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Estimating and forecasting pre-fishery abundance of Atlantic salmon (*Salmo salar* L.) in the Northeast Atlantic for the management of mixed-stock fisheries

E. C. E. Potter, W. W. Crozier, P-J. Schön, M. D. Nicholson, D. L. Maxwell, E. Prévost, J. Erkinaro, G. Gudbergsson, L. Karlsson, L. P. Hansen, J. C. MacLean, N. Ó Maoiléidigh, and S. Prusov

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Most exploitation of Atlantic salmon (*Salmo salar*) is restricted to "homewater fisheries", which operate close to or within the rivers of origin of the stocks, but two "distant-water fisheries" are permitted to operate off the west coast of Greenland and in the Norwegian Sea, and take salmon from a large number of rivers over a wide geographical area. Providing robust quantitative catch advice for these mixed-stock fisheries depends upon the ability to forecast stock abundance for about 2000 salmon river-stocks around the North Atlantic, more than 1500 of which are in Europe. A "run-reconstruction" model is presented for estimating the historic pre-fishery abundance (PFA) of salmon for countries or regions around the Northeast Atlantic, based upon catch data and estimates of non-reporting rates and exploitation rates. These estimates are then used to develop predictive models of PFA on the basis of estimates of the egg deposition, derived from the run-reconstruction model and various environmental data. Although the selected environmental indices correlated with the PFA of both southern and northern European stock complexes, the main statistical significance in the forecast models was provided by temporal trends in the PFA. Clearly, such a model is only tenable in the short term, and will be poor at predicting a major change in stock status. Alternative approaches, based upon juvenile production indices and including Bayesian techniques, are therefore being considered.

Keywords: Atlantic salmon, mixed-stock fisheries, stock assessment, stock forecasts.

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E. C. E. Potter, M. D. Nicholson, and D. L. Maxwell: CEFAS, Fisheries Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 OHT, England, United Kingdom. W. W. Crozier: DARDNI, Agricultural and Environmental Sciences Division, Newforge Lane, Belfast BT9 5PX, Ireland, United Kingdom. P-J. Schön, Queen's University of Belfast, School of Agriculture and Food Science, Newforge Lane, Belfast BT9 5PX, Ireland, United Kingdom. E. Prévost, Institut national de la recherche agronomique, UMR ECOBIOP, Station d'hydrobiologie, Quartier Ibarron, 64310 Saint Pée s/ Nivelle, France. J. Erkinaro, Finnish Fame and Fisheries Research Institute, Tutkijante 2, Oulu, FIN-90570, Finland. G. Gudbergsson, Institute of Freshwater Fisheries, Vagnhöfda, Reykjavik 112, Iceland. L. Karlsson, Swedish Salmon Research Institute, Forskarstigen, lvkarleby S-81494, Sweden. L. P. Hansen, Norwegian Institute for Nature Research, PO Box 736, Sentrum, Oslo N-0105, Norway. J. C. MacLean, FRS Field Station, 16 River Street, Montrose, Angus DD10 8DL, Scotland, United Kingdom. N. Ó Maoiléidigh, Marine Institute, Abbotstown, Castleknock, Dublin 15, Ireland. S. Prusov, Polar Research Institute of Marine Fisheries and Oceanography, 6 Knipovitch Street, 183767 Murmansk, Russia. Correspondence to E. C. E. Potter: tel: +44 1502 524260; fax: +44 1502 513865; e-mail: e.c.e.potter@cefas.co.uk.

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Introduction

Most exploitation of Atlantic salmon (*Salmo salar* L.) is restricted to fisheries close to or within the rivers of origin of the stocks, known as "homewater" fisheries. However, two "distant-water" fisheries operate off the west coast of Greenland and in Faroese waters, and they take salmon from a large number of rivers over a wide geographical range. In adopting a precautionary approach to salmon fishery management, the North Atlantic Salmon Conservation Organization (NASCO, 1998) agreed that fisheries for Atlantic salmon should be managed to ensure that stocks are maintained above conservation limits (CLs). Applying this approach to distant-water, mixed-stock fisheries has required that methods be developed not only to set CLs for each North American and European salmon stock, but also to forecast the numbers of salmon alive prior to any fisheries (termed the pre-fishery abundance, PFA). This paper considers the latter part of this process, and describes some of the work undertaken, in part by the EU "SALMODEL" Concerted Action (Crozier *et al.*, 2003), to develop methods to forecast PFA for salmon stocks in the NASCO North East Atlantic Commission (NEAC) area.

Although the main imperative has been to derive PFA predictions for the management of distant-water salmon fisheries, there is also merit in developing forecasts at national, regional, or even local scales, to facilitate management of homewater fisheries. Indeed, it might be possible to combine a number of PFA predictions made at local or regional levels, perhaps derived using differing approaches and different types of data, to give PFA predictions for the total stock contributing to the distant-water fisheries. However, there are more than 2000 salmon river-stocks around the North Atlantic, more than 1500 in the NEAC area alone, and river-stocks from all regions are thought to be exploited in one or both of the distant-water fisheries. The initial requirement has therefore been to ensure that compatible estimates of PFA can be obtained for all stocks, and that these can be combined to develop PFA forecasts for the stock groupings used by ICES to provide management advice (ICES, 2002b).

At its simplest, estimating PFA requires information on the size of a cohort of salmon at a key stage in the life cycle, as well as a measure of the mortality between the time of the key stage and the time for which the PFA estimate is required. Clearly, the shorter the interval between these two times, the more viable such an approach is likely to be. If relationships between cohort abundance and subsequent PFA can be established, and/or if factors influencing marine mortality in the post-smolt phase can be identified and measured at an appropriate time, it may be possible to forecast PFA in advance of fishing. Such forecasts can then be set against the conservation requirements to provide the basis for recommending management options for fisheries. These may take the form of quota or effort controls, which should be designed to limit the catch to a level that ensures a high probability of the spawning escapement exceeding the CL for the stock (or stocks) in question. CLs for Atlantic salmon are generally expressed as numbers of spawners or, in order to take account of differences in sex ratios and fecundities between stocks, as numbers of eggs deposited.

