf, Québec, and Newfoundland regions are anticipated to be proportionally greater than expected based on the relative 2SW spawner requirements within North America (Figure 8).

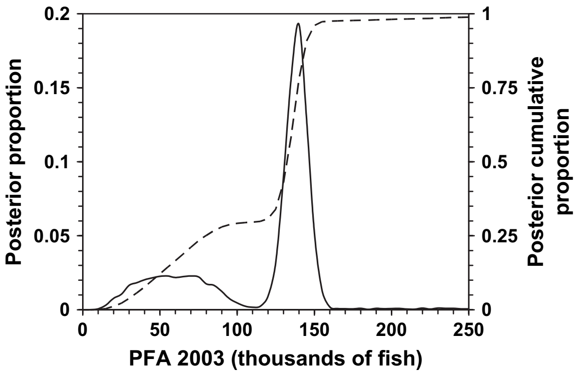


Figure 7. Posterior distribution of predicted PFA (thousands of fish) in 2003.

The combination of the PFA for 2003, expected harvest of 1SW salmon of North American origin for catch options, expected returns to each region and the analysis of the probability of meeting the spawner and return objectives are summarized in Table 7. Even in the absence of any fisheries at West Greenland in 2003 and no subsequent exploitation in North America in 2004, there is a near zero chance that the PFA abundance of salmon in 2003 will be sufficient to meet the spawner objectives for the four northern areas of North America (Table 7). The probability of simultaneous achievement of the spawning requirement is determined by the region most at risk of failing to meet conservation, i.e. Labrador (Table 7). The probability of seeing an increase in returns to USA and Scotia-Fundy regions declines to less than 75% at a harvest at West Greenland (and subsequent sharing fraction in North America) greater than 15 t (Table 7). The greater risk of failing to achieve the management objectives is for the northern region and subsequently the advice would be that there should not be any marine fisheries on the 2003 Atlantic salmon marine cohort.

Discussion

All the commercial fisheries for Atlantic salmon in eastern North America are now closed. The closure of the commercial fisheries follows on declines in stock status observed throughout eastern North America. The only remaining mixed stock marine fishery is at West Greenland

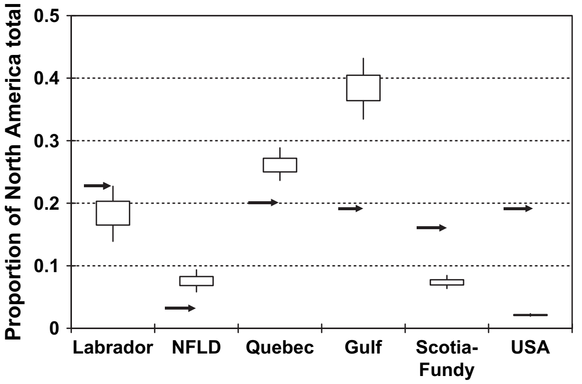


Figure 8. Regional 2SW lagged spawner abundance expressed as the proportion of the region within the total for North America estimated during 1998 to 2002. The rectangle is the interquartile range and the vertical bar is the 5th to 95th percentile range. The horizontal arrow for each region represents the proportion of the 2SW spawner requirement for each region within North America.

Table 7. Risk analysis results of fishery options at West Greenland for the 2003 fishery relative to the objective of meeting or exceeding the spawner requirements in the four northern regions (Labrador, Newfoundland, Québec, Gulf, and simultaneously) and of achieving a simultaneous increase of 25% or greater in returns of 2SW salmon to the two southern regions (Scotia-Fundy and USA) relative to a predefined period (1998 to 2002).

