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ASPIC - A SURPLUS-PRODUCTION MODEL INCORPORATING COVARIATES

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SUMMARY

Surplus-production modeling has often assumed equilibrium conditions, although stocks are rarely thought to be in equilibrium. This paper describes a simple non-equilibrium approach (ASPIC) to fitting a logistic production model to catch and effort data. From such data, ASPIC provides estimates of the two logistic parameters r and K, catchability q, and the stock biomass B_1 in the first year of the time series. From these four quantities, estimates can be made of MSY, stock size at MSY, optimal effort at MSY, optimal fishing mortality at MSY, and the time series of stock biomass levels, surplus production levels, and fishing mortality levels. The general optimization approach is similar to that used by Pella and Tomlinson in their GENPROD computer program; however ASPIC uses an analytical solution of the yield equation, a revised loss function, and incorporates several other refinements including bootstrap estimates of variability. The method handles missing data (years with no fishery) correctly without modification and is extremely flexible in handling different patterns of fishing, such as (i) two or more simultaneous fisheries with different types of gear, (ii) a fishery that ends and then resumes with a different type of gear, (iii) density-dependent catchability; and (iv) time trends in catchability. The model can be adapted easily to use auxiliary information (e.g., external estimates of population biomass) to tune the model. The major advantages of the ASPIC model are as follows; it is a true non-solution of the production equations; it retains true population persistence; it eliminates the need to use catch-per-unit-effort as an index of abundance, a practice that has been criticized on statistical grounds; and it can be modified easily. The paper describes the structure of the model and its performance on several simulated and real data sets.

RESUME

La modélisation de la production excédentaire a souvent postulé des conditions d'équilibre, bien que les stocks soient rarement jugés être en équilibre. Le présent document décrit une méthode simple ne postulant pas de conditions d'équilibre (ASPIC) pour ajuster un modèle de production logistique aux données de prise et d'effort. A partir de ces données, l'ASPIC fournit des estimations de deux paramètres logistiques r et K, de la capturabilité q, et de la biomasse du stock B_1 pendant la première année de la série temporelle. A partir de ces quatre chiffres, il est possible d'estimer la PME, la taille du stock au niveau de la PME, l'effort optimum à la PME, la mortalité par pêche optimale à la PME, et la série temporelle de niveaux de biomasse du stock, de production excédentaire et de mortalité par pêche. La méthode générale d'optimisation est semblable à celle de Pella et Tomlinson dans leur programme informatique GENPROD; cependant, l'ASPIC utilise une solution analytique de l'équation de production, une fonction révisée de pertes, et comprend plusieurs autres nuances, dont des estimations "bootstrap" de la mortalité. La méthode traite les données manquantes (années sans pêche) de façon correcte sans modification, et est extrêmement flexible au moment de traiter différents modes de pêche, tels que (1) deux pêcheries ou plus travaillant simultanément avec des engins différents, (ii) une pêcherie qui cesse, puis reprend avec un différent type d'engin, (iii) une capturabilité fonction de la densité, et (iv) des tendances temporelles de la capturabilité. Le modèle peut être facilement adapté pour utiliser une information auxiliaire (par exemple, des estimations externes de la biomasse de la population) pour ajuster le modèle. Les principaux avantages du modèle ASPIC sont les suivants: il s'agit d'un modèle ne postulant vraiment aucune condition d'équilibre et qui rend compte correctement des prises; il est de conception simple, et utilise une solution analytique de l'équation de production; il maintient la véritable continuité de la population; il élimine la nécessité d'utiliser la CPUE comme indice de l'abondance, méthode qui a été critiquée du point de vue statistique; et il peut être aisément modifié. Le document décrit la structure du modèle et ses performances avec plusieurs jeux de données simulés et réels.