Establishing historical time-series of PFA

Much of the work on the development of forecast models has depended initially upon establishing historical time-series of PFA estimates. ICES (1992) differentiated between two approaches, "life history models" and "run-reconstruction models", for estimating the size of salmon stocks during the marine phase of the life cycle. These approaches use "key stages" during the freshwater phases (juveniles or returned adults) of the life cycle to estimate stock numbers. The numbers are then adjusted to take account of both natural and, if appropriate, fishing mortality between the key stage and a date during the marine phase, before the start of the first fishery.

Life history models will normally use smolt emigration as the key stage, and smolt production may be estimated directly, when the fish leave freshwater, or indirectly from surveys of parr populations. The PFA is then estimated by accounting for the factors causing changes in natural mortality in the intervening period. For run-reconstruction models, the key stage is normally the return of the adult fish to freshwater. Thus, the model estimates the number of returning adults of each sea-age group, then back-calculates the numbers of fish that were alive earlier in the life cycle by adding the numbers estimated to have been caught or to have died naturally. The number of one sea-winter (1SW) salmon in the sea is thus estimated by summing the back-calculated numbers from each sea-age group.

The life history method has obvious advantages, because the juvenile data required to forecast abundance of stocks are available before any fisheries begin. Despite this, they have not generally been favoured for developing historical estimates of PFA for Atlantic salmon because of the limited coverage, both spatially and temporally, of good data on parr or smolt production. Furthermore, although this approach can be used to estimate the total number of 1SW fish in the sea, the maturing and non-maturing components (i.e. fish that will potentially return to home-waters as 1SW and multi-sea-winter, MSW, salmon, respectively) contribute to different fisheries, and therefore need to be accounted for separately to develop management advice. This requires an estimate of the proportion of the stock that will mature after their first sea-winter, which creates an additional complexity for the approach, because this proportion varies between stocks and, to a lesser extent, between years. Nevertheless, life history methods have been successfully applied in the Baltic Sea, where there are fewer wild salmon stocks, and a large proportion of the smolt production is derived from hatcheries, and is therefore easily quantified (ICES, 1989, 2002a).

Run-reconstruction models for salmon stocks

The main advantage of backwards-running, run-reconstruction models has been that more extensive data are available on adult returns (e.g. from traps, counters, and catch data) than on freshwater production of juveniles. In addition, rates of natural mortality (M) were thought to be lower and more stable for large salmon after their first winter in the sea than during the post-smolt phase (Potter *et al.*, 2003), and an estimate of M for adult salmon was available in the literature (Doubleday *et al.*, 1979). These models employ standard fishery equations to estimate the PFA before the start of the first distant-water fishery, from the numbers surviving to return to homewaters and the catches in intervening fisheries. Thus, the models take the generalized form:

$$\mathrm{PFA} = \mathrm{Nh} \times \exp(\mathrm{Mt_h}) + \sum_{i} \mathrm{C_i} \times \exp(\mathrm{Mt_i}) \qquad (1)$$

where Nh is the number of adult fish returning to homewaters, C_i the catch of fish from the stock in each interception fishery i (operating before the fish return to homewaters), M the monthly instantaneous rate of natural mortality of salmon in the sea after the first sea-winter, t_i the time in months between the PFA date and the midpoint of fishery i, and t_h is the time in months between the PFA date and the midpoint of the return of fish to homewaters.

This approach has been employed in the NASCO North American Commission (NAC) area to estimate the PFA of both 1SW and 2SW salmon, which are defined as the cohorts of salmon maturing as 1SW and 2SW fish that are alive prior to all the marine fisheries for 1SW salmon (Rago *et al.*, 1993a). In this case, the returns to North American rivers are estimated in a variety of ways, including counts at fishways and counting fences, mark and recapture studies, visual counts by snorkelling or from the shore, and angling catches and redd counts (ICES, 2002b). Coastal catches are also added to the estimate when appropriate. A detailed evaluation of this approach has indicated that, even after major reductions in the fisheries in recent years, a substantial part of these PFA estimates is still based upon real observations of fish (ICES, 2000). However, one problem with the NAC model is that it does not include all sources of non-catch fishing mortality, although unreported catches are partly taken into account by adjusting the declared catch figures.

Similar approaches have been developed for the NEAC area, to estimate the PFA of maturing and non-maturing 1SW salmon recruiting to the marine salmon fisheries (Potter and Dunkley, 1993; Potter *et al.*, 1998). As there are relatively few fish of sea-age three or more in most stocks, the NEAC model caters for two age groups, 1SW and MSW, the latter including all fish of sea-age two or more that are treated as a single cohort. The model uses the catches of 1SW and MSW salmon in each country within the NEAC area (or in regions within countries), which are first raised (i.e. scaled) to take account of non-reported catches, then divided by the exploitation rates for the two age groups, to estimate the number of returning fish. Finally, they are raised again to take account of natural mortality between the "PFA date" and the midpoint of the respective national (or regional) fisheries. For the NEAC area, the PFA date is taken as 1 January in the first sea-winter, which approximates the date that they may first be exploited as 1SW fish in the Faroese fishery.