Harvest at West Greenland (t)	Probability (%) of meeting or exceeding spawning requirement					Probability (%) of achieving a 25% or greater increase	
	Labrador	Newfoundland	Québec	Gulf	Simultaneously to four northern areas	Scotia-Fundy	Simultaneously to two southern areas
0	1.2	77.1	3.1	70.0	1.2	77.3	77.2
10	1.1	75.0	2.5	69.0	1.1	75.1	75.1
20	1.0	73.1	2.3	65.9	1.0	73.4	73.4
30	0.9	71.8	2.2	59.5	0.9	72.1	72.1
40	0.8	70.6	2.1	48.0	0.8	71.1	71.1
50	0.7	68.7	2.0	32.0	0.7	69.5	69.5
60	0.7	66.0	1.9	17.8	0.7	66.4	66.4
70	0.6	60.9	1.9	8.6	0.6	60.5	60.5
80	0.5	52.8	1.7	4.5	0.5	51.1	51.0
90	0.5	41.3	1.6	2.9	0.5	39.2	39.2
100	0.5	29.8	1.5	2.4	0.5	27.1	27.0

and the level of fishing activity has generally been reduced to less than 20 t per year and for local consumption (ICES, 2003). Since 1993, the fishery at West Greenland has been managed by quota with the levels negotiated relative to the fixed escapement objective for North America and a pre-fishery forecast model. In the initial years, the pre-fishery abundance model considered only an environmental variable as conditioning PFA and this variable was able to describe an important component of PFA variation (77%; ICES, 1998). In more recent years, a spawning stock variable was added to the model to improve the description of PFA variation as the explanatory power of the environmental variable by itself was declining (ICES, 1998). As well, the WGNAS introduced a risk analysis framework for incorporating uncertainty in the input data, uncertainty in the fishery harvest characteristics, and presented the catch advice as probability plots of meeting or exceeding the conservation objectives (ICES, 1997).

In this paper, we presented a further refinement to the modelling reported by ICES (2003) which considers the possibility of a shift in productivity and incorporates that feature and its associated uncertainties in the selection of the most parsimonious model for providing catch advice. Of the models examined, it could be argued that the choice is essentially between two competing hypotheses: that there was a phase shift in productivity (models 2 to 5) vs. there has not been a phase shift in productivity (model 1) (Hilborn and Mangel, 1997). There is overwhelming evidence from the analyses presented that there has been a phase shift in productivity. In the model formulation chosen, the phase shift was assumed to have occurred abruptly. An alternative which was not considered was that the shift was more gradual, extending over several years, in the late 1980s and early 1990s. The catch advice resulting from this alternative formulation would not have been different for 2003.

The measure of 2SW Atlantic salmon abundance at the PFA stage was derived using a run-reconstruction model. This is essentially a catch based model which is effective when a large proportion of the fish are accounted for in fisheries. When the commercial fisheries closed in 1984 for the Gulf and Scotia-Fundy regions, in 1992 for Newfoundland, and finally in 1998−2000 for Labrador and Québec, the estimated abundance of 2SW salmon became based predominantly on estimated returns to rivers, raised to production areas, and adjusted for assumed natural mortality. The proportion of the PFA estimate which consisted of direct observations (fisheries landings, counts, experimentally designed assessments) has declined since the reduction and closures of marine fisheries (ICES, 2000). Closures of fisheries would not necessarily result in biased estimates of abundance if the natural mortality rates were known. It was assumed that the mortality rate has been constant through the time-series such that reduced returns to rivers in the 1990s are the direct result of reduced PFA abundance almost one year hence. Return rates and measured survival rates to rivers in North America have varied and generally declined into the 1990s such that the assumption of constant mortality over the time-series is questionable (ICES, 2003). The decline in abundance of 2SW salmon to rivers of North America is real, however, the large decline in PFA may be exaggerated.

When uncertainties in the input data are ignored, the association between PFA and the spawner index is best characterized by a model describing a shift in absolute abundance and a shift in relative productivity after 1990.