RESUMEN

Al aplicar el modelo de producción excedente, con frecuencia se asumen condiciones de equilibrio, aunque de hecho rara vez se supone que el stock se encuentra en esas condiciones. Este documento describe un sencillo enfoque de no equilibrio (ASPIC) para ajustar un modelo de producción logístico a los datos de captura y esfuerzo. Partiendo de estos datos, ASPIC facilita estimaciones de los dos parámetros logísticos r y K, capturabilidad q y la biomasa del stock B_1 en el primer año de la serie temporal. Partiendo de estas cuatro cantidades, se pueden hacer estimaciones del RMS, tamaño del stock con RMS, esfuerzo óptimo con RMS, mortalidad por pesca óptima con RMS, y la serie temporal de niveles de biomasa del stock, niveles de producción excedente y niveles de mortalidad por pesca. El enfoque general de optimización es similar al aplicado por Pella y Tomlinson en su programa de ordenador GENPROD; sin embargo, ASPIC emplea una solución analítica de la ecuación de rendimiento, una función de pérdidas revisada e incorpora varios refinamientos más que incluyen estimaciones de variabilidad. El método aplica correctamente datos que faltan (años sin pesquería) sin modificación y es extraordinariamente flexible para el manejo de los diferentes esquemas de pesca, tales como (i) dos o más pesquerías simultáneas con diferentes tipos de arte, (ii) una pesquería que termina y se reanuda con artes diferentes, (iii) capturabilidad dependiente de la densidad y (iv) las tendencias temporales en la capturabilidad. El modelo es fácilmente adaptable para usar información auxiliar (por ejemplo, estimaciones externas de la biomasa de población) en el ajuste del modelo. Las principales ventajas del modelo ASPIC son: se trata de un auténtico modelo en condiciones de no equilibrio que tiene en cuenta las capturas de forma correcta; su concepto es sencillo, empleando una solución analítica de la ecuación de producción; mantiene una auténtica persistencia de la población; elimina la necesidad de emplear la captura por unidad de esfuerzo como índice de abundancia, práctica que ha sido criticada desde el punto de vista estadístico; puede modificarse fácilmente. El documento describe la estructura del modelo y su funcionamiento con varios conjuntos de datos, auténticos y simulados.

INTRODUCTION

Surplus-production modeling has often assumed equilibrium conditions, although stocks are rarely thought to be in equilibrium. This paper describes a simple approach, termed ASPIC, to fitting a non-equilibrium surplus-production model. Other non-equilibrium production models have preceded this one (e.g., Pella and Tomlinson 1969, Schnute 1977, Fletcher 1978), but the present treatment has the benefits of simplicity and extensibility. The general algorithm used by ASPIC is similar to that of Pella and Tomlinson (1969), a forward solution of the model. However, ASPIC uses an analytical solution of the yield equation, a revised loss function, and incorporates several other refinements including bootstrap estimates of variability. Another difference is that ASPIC is based on the Graham–Schaefer logistic production model (Graham 1956; Schaefer 1954, 1957). The ASPIC framework could be applied to the Pella-Tomlinson (1969) or Fox (1970) surplus-yield models equally well, but the logistic model has the desirable property of being solvable in closed form for the yield in a given year.

REVIEW OF PRODUCTION MODELS

In all production models, a quantity termed ***surplus production*** characterizes population dynamics at different levels of population size, usually measured in biomass. Surplus production is a lumped quantity that incorporates three major forces: recruitment, growth, and natural mortality.[1] The mathematics of the ASPIC model begins with a logistic (Schaefer) production model under the condition that no fishing mortality occurs. Under those dynamics, the following differential equation (Lotka 1924) describes the rate of change of the stock biomass B_t due to surplus productic

$$\frac{\partial B_t}{\partial t} = rB_t - \frac{r}{K} B_t^2 \quad (1)$$

This equation uses the parameterization of population ecology, in which K is the maximum possible population size, or carrying capacity, and r is the stock's intrinsic rate of increase (the limit of an individual's rate of increase as the population size approaches zero). Both quantities

[1] The adjective "surplus" refers to the surplus of recruitment and growth over natural mortality; i.e., the net production. In this paper, surplus production is often be termed simply "production."

are assumed constant over time. Other parameterizations could be used equally well; e.g., $\alpha = r$ and $\beta = r/K$.

To make the model more realistic, a term is often added to equation (1) to represent the change in biomass due to fishing mortality. Assume the common formulation that fishing mortality rate F is proportional to the fishing effort rate f with proportionality constant q; i.e., that $F = qf$. Then the model including fishing is

$$(2) \qquad \frac{\partial B_t}{\partial t} = rB_t - \frac{r}{K}B_t^2 - qf_tB_t \; .$$

Model Solutions that Incorporate Catch

To compute the change in biomass from one point in time to another, during which period f_t remains constant[2], we integrate equation (1). Let the time period of interest begin at $t = 0$, when the stock biomass is B_0, and end at time $t = \tau$, when the biomass is B_τ. The solution in this very general case is

$$(3) \qquad B_\tau = \frac{-B_0K(qf-r)e^{r\tau-qf\tau}}{B_0re^{r\tau-qf\tau} + r(K-B_0) - qfK} \; .$$

Whereas equation (2) merely described the rate of change of the population biomass, equation (3) describes the dynamics of the biomass through time. By adopting the common assumption that f_t is constant within each year (or quarter, month, etc.) but may change from year to year, we can modify equation (3) slightly to express $B_{\tau+1}$ in terms of B_τ. The modified equation is

$$(4) \qquad B_{\tau+1} = \frac{-B_\tau K(qf_\tau-r)e^{r-qf_\tau}}{B_\tau re^{r-qf_\tau} + r(K-B_\tau) - qf_\tau K} \; .$$

[2] Other conditions are treated by dividing time into shorter periods during which f is constant and applying equation (3) to each period separately.