Thus, for each country (or region) c in year y, the total number of fish of sea-age a caught in homewater fisheries ($\mathrm{Ch_{a,y,c}}$) is calculated by dividing the declared catch ($\mathrm{Cd_{a,y,c}}$) by the non-reporting rate ($1 - \mathrm{U_{a,y,c}}$):

$$\mathrm{Ch_{a,y,c}} = \mathrm{Cd_{a,y,c}} / \left(1 - \mathrm{U_{a,y,c}}\right) \qquad (2)$$

where $\mathrm{U_{a,y,c}}$ is the estimated proportion of the total catch that is unreported or discarded. The number of fish returning to homewaters ($\mathrm{Nh_{a,y,c}}$) is estimated by dividing the total homewater catch by the exploitation rate ($\mathrm{H_{a,y,c}}$):

$$\mathrm{Nh_{a,y,c}} = \mathrm{Ch_{a,y,c}} / \mathrm{H_{a,y,c}} \qquad (3)$$

As the model provides estimates of total returns and total catch (including non-catch fishing mortality), it is then also possible to estimate the spawner escapement:

$$\mathrm{Ns_{a,y,c}} = \mathrm{Nh_{a,y,c}} - \mathrm{Ch_{a,y,c}} \qquad (4)$$

Total catches in the Faroese ($\mathrm{Cf_{a,y}}$) and West Greenland ($\mathrm{Cg_{a,y}}$) fisheries are similarly calculated by correcting the declared catches for non-reporting, but they are not raised for the exploitation rate, because the uncaught fish are accounted for from the returns to homewaters. The West Greenland fishery only exploits salmon that would otherwise mature as MSW fish, although the majority are 1SW in the summer that they are caught; for the purpose of the model, all are classed as 1SW. The Faroese fishery exploits predominantly MSW salmon, but also a small number of 1SW fish, 78% of which have been estimated to be maturing (ICES, 1994). Over the past two decades, a substantial proportion of the fish caught in the Faroese fishery have been escapees from salmon farms, and these are discounted from the assessment of wild stocks on the basis of data from Hansen *et al.* (1999). The incidence of farm escapees in the West Greenland catch is thought to be $<1.5\%$ (Hansen *et al.*, 1997), so this portion is ignored in the model. The total estimated catches of wild fish in both distant-water fisheries are assigned to the PFA for different countries on the basis of historic tagging studies (Potter, 1996).

The returns to homewaters and catches in the distant-water fisheries of 1SW and MSW salmon are then raised to take account of the marine mortality between the PFA date and the respective enumeration dates. Thus, the PFA of maturing 1SW fish (PFAm), survivors of which will return to homewaters as 1SW adults, is

$$PFAm_{y,c} = Nh_{1,y,c} \times \exp(Mt_{h,1,c}) + 0.78 \times Cf_{1,y} \times w_y \times pf_{1,c} \times \exp(Mt_{f,1,c}) \quad (5)$$

and the PFA of non-maturing 1SW fish (PFAn), survivors of which will return to homewaters as MSW adults, is

$$PFAn_{y,c} = Nh_{2,y+1,c} \times \exp(Mt_{h,2,c}) + Cg_{1,y} \times pg_{1,c} \times \exp(Mt_{g,1,c}) + 0.22 \times Cf_{1,y} \times w_y \times pf_{1,c} \times \exp(Mt_{f,1,c}) + Cf_{2,y+1} \times w_{y+1} \times pf_{2,c} \times \exp(Mt_{f,2,c}) \quad (6)$$

where indices y and c represent year and country/region, indices 1 and 2 the 1SW and MSW sea-age groups, w is the proportion of the Faroese catch that is of wild origin, pf and pg are the proportion of the catches in the Faroese and West Greenland fisheries originating from each country (as indexed), and t_h, t_f, and t_g are the times in months between the PFA date and the midpoints of the homewater fisheries, the Faroese fishery, and the West Greenland fishery, respectively, for the year classes and country/region as indexed.

Total 1SW recruitment for the NEAC area in year y is therefore the sum of the maturing 1SW and non-maturing 1SW recruitments for that year for all countries:

$$PFA_y = \sum_c PFAm_{y,c} + \sum_c PFAn_{y,c} \quad (7)$$

The non-reporting rates, exploitation rates, natural mortality, and migration times in the above equations cannot be estimated precisely, so national experts provide minimum and maximum values based upon best available knowledge (ICES, 2003). These values are considered likely to be centred around the true values, and are used to delimit uniform distributions for these parameters in a Monte Carlo simulation (MCS). The simulation, which uses the software package Crystal Ball (Decisioneering, 1996), is run in Excel to generate estimated distributions of the PFA values by simulating 1000 runs of the model.

Where appropriate for the provision of management advice, the national outputs from the model are combined into stock complexes, such as those for southern and northern Europe. The former group consists of Ireland, the UK, and France, which are the main European stocks contributing to the West Greenland fishery, and the latter group includes Russia, Finland, Norway, Sweden, and Iceland (ICES, 2002b). The confidence limits for these combined estimates are derived from the sum of the national variances obtained from the MCS (the co-variances are assumed to be small). This model has provided time-series of PFA estimates for NEAC salmon stocks from 1971 to the present (Figure 1; ICES, 2003).

One weakness of the NEAC model is that it is heavily dependent upon catch data and the estimates of exploitation rate. In most salmon fisheries in the NEAC area, more than half the catch is reported, and in many cases it approaches 100%. However, as stocks have declined, exploitation rates have been reduced to very low levels, and estimates of abundance are therefore becoming increasingly sensitive to this parameter. This inevitably means that uncertainty in the estimates is increasing, and it therefore strengthens the need to make use of alternate sources of information on stock abundance, such as juvenile surveys.

The rate of natural mortality was originally taken as 0.01 per month, based upon Doubleday *et al.* (1979), with a range of 0.005–0.015 being used in the MCS. However, following a re-evaluation of historical data (Potter *et al.*, 2003), ICES adjusted the value employed to 0.03 per month (ICES, 2002b), and the range used in the model was changed to 0.02–0.04. This has substantially affected the influence of this parameter on the model, because it has increased the estimated losses between 1SW recruits and