When the uncertainties in the input data are considered, the most parsimonious model suggests that there has been a shift in absolute abundance independent of variations in the spawner index. The basis for the management of Atlantic salmon is predicated on the maintenance of spawning stock (Potter, 2001). That there should be a weak association between spawners and recruitment should not lead us to discount the value of spawning stock to recruitment (Walters and Korman, 2001; Brodziak *et al.*, 2002). In this case, there are a number of reasons why there may be a lack of compelling evidence of an association between spawners and recruitment. Both variables, particularly the spawner index, have large measurement errors and this may mask any association. The spawner index may also be inappropriate. It was assumed that only 2SW spawners contribute to the PFA. In most rivers of mainland North America that produce 2SW salmon, that is a reasonable assumption since the 1SW salmon spawners are predominantly male however it ignores the contributions of 3SW salmon and repeat spawning fish which in a number of rivers may represent a large portion of the spawning stock (O'Connell *et al.*, 1997). The parental contribution to age at maturity has been shown to be important both experimentally and from long-term stock characteristics (Porter *et al.*, 1986; Ritter *et al.*, 1986). The index excludes a large area of production from North America (Labrador) and in so doing makes the implicit assumption that the trend in spawners from Labrador is identical to the other five regions combined. The smolt age proportions by region are assumed to be constant through time. It also assumes that the relative productivity (recruits per spawner) in all regions of North America is similar and additive regardless of regional spawner abundance. In recent years, three regions contribute spawners to the index disproportionately to their expected contributions. Although the relationship between spawners and recruitment for North America is modelled using a compensatory function, the individual regional relationships are modelled as direct proportions. This could result in model misspecification and the subsequent conclusion that spawning stock is not a relevant factor.

Survival in the marine environment will also be conditioned by factors unrelated to spawning stock. The association between recruitment and spawners is likely to have changed over time such that the relative survivals of the past are not representative of the present. This is the problem of non-stationarity described extensively in the literature (Walters and Korman, 2001). Failure to account for such a phenomenon in the modelling of stock and recruitment associations can lead to rejection of the value of maintaining spawning stock. The evidence for Atlantic salmon points to a change in marine survival in the first and possibly second years at sea which occurred in the 1990s and has persisted to date. The identification of a phase shift is suggestive that marine survival has changed, and quite dramatically, in the last three decades.

Sudden changes in productivity or survival rates have been documented in Pacific salmon and this phenomenon has been referred to as a regime shift (Beamish and Bouillon, 1993; Beamish *et al.*, 1999). A regime shift refers to a change of state (Beamish *et al.*, 1998). In the case of Atlantic salmon, the estimated PFA abundance initially showed oscillations during the period 1971−1991, but post 1991, abundance has declined continually but slowly. It is only when the PFA is plotted relative to the index of spawning escapement that the change in productivity becomes evident and consistent with a regime shift. Measured marine survival rates of wild Atlantic salmon to several Newfoundland rivers remained low or declined after 1990 (Dempson *et al.*, 2003). Return rates in wild multi-sea-winter salmon stocks of mainland Canada also declined in the 1990s, which is consistent with the low productivity phase described by the PFA time-series (Caron *et al.*, 2002). In the LaHave River (Nova Scotia, Canada), an index of recruits to spawners fell and has remained below the replacement level post 1985 year class, equivalent to post 1990 PFA (DFO, 2003). The marine environment in the Northwest Atlantic in the first half of the 1990s was characterized by colder water temperatures, an extension in the southern distribution of Arctic species, delayed spawning of capelin, and increases in cold-water invertebrates such as snow crab (DFO, 1998). Although these changes in the Northwest Atlantic have not been referred to as regime shifts, they are coincident with the reduced abundance of Atlantic salmon.

There continues to be an important component of uncertainty in the abundance and population dynamic of Atlantic salmon. Despite this uncertainty, there is a critical need to provide management advice for Atlantic salmon fisheries (Potter, 2001). It must be recognized that the advice which can be realistically provided for the West Greenland fishery example is not at the resolution desired by managers. For Atlantic salmon at West Greenland, the advice can be provided on the scale of hundreds of tonnes, rather than tens of tonnes which is the current level of exploitation. In the example we used, there are no harvest levels in the mixed stock marine fisheries which would provide a high probability of achieving the conservation objectives and a range of harvests between 0 and 100 t may not be detectable as changes in returns to those regions. The inability to resolve the influence of mixed stock fisheries on the attainment of spawning objectives does not deny the reality that harvested salmon have no opportunity to spawn. Uncertainty in the understanding of population dynamics does not necessarily equate to uncertainty in management advice. Despite uncertainty about the survival of these salmon between the fishery and spawning, the one controllable element is harvest level. If model results suggest that spawning objectives are unattainable even when harvest rates are zero, then any harvest level will either accelerate the rate of decline if the model prediction is correct or diminish the probability of recovery if the model prediction is wrong. It is the role of the science advisors to characterize the uncertainties as completely as possible and management needs to be made aware of the uncertainty.