Where f_τ is the value of f_t during the period of time from $t = \tau$ to $t = \tau + 1$. The model structure also defines the yield expected during a time period. We designate the expected yield during the same period as $\hat{Y}_\tau$. From the definition of yield and equation (3),

$$(5) \qquad \hat{Y}_\tau = \int_\tau^{\tau+1} qf_tB_t\,dt = \int_\tau^{\tau+1} qf_\tau \frac{B_\tau K(qf_\tau-r)e^{rt-qf_\tau t}}{B_\tau re^{rt-qf_\tau t} + r(K-B_\tau) - qf_\tau K}\,dt \; .$$

The solution of equation (5) may be new to fishery science. It is

$$(6) \qquad \hat{Y}_\tau = \frac{qf_\tau K}{r} \ln\left(\frac{B_\tau re^{r-qf_\tau} - qf_\tau K + Kr - B_\tau r}{Kr - qf_\tau K}\right) .$$

The estimated production P_τ of the stock during the period can be computed by mass balance:

$$(7) \qquad P_\tau = B_{\tau+1} - B_\tau + Y_\tau \; .$$

FITTING THE MODEL: THE ASPIC APPROACH

The time-trajectory aspect of production models is often neglected by assuming that the stock is in equilibrium and treating each year's data as independent. Under this assumption, $B_{t+1} = B_t$, and therefore production in each year is assumed to equal yield. In such a treatment, the observations of biomass (or its index, Y/f) and yield are fitted by least squares, frequently with some form of smoothing added to the observations on fishing effort. One view is that this smoothing serves to restore the population persistence that has been removed from the model by artificially imposing equilibrium conditions. In any case, smoothing also requires dropping the first few years' data, which reduces the effective size of the data set (Gulland 1961; Mohn 1980).

The ASPIC model avoids the equilibrium assumption by fitting a series of equations (4) and (6) to the data directly, using standard optimization techniques. The data required are yield Y (harvest in weight) and fishing effort f for T periods (years) $t = \{1, 2, ..., T\}$, where $T > 4$. Also required are starting estimates of the four parameters that are directly estimated, B_1, r, K, and q. To perform the estimation, the following algorithm is used:

1. Obtain starting estimates of the four parameters. The optimization method suggested below is quite insensitive to the choice of starting values.
2. Set iteration counter to 1.
3. Starting with the current estimate of B_1, simulate the population through time according to equation (4). For each year of the simulation, compute estimated yield from equation (6) and, if desired, estimated production from equation (7).
4. During the simulation, accumulate a loss function to be minimized. The choice of a loss function is discussed below. An obvious choice is some function of the sum of squares of the residuals of yield, $\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2$.
5. If the iteration counter > 1 and convergence has been achieved, end. Otherwise, adjust the parameter estimates, increment the iteration counter, and go to step 3.

In the computer program currently used to implement ASPIC; adjustment of the parameter estimates to minimize the loss function is performed with the simplex or "polytope" algorithm (Nelder and Mead 1965; Press et al. 1986). A quicker method such as that of Marquardt (1963) might work, but has not been tried in this application.[3] The optimization provides direct estimates of the four parameters B_1, r, K, and q, and indirect estimates of the stock biomass levels B_2, B_3, ..., B_T and the stock's production during each period of time. Given logistic dynamics, the estimate of maximum sustainable yield (MSY) is $Kr/4$, which is attained at stock size $K/2$; the instantaneous fishing mortality rate to generate MSY is $r/2$, and the corresponding rate of fishing effort is $r/2q$ (Schaefer 1954).

Loss Function

The choice of loss function is central to all optimization problems and can strongly influence the results of modeling. Perhaps the simplest loss function for this model is the sum of squared residuals in yield,

$$\text{(8)} \qquad \text{loss} = \sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2 .$$

[3]However, Marquardt's algorithm was used in a similar application by Rivard and Bledsoe (1978).