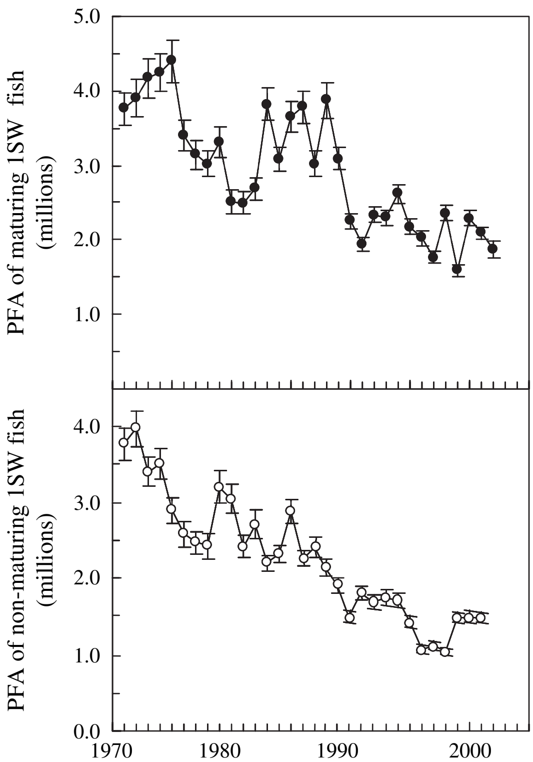

Figure 1. Estimated PFA of maturing 1SW salmon (potential 1SW returns), and of non-maturing 1SW salmon (potential MSW returns) for the NASCO NEAC area derived from run-reconstruction modelling, 1971–2002.

return to homewaters from around 8% to 21% for 1SW returns, and from 16% to 42% for 2SW returns. Therefore, whereas the PFA estimates would not previously have been very sensitive to moderate changes in M around the value of 0.01 per month, similar proportional variation around the value of 0.03 will have a greater effect. This means that the assumption that M is constant between years for adult salmon in the sea is now more critical, and needs to be examined more closely.

Output from the model also allows the relationship between spawning stock and subsequent recruitment to be investigated, and for the NEAC area this has been used to derive crude stock−recruitment relationships at a national level in order to provide preliminary national CLs (Potter *et al.*, 1998). The spawning escapement of 1SW and MSW salmon is first converted to egg deposition by multiplying the proportion of females and fecundity for each age class. However, 1SW recruitment in year y is derived from eggs deposited in a number of earlier years dependent upon the age composition of the smolt run, for example in years y−2 and y−3, if only 1- and 2-year-old smolts are produced. In order to relate egg deposition to subsequent recruitment, we therefore estimate a "lagged egg deposition" variable, which in the above example would be the sum of the egg deposition in years y−2 and y−3, multiplied by the proportions of 1- and 2-year-old smolts produced, respectively.

Direct measurement of PFA indices

There is great value in estimating historical trends in stock abundance to investigate factors affecting stocks. However, if the aim is to provide quantitative catch advice, the priority will be to forecast the PFA for the coming fishing seasons. A simple approach would be to extrapolate the historical time-series, and, where the PFA shows a clear temporal trend, as in Figure 1, there may be good reason to believe that the trend will continue. However, it would clearly be preferable to be able to estimate the stock abundance directly, or to identify factors to account for the variation in the historical estimates.

One option for obtaining estimates of stock abundance for use in fishery management is to conduct surveys in the areas where the stock is found. Such stock-estimation methods are widely employed in enclosed waters, and are commonly used to enumerate populations of salmon parr, emigrating smolts, or returning adults in rivers (Cowx, 1990). In-season estimation of the abundance of adult salmon for fishery management purposes is carried out on various salmon stocks in the NAC area, and is also widely employed in the management of Pacific salmon. However, estimation procedures are far more difficult in the open ocean, particularly to provide direct estimates of the PFA of stocks prior to or during the main mixed-stock fisheries. Atlantic salmon seem to range widely and unevenly in the open ocean, and their distribution, particularly prior to the fisheries operating at the Faroe Islands and West Greenland, is poorly understood. Only a small part of the total stock may be available to any sampling programme (Holst *et al.*, 2000), and even within specific localized areas (e.g. the fishery areas), it may be difficult to obtain a reliable index of stock abundance. For example, catch per unit effort (cpue) data were collected in the Faroese longline fishery (commercial and research) between the 1981/1982 and 1994/1995 fishing seasons, but there is no relationship between the cpue (corrected to take account of the presence of fish-farm escapees) and the estimated PFA of non-maturing 1SW salmon for the northern or southern European stock groups that constitute most of the catch (Figure 2). There could be a number of reasons for this, including uncertainties in the PFA estimates, or variation in the proportion of the stocks available to the fishery between years.

A different picture emerged for Greenland. There seems to be a relationship between the estimated PFA of both North American and southern European non-maturing 1SW salmon and cpue in the West Greenland fishery, measured as average daily landings per licensed fisher (kg licence^{-1} d^{-1}; Figure 3). Although this relationship has not been used to estimate the PFA and so to establish an annual quota for the fishery, it led to the introduction by NASCO (2001) of a new management approach for the fishery, which allowed for in-season quota adjustments. The regulatory measure was based upon three harvest periods, quotas in the last two periods being dependent on the average cpue observed during the earlier periods.

The main objective of this approach was to provide in-season confirmation of the PFA forecasts, so that if the cpue

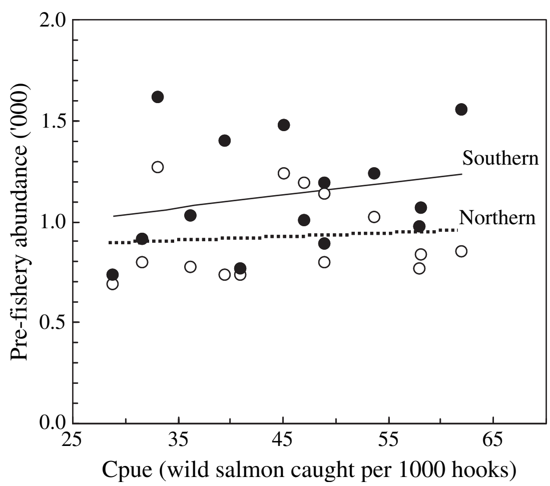

Figure 2. Relationship between estimated PFA of non-maturing 1SW salmon for the northern (open circles) and southern (closed circles) European stock complexes, and the cpue of wild salmon in the Faroese longline fishery, 1982−1995; neither relationship is significant ($p > 0.05$).