Acknowledgements

We thank the members of the ICES Working Group on North Atlantic Salmon for their contributions over the last decade to the development of the fisheries advice model for Atlantic salmon. Paul Rago and an anonymous reviewer provided supportive suggestions for improving the clarity and interpretation.

References

Beamish, R. J., and Bouillon, D. R. 1993. Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences, 50: 1002–1016.

Beamish, R. J., Noakes, D., McFarlane, G., Pinnix, W., Sweeting, R., King, J., and Folkes, M. 1998. Trends in coho marine survival in relation to the regime concept. Department of Fisheries and Oceans Canadian Stock Assessment Secretariat Research Document 98/171, 26 pp.

Beamish, R. J., Noakes, D. J., McFarlane, G. A., Klyashtorin, L., Ivanov, V. V., and Kurashov, V. 1999. The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences, 56: 516–526.

Brodziak, J. K. T., Overholtz, W. J., and Rago, P. J. 2002. Reply: Does spawning stock affect recruitment of New England groundfish? Interpreting spawning stock and recruitment data in New England groundfish. Canadian Journal of Fisheries and Aquatic Sciences, 59: 193–195.

Caron, F., Fontaine, P-M., and Picard, S-E. 1999. Seuil de conservation et cible de gestion pour les rivières à saumon (*Salmo salar*) du Québec. Faune et parcs Québec, Direction de la faune et des habitats. ISBN: 2-550-35636-5. 48 pp.

Caron, F., Gauthier, C., and Raymond, C. 2002. Travaux de recherché sur le saumon des rivières Saint-Jean et de la Trinité en 2001. Société de la faune et des parcs du Québec, Direction de la recherche sur la faune. 61 pp.

Dempson, J. B., Mullins, C. C., Bourgeois, C., O'Connell, M. F., and Reddin, D. G. 2003. Perspectives on smolt production and marine survival of Newfoundland Atlantic salmon (*Salmo salar*) related to smolt size and run timing. *In* Natural Mortality in Atlantic Salmon, pp. 24–40. Ed. by E. C. E. Potter, N. O'Maioleidigh, and G. Chaput. Dept. of Fisheries and Oceans Canadian Science Advisory Secretariat Research Document 2003/101.

DFO. 1998. Atlantic Salmon Abundance Overview for 1997. Stock Status Report DO-02 (1998). 21 pp.

DFO. 2003. Atlantic Salmon Maritime Provinces Overview for 2002. DFO Science. Stock Status Report D3-14 (2003). 46 pp.

Dunbar, M. J., and Thomson, D. H. 1979. West Greenland salmon and climate change. Meddelelser om Gronland Bd 202 Nr. 4. 19 pp.

Friedland, K. D., and Reddin, D. G. 1993. Marine survival of Atlantic salmon from indices of post-smolt growth and sea temperature. *In* Salmon in the Sea and New Enhancement Strategies, pp. 119–138. Ed. by D. Mills. Fishing News Books, Oxford.

Friedland, K. D., Reddin, D. G., and Castonguay, M. 2003. Ocean thermal conditions in the post-smolt nursery of North American Atlantic salmon. ICES Journal of Marine Science, 60: 343–355.

Hilborn, R., and Mangel, M. 1997. The Ecological Detective: Confronting Models with Data. Monographs in Population Biology. Princeton University Press, Princeton, New Jersey. 315 pp.

Horsted, S. A. 1988. Past Atlantic salmon research: how far we have come. *In* Present and Future Atlantic Salmon Management—Measuring Progress Toward International Cooperation, pp. 9–18. Ed. by R. H. Stroud. Marine Recreational Fisheries 12. Atlantic Salmon Federation and National Coalition for Marine Conservation, Inc.

ICES. 1995. Report of the North Atlantic Salmon Working Group. Copenhagen, 3–12 April 1995. ICES, Doc. CM 1995/Assess:14, Ref. M, 191 pp.

ICES. 1997. Report of the Working Group on North Atlantic Salmon. Copenhagen, 7–16 April 1997. ICES, Doc. CM 1997/Assess:10. 242 pp.