This loss function was used by Pella and Tomlinson (1969) in their generalized production model, but was criticized by Fox (1971), who pointed out that it implies infinitely great variability in population size as the population size approaches zero. Fox (1971) then performed a Monte Carlo simulation to evaluate three possible loss functions for the Pella-Tomlinson model, and obtained the best results by using the inverse of the observed yield in each year as a weight, i.e., minimizing

$$\text{(9)} \qquad \text{loss} = \sum_{t=1}^{T}\left(\frac{Y_t-\hat{Y}_t}{Y_t}\right)^2 .$$

This *additive proportional* loss function has subsequently been used by others, including Rivard and Bledsoe (1968). In either case, if the residuals [the quantities in parentheses in (8) or (9)] are independent and normally distributed with constant variance, the results will be maximum-likelihood estimates. Both loss functions are available in the ASPIC computer program, so that the analyst can examine the residuals of either procedure.

Logistic production theory implies that the stock biomass, should always be less than K. In fitting certain data sets, however, I have found that the estimate of B_1 can be much larger than K and also much larger than the biomass estimates in following years. This can occur because the loss functions (8) and (9) are relatively insensitive to the estimate of B1. Such unrealistic results can be avoided by introducing an additional penalty term into the loss function. For the additive proportional error structure, the loss function then becomes

$$\text{(10)} \qquad \text{loss} = \sum_{t=1}^{T}\left(\frac{Y_t-\hat{Y}_t}{Y_t}\right)^2 + dw_B\left(2\frac{\hat{B}_1-K}{\hat{B}_1+K}\right)^2 ,$$

where $d = 1$ if $\hat{B}_1>K$ and $d = 0$ if $\hat{B}_1 \le K$, and w_B determines the effect of the penalty relative to the residuals in yield. When $w_B = 1$, the penalty term has the same weight as any other residual. This approach (with $w_B = 1$) has been quite effective in constraining the estimate of B_1, while causing insignificant changes in the total loss function or the remaining parameter estimates.

Because catch and effort data are usually autocorrelated, the errors—whether computed by equation (8), (9), or (10)—may also be autocorrelated. A matter of statistical concern is whether a method of fitting that takes the autocorrelation into account (such as one based on time-series analysis *sensu* Box and Jenkins) might be more appropriate. Some results relevant to this question were obtained by Ludwig *et al.* (1988) in a study that fit production models to simulated data with two loss functions. The first was a total-least-squares loss function, which did not take autocorrelation into account; the second, an approximate-likelihood loss function, which did. Ludwig *et al.* found that the two methods produced very similar estimates, and concluded that the added complexity of the approximate likelihood method was probably not warranted. In addition, the approximate likelihood method frequently failed to converge when poor starting values were supplied.

Bootstrap Estimates of Variability

Estimates of variability in the estimated quantities can be made using the bootstrap method with resampled residuals (Efron and Tibshirani 1986). This has been implemented in the current ASPIC computer program, with the result that standard errors and confidence intervals can be obtained for each directly estimated parameter, for the indirectly estimated parameters (such as MSY and optimum effort at MSY), and for the retrospective estimates of biomass in any year.

Unusual Cases and Model Extensions

A great strength of the ASPIC method is the ease with which it can be used with different patterns of fishing or data collection. This is a consequence of using a forward solution of the production equations, which can be changed nearly as easily as a simulation model.[4] Adapting ASPIC to fisheries divided by space, time, or gear type is relatively simple, because the underlying population model can be changed even though the basic algorithm remains the same. Some realistic cases would include analysis of data series that include years of zero effort, as would occur during a closure; analysis of data series with years of missing or highly uncertain effort data; modeling a stock exploited by two or more types of gear; or incorporating changes in catchability at a certain times within the data series, perhaps after periods of closure or following regulatory changes.

Years with effort and yield equal to zero are treated correctly by the unmodified ASPIC algorithm as described above. Because the loss function is based on yield, it is zero for such years, which therefore do not influence parameter estimation directly. However, the model population persists through such years, obeying the dynamics of logistic growth. Thus the time lag during the years of closure carries information that is incorporated in fitting the model.

[4]For the same reasons, Methot (1989, 1990) has found a forward solution fruitful to use in his stock-synthesis model, an age-structured population model similar to a tuned VPA.

A slightly more difficult problem is the correct treatment of years in which effort and yield are known to have existed, but for which the data are missing or highly uncertain. In such a case, the ASPIC framework can be used to estimate, simultaneously with the other parameters, the effort levels for a limited number of years within the series. One would use the basic algorithm described above, except that one or more additional parameters (the missing values of effort) would be subject to estimation. If yield data were also missing for those years, they would not contribute to the loss function, but the information from the surrounding years would nonetheless provide a reasonable basis for estimating the missing values of effort. As in any estimation scheme, the total number of parameters should be kept reasonably small in comparison to the number of years of nonzero data.