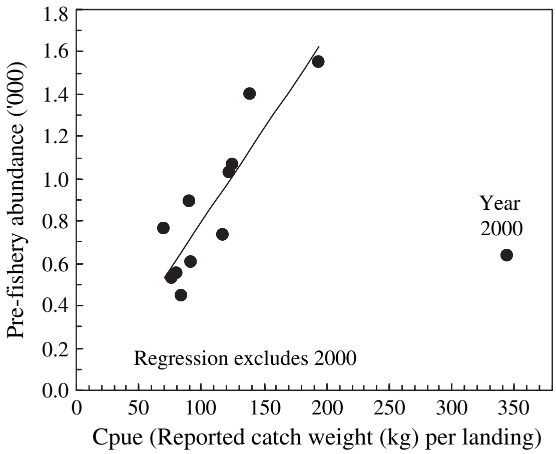

Figure 3. Relationship between estimated PFA of non-maturing 1SW salmon for the southern European stock complex, and the cpue in the West Greenland fishery, 1986−2000 (excluding 1993−1994, when there was only a subsistence fishery). For the relationship excluding 2000, $r^2 = 0.79$, $p < 0.001$.

in the fishery indicated that the PFA was as great as predicted, the fishery would be permitted to continue, but if not, it would be reduced or closed. A major disadvantage with such an approach is that it introduces considerable uncertainty for fishers. ICES (2002b) endorsed the general principle of using informative in-season measures of abundance to manage fisheries adaptively, but expressed some concerns about the sensitivity of the PFA estimates to small changes in cpue, as highlighted by the extreme outlier in 2000. It was also noted that there was a need for a more detailed characterization of fishing effort, taking account of such factors as vessel size, gear type, amount of gear deployed, soak time, documentation of zero landings, and private sales. Furthermore, there was concern that fishers could modify their behaviour in a manner that would affect the assessment (e.g. by combining landings) if they knew that the stock abundance, and therefore the quota, was being assessed from their cpue (kg $landing^{-1}$).

It has not been possible to collect the additional data required to develop this approach further, and the introduction of a subsistence quota at West Greenland since 2002 has meant that it has not been possible to continue the time-series of cpue data (ICES, 2002b). Supplementary experimental surveys may not provide comparable estimates, are likely to be expensive, and could cause conflicts in the fishery. For similar reasons, it may be difficult to obtain a long time-series of PFA estimates using this approach. More importantly, although genetic identification methods are improving, it is not currently possible to discriminate stocks originating from different countries or regions. As a result, such ocean sampling approaches would only provide an estimate of the PFA of fish available to the fishery, and the data would not allow the status of national or regional stocks to be assessed. It would be risky to base fishery management decisions on this information alone, because the proportion of individual stocks available to the fishery may vary between years, and a decreasing trend in the status of the stock from one region might be masked by an overall increase in abundance in the group of stocks.

PFA forecast models for the NEAC area

Although there has been some use of in-season surveys in the management of distant-water Atlantic salmon fisheries (NASCO, 2001), their widespread use is likely to be impractical and expensive. The alternative approach is to develop models to relate abundance estimates obtained at other life stages (e.g. juveniles or returning adults) to the PFA. The objective is to account for this relationship in terms of biological or environmental parameters that affect natural mortality, and to use this to forecast future stock levels. Such forecast models have been developed for both the NAC and NEAC areas.

A simple additive PFA forecast model for North American stocks was originally developed in 1993 (Rago *et al.*, 1993b). It utilized indices of thermal habitat from the Northwest Atlantic in March in relation to historically observed PFA (from the run-reconstruction model) to predict future PFA. The marine habitat index was thought to reflect, directly or indirectly, changes in marine mortality. Subsequent modifications were made to the model to use alternative thermal habitat data and also to include a lagged spawner variable which reflected the abundance of the parental stock that gave rise to the cohort for which PFA was being forecast.

In exploring possible PFA forecast methods for the NEAC area, efforts were made to assemble and assess the biological and environmental data that may be used in the process (Crozier *et al.*, 2003). Extensive surveys of the availability of biological data for stocks in all NEAC countries were undertaken, as well as reviews of information on the temporal and spatial distribution of salmon at sea and the environmental (e.g. temperature) preferences of salmon. This work was targeted at identifying reasonable hypotheses based on relevant environmental data sets that could then be examined in the modelling process.

The most comprehensive investigation centred on the remote sensing of sea surface temperature (SST), represented by the global ocean coverage of the Reynolds Optimally Interpolated and Reynolds Historical Reconstructed Sea Surface Temperature data sets. These data were incorporated into extensive case studies at local, regional, and international levels, using a variety of approaches and model formulations (Crozier *et al.*, 2003). Many of these initial case studies used relatively simple approaches to examine relationships between historical PFA for a variety of stocks and stock complexes and environmental parameters, such as average SST, to determine whether there were potentially informative variables that could be used in PFA prediction. Ocean temperature variables were derived for three standard areas of the Northeast Atlantic, defined on the basis of knowledge of where salmon were expected to be at particular times in their marine phase, in order to achieve consistency of approach and biological relevance of the results (Crozier *et al.*, 2003).

These studies revealed a variety of relationships at levels of a single river and wider. Abundance (as represented by PFA or analogues, such as catches or returns) and survival (estimated from smolt-to-adult return rates) of many stocks were often related to marine conditions (Crozier *et al.*, 2003). However, the relationships were not always consistent or intuitively correct, and the number of significant relationships was only slightly greater than expected by chance. Turning these relationships into predictive PFA models proved challenging, because the stock variables that should be useful as inputs, such as numbers of spawners or egg deposition, were uninformative. Where juvenile stock variables were tested, they proved informative at single stock level, but not at wider levels, possibly because of the variability in stock production over wide geographic areas.

The possibility of making better use of the information in the environmental data sets has also been investigated. A more complex treatment of the SST data was undertaken, with techniques such as projection-pursuit regression being used to compare alternative SST variables, including median and extreme values (Crozier *et al.*, 2003). These analyses concluded that statistically significant temperature indices can be constructed, but that difficulties remain in interpreting the mechanism or the biological relevance of the prediction variables.