ICES. 1998. Report of the Working Group on North Atlantic Salmon. Copenhagen, 14–23 April 1998. ICES CM 1998/ACFM:15. 293 pp.

ICES. 2000. Report of the Working Group on North Atlantic Salmon. ICES Headquarters, Copenhagen, April 3–13. ICES CM 2000/ACFM:13. 301 pp.

ICES. 2002. Report of the Working Group on North Atlantic Salmon. ICES Headquarters, Copenhagen, 3–13 April 2002. ICES CM 2002/ACFM:14. 299 pp.

ICES. 2003. Report of the Working Group on North Atlantic Salmon. ICES Headquarters, Copenhagen, 31 March–10 April 2003. ICES CM 2003/ACFM:19. 310 pp.

O'Connell, M. F., Reddin, D. G., Amiro, P. G., Marshall, T. L., Chaput, G., Mullins, C. C., Locke, A., O'Neil, S. F., and Cairns, D. K. 1997. Estimates of conservation spawner requirements for Atlantic salmon (*Salmo salar* L.) for Canada. Department of Fisheries and Oceans Canadian Stock Assessment Secretariat Research Document 97/100. 58 pp.

Paloheimo, J. E., and Elson, P. F. 1974. Reduction of Atlantic salmon (*Salmo salar*) catches in Canada attributed to the Greenland fishery. Journal of the Fisheries Research Board of Canada, 31: 1467–1480.

Porter, T. R., Healey, M. C., O'Connell, M. F., Baum, E. T., Bielak, A. T., and Côté, Y. 1986. Implications of varying the sea age at maturity of Atlantic salmon (*Salmo salar*) on yield to fisheries. *In* Salmonid Age at Maturity, pp. 110–117. Ed. by D. J. Meerburg. Canadian Special Publication of Fisheries and Aquatic Sciences 89.

Potter, T. 2001. Past and present use of reference points for Atlantic salmon. *In* Stock, Recruitment and Reference Points: Assessment and Management of Atlantic Salmon, pp. 195–223. Ed. by E. Prévost, and G. Chaput. INRA Editions, Paris.

Rago, P. J. 2001. Index measures and stock assessment in Atlantic salmon. *In* Stock, Recruitment and Reference Points: Assessment and Management of Atlantic Salmon, pp. 137–176. Ed. by E. Prévost, and G. Chaput. INRA Editions, Paris.

Rago, P. J., Reddin, D. G., Porter, T. R., Meerburg, D. J., Friedland, K. D., and Potter, E. C. E. 1993. A continental run reconstruction model for the non-maturing component of North American Atlantic salmon: analysis of fisheries in Greenland and Newfoundland–Labrador, 1974–1991. ICES CM 1993/M:25. 33 pp.

Reddin, D. G. 1986. Discrimination between Atlantic salmon (*Salmo salar* L.) of North American and European origin. Journal Conseil International pour l'Exploration de la Mer, 43: 50–58.

Reddin, D. G., and Friedland, K. D. 1999. A history of identification to continent of origin of Atlantic salmon (*Salmo salar* L.) at west Greenland. Fisheries Research, 43: 221–235.

Ritter, J. A., Farmer, G. J., Misra, R. K., Goff, T. R., Bailey, J. K., and Baum, E. T. 1986. Parental influence and smolt size and sex ratio effects on sea age at first maturity of Atlantic salmon

(*Salmo salar*). *In* Salmonid Age at Maturity, pp. 30–38. Ed. by D. J. Meerburg. Canadian Special Publication of Fisheries and Aquatic Sciences 89.

Walters, C., and Korman, J. 2001. Analysis of stock-recruitment data for deriving escapement reference points. *In* Stock, Recruitment and Reference Points: Assessment and Management of Atlantic Salmon, pp. 67–94. Ed. by E. Prévost, and G. Chaput. INRA Editions, Paris.

Windsor, M. L., and Hutchinson, P. 1994. International management of Atlantic salmon, *Salmo salar* L., by the North Atlantic Salmon Conservation Organization, 1984–1994 Fisheries Management and Ecology, 1: 31–44.