The ability to estimate effort in this way suggests two additional types of analysis that could be performed in the ASPIC framework. First, one could examine the goodness of fit of each year's data to the model. To do this, one would use a jackknife-like procedure in which each year's effort data in turn was estimated by ASPIC. The absolute or relative magnitude of the residual for each year would indicate the agreement of that datum with the logistic model and the rest of the data series. Second, one might use the residuals so derived in exploratory studies of external (e.g., environmental) effects on production or yield. This would allow one to incorporate external effects naturally into the framework of a surplus–production model.

Another simple extension of the basic ASPIC framework is analysis of stocks fished by two or more different gear types, either in the same years or serially. This would be most useful when it is desired to estimate q separately for each fishery, and thus avoid the need to standardize gears. For convenience, I refer to this situation as different fisheries on the same stock. In each year, suppose there are J different fisheries, indexed by $j = \{1, 2, ..., J\}$. The effort applied by fishery j is f_j, the catchability coefficient of that fishery is q_j, and the yield is Y_j. Note that, although q is assumed time-invariant, fishery-specific effort and yield each carry an implicit subscript denoting time period. The total instantaneous fishing mortality in year τ is

$$F_\tau = \sum_{j=1}^{J} q_j f_j \; . \tag{11}$$

By a simple modification of equation (6), the yield in that year is

$$\hat{Y}_\tau = \frac{F_\tau K}{r} \ln\left(\frac{B_\tau r e^{r - F_\tau} - F_\tau K + K r - B_\tau r}{K r - F_\tau K} \right) , \qquad (12)$$

and the yield from fishery j is

$$\hat{Y}_j = \frac{q_j f_j}{F_\tau} \hat{Y}_\tau . \qquad (13)$$

For parameter estimation in such a case, one would substitute F_τ from equation (11) for qf_τ in equation (5) and substitute equations (12) and (13) for equation (6) to model the population and estimate the loss function during optimization. A residual is obtained for each fishery having nonzero effort in a year. The loss function is composed of the sum of the squared residuals from all fisheries. The identical formulation could be used to estimate different catchability coefficients for segments of a single time series, as might be desired when a change in gear is introduced abruptly with no chance to perform standardization. In this case, the time segments would be treated as separate fisheries, each having nonzero catch and effort data only during its respective time period.

Catchability is often thought to vary in more subtle ways (e.g., Paloheimo and Dickie 1964; Gulland 1975; Peterman and Steer 1981; Winters and Wheeler 1985), and one could incorporate any number of catchability models into the ASPIC framework. For example, it would be straightforward to model a linear trend (increase or decrease) in catchability with time. A simple method of parameterizing this model would be to estimate the first and last years' values of q_t and to generate intermediate years' values by interpolation during the simulation process. This would add only one parameter to the estimation process. Alternatively, the parameters of a density-dependent catchability model could be estimated simultaneously with r, K, and B_1.

If an auxiliary series of population biomass estimates is available, it could be incorporated into an ASPIC analysis in a procedure analogous to tuning a cohort analysis. The external estimates would be compared to the population estimates derived within ASPIC and the residuals incorporated in computation of the loss function (Rivard and Bledsoe 1978). An interesting aspect of this approach is that the external biomass series need not be continuous, but could contain missing values; the loss function would not be incremented for such years. An external *index* of biomass could be used similarly, perhaps by normalizing it to the same mean abundance as the ASPIC estimates and then proceeding as with a series of biomass estimates. As well as contributing to the loss function, biomass estimates or indexes might be used to correct for process error within the ASPIC simulation, as described in Prager and MacCall (1990), although this is a more difficult problem than implementing a tuning procedure.

APPLICATION TO SIMULATED AND REAL POPULATIONS

Two simulated populations and one real population were analyzed to provide examples of results from ASPIC. Each analysis used the additive-proportional loss function with added penalty term (equation 10). As only a few data sets were analyzed, the results do not constitute conclusive evidence about the properties of the ASPIC model, but are intended to serve as examples only.

The first simulated data set represents a fishery following logistic dynamics, but with 15% proportional noise added to the observed values of yield. (In simulating the data, residuals were added according to the additive-proportional model: The quantity in parentheses in equation 9 was distributed normally with mean 0 and standard deviation 0.15.) The second simulated data set was identical, except that 15% proportional noise was also added to the observed values of effort. To examine the effects of the added penalty term in the loss function, each model was fit by ASPIC twice, once with $W_B = 1$ and once with $W_B = 0$. The true parameter values and the ASPIC estimates for these two examples are shown in Table 1. The results demonstrate that ASPIC can provide good parameter estimates, and that the introduction of the penalty term into the loss function (equation 10) constrained the estimate of B_1 to more reasonable values but did not degrade the other parameter estimates. If one may draw even tentative conclusions from Table 1, it appears that the estimates of MSY and effort at MSY are quite robust to errors in the data. All estimates of MSY were within a few percent of the true value, as were the estimates of effort at MSY. This is a reasonable result. Yield and effort are the two quantities directly represented in the data, so it is not surprising that they should be estimated the best.