In investigating options for forecasting PFA for salmon in the NEAC area, a variety of model formulations can be applied to relevant stock groups, using the historical PFA estimates together with appropriate environmental data. An equation of the following form allows a number of model permutations to be considered:

$$\mathrm{PFA} = \mathrm{E}^{\lambda} \times \exp(\beta_0 + \beta_1 \mathrm{T} + \beta_2 \mathrm{Y} + \gamma) \quad (8)$$

where PFA is the historical time-series of PFA derived from the run-reconstruction modelling, E the lagged egg deposition for the same period, T the environmental (e.g. SST) variable, Y the year, and γ is a noise term. The additional parameter, λ, allows for a non-proportional relationship between PFA and number of eggs for fixed environmental conditions; a non-zero value of β_2 implies that there is a trend in the efficiency of conversion of eggs into PFA.

To investigate this general model further, it was applied to the specific example of the non-maturing 1SW component of the southern European stock complex ($\mathrm{PFAn_s}$), which is the main European stock component contributing to the West Greenland fishery. The model in Equation 8 was fitted in terms of $\log(\mathrm{PFAn_s}/\mathrm{E_s})$, using multiple regression, and was implemented in S-Plus for Windows and Microsoft Excel; thus

$$\log(\mathrm{PFAn_s}/\mathrm{E_s}) = (\lambda - 1)\log(\mathrm{E_s}) + \beta_0 + \beta_1 \mathrm{T} + \beta_2 \mathrm{Y} + \gamma \quad (9)$$

where $\mathrm{PFAn_s}$ is the PFA of non-maturing 1SW salmon from southern Europe derived from the run-reconstruction model for the period 1977–2001, $\mathrm{E_s}$ the lagged egg deposition for southern Europe for the period 1977–2001, and T is the thermal habitat index used in the North American PFA model (full data sets in ICES, 2003).

The data suggest that the noise term is, at least approximately, normally distributed with constant variance. However, to provide a more general method, bootstrapping of the model residuals was used for variable selection and construction of prediction confidence intervals (Davison and Hinkley, 1997). Guidance as to which of the variables in Equation 8 might provide better predictions was evaluated by displaying the aggregate prediction error for a series of models (Figure 4). The models Null(PFAn) and Null(PFAn/E) use only mean $\log(\mathrm{PFAn_s})$ and mean $\log(\mathrm{PFAn_s}/\mathrm{E_s})$ for prediction, respectively. There was a marked decrease in the aggregate prediction error at Null(PFAn/E), and again at model Y. This approach agreed with the traditional analysis of variance, and indicates that these parameters have the greatest predictive capacity.

As a result, the model was applied using only $\mathrm{E_s}$ and Y. Predictions one year ahead, obtained by fitting such a model sequentially to data from the previous years from 1985 to 2001 (Figure 5, left panel), tend to underestimate the realized values of PFA in the 1980s, overestimate them

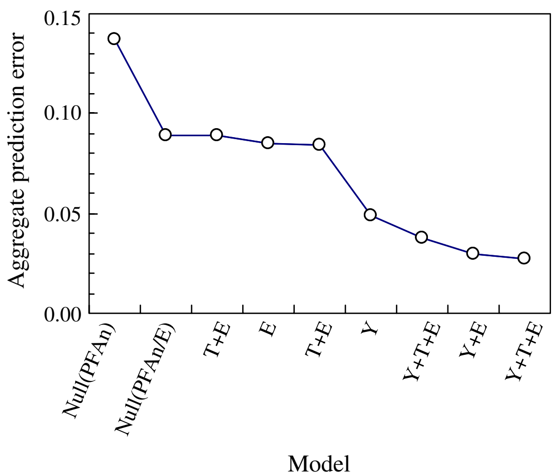

Figure 4. Aggregate prediction error for the forecast of PFA of non-maturing 1SW salmon (PFAn) for the southern European stock complex, using different combinations of variables in Equation 8, where T is the thermal habitat index, E the lagged egg deposition, and Y is the year.

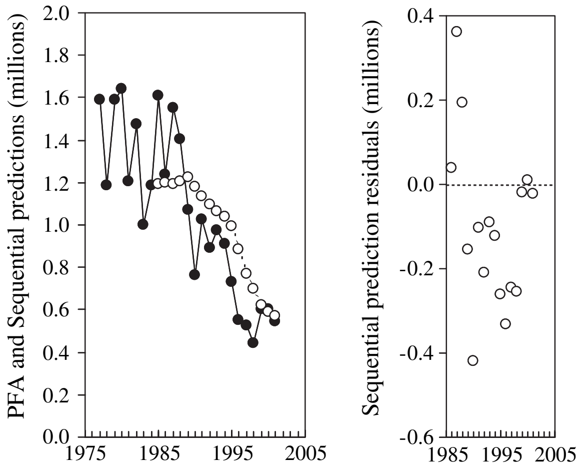

Figure 5. Total estimated PFA of salmon for the southern European stock complex (1977–2001) with sequential predictions (1985–2001) based on preceding years (left panel), and residuals for sequential predictions (right panel).

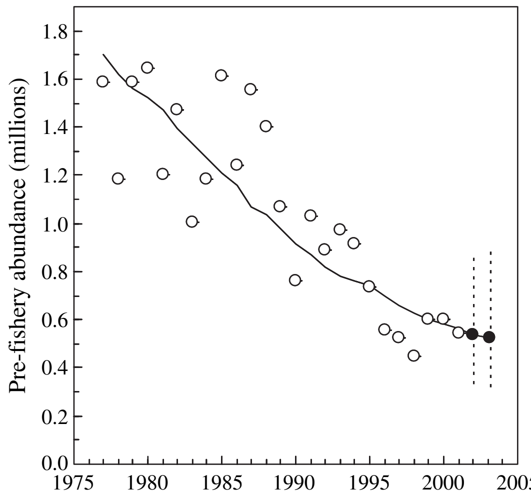

Figure 6. Total estimated PFA (open circles), with model trend and forecasts for 2002 and 2003 (closed circles), with 95% confidence intervals, for non-maturing 1SW salmon from the southern European stock complex.

during much of the 1990s, but become quite accurate in the most recent years (Figure 5, right panel).