Standard errors of the parameter estimates for these simulated populations were computed by bootstrapping with 300 trials. In practice, it would be better to use more trials (perhaps 1000), but 300 should suffice to demonstrate the results. The estimated standard errors and coefficients of variation for simulated population 2 are given in Table 2. Results for simulated population 1 (not shown) were quite similar. Table 2 illustrates that of all parameters, B_1 is known the least precisely. As mentioned above, this occurs because the loss functions are insensitive to the estimate of B_1, which affects mainly the first few years' results. It is possible that B_1 would be more precisely estimated from a population with larger yields in the first few years of the catch-effort history. It is worth noting that fishing *effort* at MSY is much more precisely estimated than fishing *mortality* at MSY.

The ability of the model to track the simulated data is shown in Figures 1–4, which summarize results of the second simulated population. Results for the first population are similar but show smaller errors. Even in the presence of substantial errors in both catch and effort, the model's estimate of the population trajectory is quite close to the simulated population from which the catch and effort data were simulated (Figure 1). The trends of the two curves differ most in the first few years of the series, when the estimates have not converged as strongly as they do later. The estimated fishing mortality rate also mimics the unknown pattern of fishing mortality; it seems probable that the residuals are to a large degree a function of the errors included in the simulated effort data (Figure 2). The predicted and observed yield trajectories are shown in Figure 3. The larger errors during periods of high yield are to be expected, as a consequence of the assumed additive-proportional error structure. The estimated surplus production of the stock, shown in Figure 4, is useful in determining whether, in a given year, the catch or the production is larger; in other words, whether the population is getting larger or smaller. As with the estimates of population biomass, some lack of fit is seen in the first few years.

The real data used as an example are from Fonteneau's (1989) analysis of yellowfin tuna in the east Atlantic during recent years (Table 3). Data on fishing effort (time) and catch are taken from Fonteneau's Table 1. I emphasize that this is not intended as an analysis of yellowfin in the eastern Atlantic, but merely as an example of application of the ASPIC procedure. Results are shown in Table 4. In general, the ASPIC estimates of MSY are near the lower range of those of Fonteneau (1989). I have no definite explanation of why this should be so. Fonteneau (1989) hypothesized that the catchability of tunas in the period 1983–1984 was low because of environmental conditions, and if his hypothesis is correct, it would undoubted affect the results of the ASPIC analysis, which as configured here assumes constant catchability.

DISCUSSION

The ASPIC framework provides a flexible format for production modeling. A number of additional scenarios could be handled with it. One might model two populations with restricted mixing between them, as described by Fox (1977), or adjust catch by area, as done for the equilibrium case by Munro (1979) and Caddy and Garcia (1982), and the nonequilibrium case by Polovina (1989). Another modification that could easily be incorporated is the dependence of harvest upon fished area, as introduced by Die et al. (1990).

The ASPIC framework as described here is based upon the logistic surplus-production model. The history of this model was summarized by Kingsland (1982), who pointed out that the model originated in the work of Verhulst (1845) and Robertson (1923), was popularized by Pearl (1920) and was also studied by Lotka (1925). The model was introduced to fishery science by Graham (1935) and Schaefer (1957). In modeling fish populations, ASPIC could just as easily incorporate the exponential yield model of Fox (1970) or a more general model, such as that of Pella and Tomlinson (1969) or the alternative formulation of Fletcher (1982), which lacks the variable exponent that has been found to make unconstrained estimation troublesome (Ricker 1975, p. 326). Unfortunately, not all of those can supply an explicit formulation for yield similar to equation (6), which means that numerical integration would have to be used, as it was by Pella and Tomlinson (1969) in the GENPROD computer program.

Besides its inherent flexibility, the ASPIC approach has at least three strong advantages. First, it is a true non-equilibrium model, accounting for catches in a natural way. This avoids the need to assume that a dynamic stock can be described by a population dynamic model of equilibrium conditions, an assumption that is may be called into question when catch rates are changing. Second, the model retains true population persistence. This conforms to biological reality and saves degrees of freedom at the beginning of the data set, by avoiding the need to average the effort data. Third, the model does not form a regression between two quantities (effort and CPUE) that, as one contains the reciprocal of the other, would be correlated even if effort and catch were uncorrelated random variables. Such regressions have been criticized by Sissenwine (1978) and by Roff and Fairbairn (1980).