The final model chosen for the full time period was

$$\log(PFAn_s/E_s) = -1.127\log(E_s) + 114.8 - 0.050Y \quad (10)$$

with residual variance 0.185 on a log scale (equivalent to a residual standard deviation of about 18% of the PFA). The fitted model is equivalent to

$$PFAn_s = E_s^{-0.127} \times \exp(114.8 - 0.050Y) \quad (11)$$

Although this model provided a forecast for $PFAn_s$ for 2002 and 2003 (Figure 6), the outcome was driven overwhelmingly by the downwards linear trend in $\log(PFAn_s/E_s)$, which was clearly time-dependent. The negative value of λ is counter-intuitive, because it implies that the PFA decreases with increase in egg deposition. However, the influence of this parameter is small, and it is possible that the negative value may be accounted for by changes in the contribution of different river-stocks to the stock complex, or non-stationarity in the individual stock–recruitment relationships.

This analysis has been extended by applying the model to the PFA of both maturing and non-maturing salmon from northern and southern European stock complexes, together with three additional temperature-preference habitat indices (Crozier *et al.*, 2003). Although the selected habitat indices were correlated to the PFA of both southern and northern European groups, the main statistical significance was again provided by temporal trends in PFA.

In a further development, the southern European model was extended to assess the PFA of maturing 1SW salmon (PFAm), as a potential predictor variable for forecasting the PFA of non-maturing 1SW salmon (PFAn). This is based on the recognition that there is a good correlation ($r^2 = 0.602$, $p < 0.001$) between PFAn and PFAm for the same cohort, estimated using the run-reconstruction model (Figure 7). This is probably because both PFAm and PFAn are largely determined by the size of the smolt cohort and post-smolt mortality, which are the same for both groups.

Equation 8 may therefore be extended to

$$PFAn_s = E_s^{\lambda} \times \exp(\beta_0 + \beta_1 T + \beta_2 \log(PFAm_s) + \beta_3 Y + \gamma) \quad (12)$$

where $PFAm_s$ is the PFA of maturing 1SW salmon from the southern European stock complex. Thus:

$$\log(PFAn_s/E_s) = (\lambda - 1)\log(E_s) + \beta_0 + \beta_1 T + \beta_2 \log(PFAm_s) + \beta_3 Y + \gamma \quad (13)$$

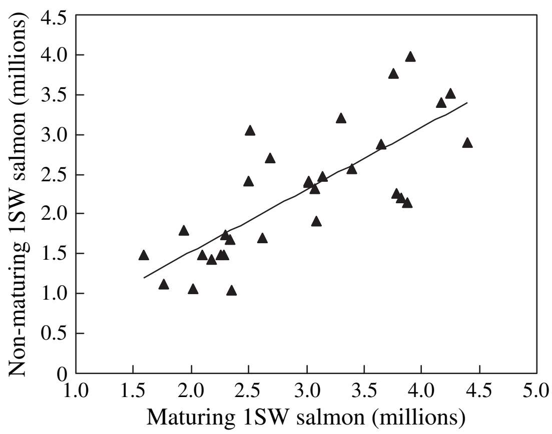

Figure 7. Relationship between the estimated PFA of maturing and non-maturing 1SW salmon for the same smolt cohorts in the NEAC area, 1971–2001 ($r^2 = 0.602$, $p < 0.001$).

The aggregate prediction errors were calculated for a series of 17 possible models for the southern European stock complex. The models Null(PFA) and Null(PFA/E) use only the mean log($PFAn_s$) and mean log($PFAn_s/E_s$) for prediction, respectively, and the subsequent models are named in terms of the variables included (Figure 8). There was a marked decrease in the aggregate prediction error with model PFAm, and again with model Y. This reflects the shared downward temporal trend of $PFAn_s$ and $PFAm_s$. There is a subsequent smaller reduction for model Y + E. These results are consistent with a conventional analysis of variance.

While significantly improving the model, the use of PFAm presents additional problems because, in most circumstances, the forecast of PFAn is required before PFAm for the same cohort is known. This value in the time-series therefore has to be estimated, in this example by taking the mean of the previous three values. This approach has some advantages over the model in Equation 11, where the forecast is strongly driven by year, because such models will be very poor at picking up a change in the trend in PFAn. A model derived from Equation 13, even using an estimated value of PFAm, should be able to detect a change in the trend more quickly, although there will still be a lag. More importantly, for the provision of management advice for the Faroese salmon fishery, it might be possible to estimate PFAm prior to (or during) the fishery, because the majority of 1SW salmon have returned to homewaters before the fishery for non-maturing 1SW salmon takes place around the Faroe Islands, during and after the second sea-winter.

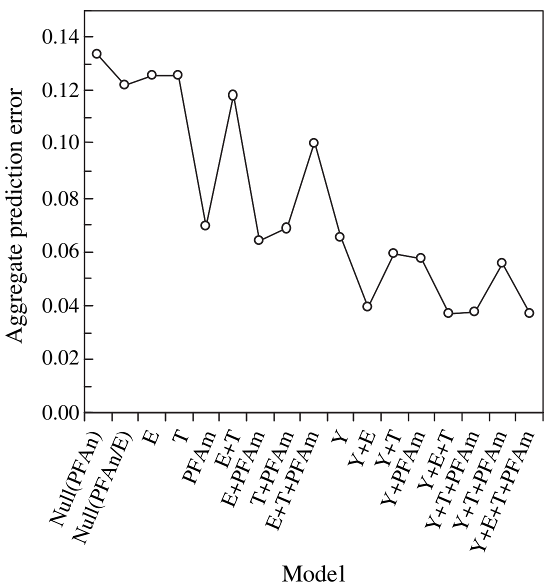

Figure 8. Aggregate prediction error for the forecast of PFA of non-maturing 1SW salmon (PFAn) for the southern European stock complex, using different combinations of variables in Equation 13, where T is the thermal habitat index, E the lagged egg deposition, PFAm the PFA of maturing 1SW salmon, and Y is the year.