The greatest concern in the ongoing development of ASPIC is to quantify bias that may occur from errors in effort. (Such biases would be analogous to the "errors-in-variables" problem in classical linear regression.) Because effort is generally known with less precision than yield, it may prove statistically preferable to use the observed catches as given and develop a loss function in residuals of effort, rather than residuals of yield.

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Table 1. Parameter estimates obtained by the ASPIC procedure for two simulated populations. Both populations follow logistic dynamics with the parameters shown in the table. Data for population 1 had 15% noise added to observed yields only; population 2 had 15% noise added to observed yields and observed efforts. The symbol W_B is the weighting of the penalty term in the loss function to discourage unrealistically high estimates of B_1.

Parameter	Actual value	Estimate, population 1 with $W_B = 0$	Estimate, population 1 with $W_B = 1$	Estimate, population 2 with $W_B = 0$	Estimate, population 2 with $W_B = 1$
B_1	2 600	3 035	2 826	3 723	2 711
K	3 000	2 761	2 770	2 523	2 560
r	1.200	1.29	1.29	1.42	1.42
q	6.0×10^{-5}	6.43×10^{-5}	6.44×10^{-5}	6.86×10^{-5}	6.86×10^{-5}
MSY	900	893	896	895	905
Stock size at MSY	1 500	1 380	1 385	1 261	1 280
Fishing mortality at MSY	0.600	0.647	0.647	0.710	0.708
Effort at MSY	10 000	10 052	10 046	10 343	10 314

Table 2. Standard errors and coefficients of variation, estimated by a bootstrap procedure, of parameter estimates for the second of the two simulated populations given in Table 1. Results for the first population were similar.

Parameter	True value	Estimate	Standard Error	C.V.
B_1	2 600	2 711	607.4	26.3%
K	3 000	2 560	326.4	13.5%
r	1.200	1.42	0.16	11.3%
q	6.0×10^{-5}	6.86×10^{-5}	7.13×10^{-6}	10.2%
MSY	900	905	69.4	8.1%
Stock size at MSY	1 500	1 280	163.2	13.5%
Mortality (F) at MSY	0.600	0.708	0.0819	11.3%
Effort (f) at MSY	10 000	10 314	256	2.5%

Table 3. Data from Fonteneau (1989) on catch and effort of yellowfin tuna in the eastern Atlantic.

Year	Effort	Catch
1967	13.77	52.60
1968	19.29	73.70
1969	13.93	80.40
1970	18.62	59.20
1971	21.30	57.50
1972	21.48	78.20
1973	24.33	79.80
1974	27.12	92.20
1975	43.59	108.10
1976	44.43	109.30
1977	39.35	115.30
1978	55.62	115.70
1979	55.29	111.70
1980	67.13	112.10
1981	81.20	134.80
1982	95.93	134.30
1983	89.42	123.40
1984	57.48	75.30
1985	60.86	112.60
1986	44.83	106.70
1987	51.32	101.10
1988	41.49	100.00

Table 4. Results of fitting the data of Fonteneau (1989) by the ASPIC method, using additive-proportional loss function. The results of Fonteneau are included for reference, and are given as ranges to reflect variations of his model (different values of his parameters *k* and *m*) presented in his paper. Standard errors of ASPIC parameters are estimated with a bootstrap method using 1000 trials. (See text for discussion of differences between Fonteneau's results and results from ASPIC.)

Parameter	Fonteneau's estimate	ASPIC estimate	Std. error of estimate	Coefficient of variation
B_1	–	216.5	72.3	35.8%
K	–	210.7	67.5	31.4%
r	–	2.25	1.036	42.2%
q	–	0.0182	0.00795	40.2%
MSY	117–172	118.7	3.89	3.3%
Stock size at MSY	–	105.3	33.8	31.4%
Fishing mortality at MSY	–	1.13	0.518	42.1%
Effort at MSY	62–74	61.9	3.18	5.14%

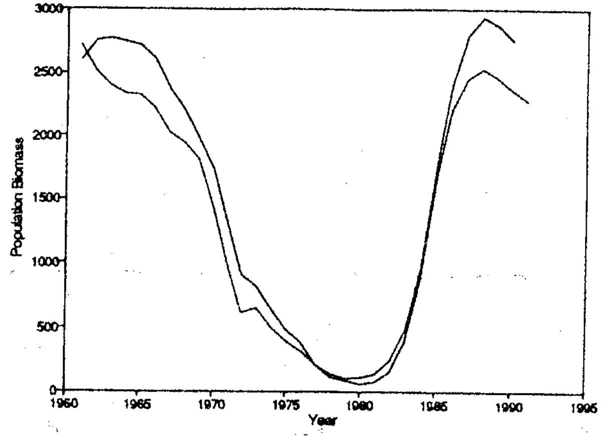

Figure 1. ASPIC results on simulated population #2 (with 15% error in observed data; see text for details). True (solid line) and predicted (dashed line) population biomass at the start of each period.

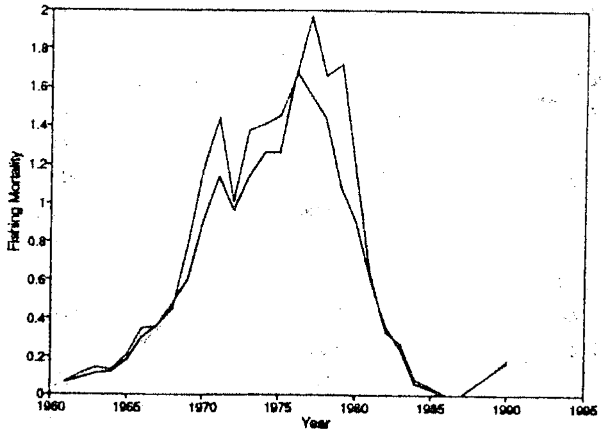

Figure 2. ASPIC results on simulated population #2. True (solid line) and predicted (dashed line) instantaneous fishing mortality for each period.

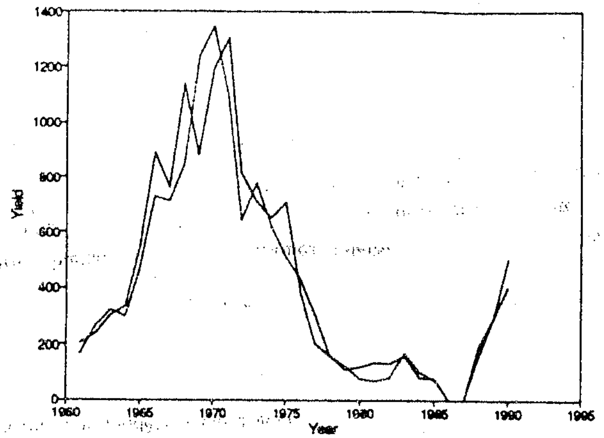

Figure 3. ASPIC results on simulated population #2. True (solid line) and predicted (dashed line) yield for each period.

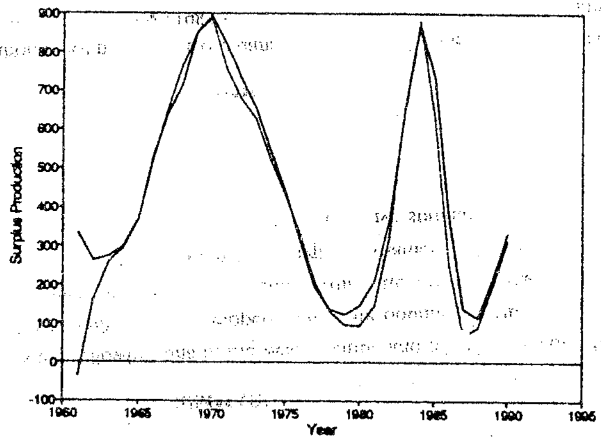

Figure 4. ASPIC results on simulated population #2. True (solid line) and predicted (dashed line) surplus production for each period.

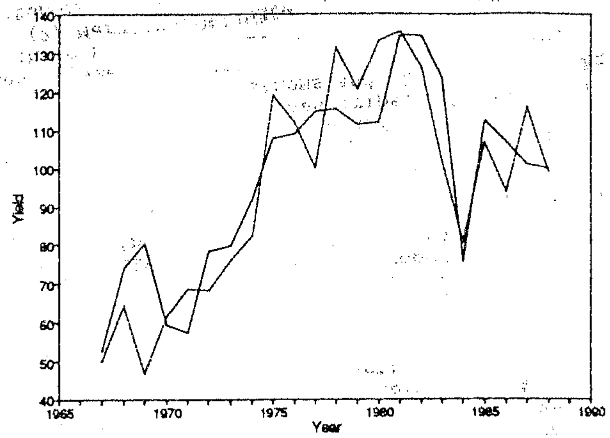

Figure 5. ASPIC fit to the data of Fonteneau (1989) on yellowfin tuna in the eastern Atlantic. Solid line: observed yield. Short dashed line: predicted yield.