Conclusions and alternative approaches

In responding to the request for scientific advice from NASCO, ICES scientists try to estimate PFA for large groups of salmon river-stocks on a regional scale, and then build upwards to estimate the numbers of fish available to distant-water fisheries on an international scale. The run-reconstruction model has provided an effective common approach for all countries to apply, but the dependence of the model on catch data means that uncertainties in the estimates are increasing, as exploitation rates are reduced to protect declining stocks. The model also uses standard values of M, which in reality are likely to vary between stocks and between years. There is therefore a need for individual countries to develop their own models to estimate PFA, and these need to take better account of the specific data available for each region. This would match the approach taken with the development of CLs. Many CLs are currently derived on a national scale, using stock−recruitment relationships based on the outputs of the run-reconstruction model (Potter *et al.*, 1998), but they are being substituted by better, river-specific, or regional estimates as these are developed (ICES, 2003).

The development of forecast models presents similar problems. It is apparent from the modelling exercises that have been undertaken that it may not be possible to develop good predictive models for the PFA of large stock complexes. This is probably because the factors affecting natural mortality vary too much within such groups. Thus, in the current model for the PFA of southern European non-maturing 1SW salmon, year is by far the dominant factor in predicting the declining trend in abundance. Clearly such a model is only tenable in the short term, and will be poor at predicting a major change in the stock status, but its use is consistent with the observations of close serial correlation between year classes in salmon stocks, and the recognition that salmon abundance tends to persist in poor or good states for a number of years (ICES, 1994).

A further concern is that the models currently applied provide only crude quantification of the uncertainties. Alternative approaches that more explicitly address the errors in the models and therefore the risks associated with particular management options need to be considered. Bayesian methods for predicating PFA are already used to provide catch advice for Baltic salmon fisheries ICES (2002a), and a preliminary evaluation has been undertaken on their use in the North Atlantic (Crozier *et al.*, 2003). The initial investigations for Atlantic stocks were based on a single river data set, using a variety of model formulations, ranging from models with year and sea surface temperature as covariates to a dynamic autoregressive model. While the former approaches yielded PFA predictions, the latter model captured more fully the evolving dynamic trend in sea survival, which underpins variations in PFA for the stock. Clearly, it would be preferable to model directly the mechanisms determining the trend in survival, but these are unknown, and we must therefore model the trend itself. In this respect, the Bayesian dynamic autoregressive model provided a good prediction of the irregular trajectory of the PFA time-series, and Crozier *et al.* (2003) recommended that the approach be further investigated for other stocks having suitable data (with additional environmental indicators being examined), and at wider scales.

There is also need to develop further the use of juvenile indices in the NEAC forecast models. There are several reasons why this would be preferable to the lagged spawner or lagged egg deposition variables currently used. The main biological reason is that the major period of density-dependent mortality is between estimation of egg deposition and the PFA stage. Also, as fishery restrictions increase in the NEAC area, the ability to estimate spawner escapement is falling. This has already been a problem in North America, with the loss of data for Labrador spawners, following the closure of the fisheries (ICES, 2003).

In the NEAC area, the specific impetus to develop juvenile indices arises from a demonstration that the lagged egg deposition variable does not provide sufficient indication of stock status (at river or wider levels), so alternative stock variables are necessary. It is clear from the work undertaken on juvenile indices as potential stock variables for input to PFA prediction (Crozier *et al.*, 2003) that there are limitations to the currently available NEAC data, but there is potential to develop new and alternative data sources. The provisional juvenile indices developed for southern and northern European stock groups using smolt counts available from ICES reports and other sources indicate that the data vary in time-series coverage, as well as in quality and consistency, such that meaningful juvenile indices cannot yet be produced. However, relationships between smolt counts and PFA at individual stock level, and between other juvenile data and PFA, indicate that juvenile data can help to predict PFA, and that differing types of juvenile data can be combined, with parr surveys being almost as useful as smolt counts. Further evidence of this is provided from the Baltic, where parr survey data in combination with smolt counts have been used for the assessment of Baltic salmon, in order to be able to estimate smolt production for rivers without smolt counts (ICES, 2002a).

To develop the juvenile production estimates (or indices) required for this approach, it will be necessary to collate all the available parr or smolt production data from monitored rivers, and to weight or scale this to represent the assumed production from the area or region being modelled. This will require the collection of data on productive habitat, or other measures of river size or production such as egg deposition requirements, for rivers with and without smolt data. If parr data are to be used, they must also be converted or lagged to the appropriate year of smolt migration, so they can be combined with the smolt data. Variation during the parr-to-smolt phase should ideally be taken into account, although data on these factors may be unavailable or only locally acting, and therefore not suitable for widespread use. In the interim, a constant parr-to-smolt transformation could be assumed, and the suitability of this approach could be tested where data are available. A number of approaches for combining parr and smolt data can be envisaged, ranging from methods currently used in North America (ICES, 2003) to Bayesian or GLM approaches.

As with all such variables scaled-up from a few observations, validating the representivity of the indices will be important. There may be a role for existing lagged spawner data to validate the scaled-up juvenile production indices, because trends in spawners should yield broadly comparable trends in juvenile output. In order to pursue this approach, efforts will need to be made to collect data on smolt and juvenile production on as many NEAC rivers as possible in future years. Countries will also need to seek to standardize these data, as much as possible, within the constraints of their national data collection programmes, to ensure that they serve both national and international needs.

It is inevitable that the scale of the distant-water fisheries and the stock complexes being managed, in terms of the number of river-stocks exploited, limits ability to respond to the differing biology and status of individual stocks. These problems may only be resolved when fisheries are limited to single or small groups of river-stocks, where exploitation patterns can be matched to specific stock characteristics.

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