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Recent development of methods for analytical fish stock assessment within ICES

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Analytical age-structured stock assessments commenced in ICES in the late 1960s and have constituted the basis for ICES advice on fish stock management for the last 20–30 years. In this paper, the age-disaggregated assessment methods that have been standard tools in ICES are described and discussed both in a methodological and a historical perspective. The general theoretical framework for these methods is outlined, including the virtual population analysis (VPA) algorithm, *ad hoc* tuning of the VPA, separable VPA, and statistical catch-at-age methods exemplified by ICA. Why did the assessment methodology develop as it did in ICES and, in particular, why were age-structured models preferred to production models? Why did VPA-type models dominate for so long? We suggest in this paper that this was caused by a combination of institutional tradition, the availability of data, historical emphasis on year-class variation, and, later, the managers' preference for advice in absolute terms.

Keywords: ICES, stock assessment, VPA.

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Introduction

Within ICES, the primary purpose of assessing the state of a stock is to provide a basis for management advice. The basis for this advice is a perception of how the stock has been exploited and suggestions on how to further exploit the stock. In 1899, when ICES was about to be established, D'Arcy Thompson wrote the following (Went, 1972): "That…it be recognized as a primary object to estimate the quantity of fish available for the use of man, to record the variations in its amount from place to place and from time to time, to ascribe natural variations to their natural causes, and to determine whether or how far variations in the available stock are caused by the operations of man, and, if so, whether, when or how measures of restriction and protection should be applied."

It took, however, several decades before the first virtual population analysis (VPA) assessment in ICES was done by Gulland in the Arctic Fisheries Working Group in 1965. In these and following years, ICES was increasingly asked for advice, which led to the establishment of ICES assessment working groups. This was important for the recent development of assessment methodology.

Compared with the development in other places in the world, statistical methods were taken up rather late in the ICES system, i.e., in the 1990s. The precautionary approach in fisheries management increased the importance of communicating uncertainty and encouraged the activity on, and the use of, statistical models.

In this paper, we describe the most important methods that have been in use in the ICES system in recent decades. We first consider this from a methodological point of view to illustrate how these methods developed mathematically and statistically as the tools for doing the necessary computations became available. Furthermore, we consider why the development took these directions instead of keeping the methods as they were or following other routes, as happened in other parts of the world.

The development of many of the basic concepts has been a gradual process, elements of which have been outlined by others (e.g., Ulltang, 2002) during this Symposium. An overview of the basic concepts, definitions, and notation that are currently used is given in the Appendix.

The general VPA algorithm

For many people, VPA is almost synonymous with the term "assessment". Although this is an over-simplification, it is true to say that the VPA has been the backbone of most assessment methods used in ICES since the early 1970s.

Derzhavin was perhaps the first (1922) to conceive the idea of applying the VPA algorithm on catch-at-age data (Megrey, 1989). In simple terms, the basic idea was to compute the stock numbers at any time that are needed to account for the subsequent catches from the cohort, plus the amount needed to account for the remaining number of fish. This is easily forgotten when faced with the technicalities of the backward calculation, but was actually the original idea behind the concept. The losses due to natural mortality were not taken into account, which explains the later naming of the algorithm (Fry, 1949): *virtual* population analysis. When the method was picked up within ICES, natural mortality was included in the algorithm and in all the following VPA variants.

The computed stock number at any time will then become a weighted sum of the subsequent catches from the cohort plus the number of fish remaining at the present time, where the weighting is derived from the cumulated natural mortality realized before the catch is taken.

It is important to stress that the VPA is not a model in the population dynamic sense, but rather an algorithm that follows directly from the definition of yearly mortalities. The model assumes that the reported catches cover the mortality in addition to the assumed natural mortality. Even if the assumed natural mortality is quite representative of the rate of loss from an unexploited stock, this model assumption is violated if the reported catches cover only parts of the mortality induced by the fishery. This leads to the paradox that underreporting of catches implies underestimation of the stock backwards in time.

To decide the numbers of a year-class cohort, the numbers caught from this year class need to be known for each year of its life. Using the notation in the Appendix, if the fishing mortality rate F (or number N_1) is assumed in the last year, equations (A2), (A5), and (A6) in the Appendix allow us to compute N_0 and N_1 (or F), based on known catches. Since N_0 in one year is the same as N_1 the year before, F and N_0 in the year before can be computed using the known catches in that year. Repeating this process for each year backwards in time gives stock numbers and fishing mortality rates for each year. This algorithm is commonly termed the VPA [or SPA (sequential population analysis)]. The contribution from the term representing the fish remaining at the present time (N_1 or terminal F) becomes less important backwards in time. This phenomenon is termed *convergence* of the VPA.

Apart from the catch numbers at age, two kinds of information are needed to fully determine the stock abundance. The first is stock abundance in the last year, which can be derived by tuning the VPA to catch-per-unit-effort (cpue) indices, as described later, or simply assumed. The other is the natural mortality which generally has to be assumed.

Natural mortality – multispecies models

The natural mortality rate includes all causes of death except for the catches. One important cause of natural mortality for many stocks, in particular at younger ages, is predation. Within ICES, a multispecies model (MSVPA) was developed throughout the 1980s for the North Sea. This is a VPA where the natural mortality is the sum of predation mortality (M2) and a residual natural mortality (M1). The basis for this model was the work by Andersen and Ursin (1977), which led to the suggestion by Helgason and Gislason (1979) and by Pope (1979) that M2 can be estimated from data on the relative food composition in predator stomachs, together with data for consumption rates by predators. The underlying assumption was that suitabilities (the predators' preference for each kind of prey, analogous to the selection pattern by the fishing fleets) remain constant over time. To get the necessary data, extensive stomach sampling programmes were carried out in 1981 and again in 1991. The analyses were conducted within the framework of the ICES Multispecies Assessment Working Group and have had a great impact on understanding the role of predation mortality for the younger ages of fish stocks (Pope, 1991). To some degree, the exploitation levels have been adjusted accordingly. The assumed natural mortality rates for most North Sea stocks, as used in single-species assessments, are by now adapted to the findings from the MSVPA.

More general models

The VPA can be viewed as a special case of a more general application of the definitions of mortalities. The time course of each cohort is uniquely defined by all mortalities relating to the cohort, and one stock number in each cohort will serve as a scaling of the whole cohort to absolute terms. A parametric model population can be constructed by specifying as parameters all mortalities and one stock number for each cohort and derive what the observations of the population (catches, survey indices) should have been at given values of the parameters. Then one may estimate the parameters as those that give the best fit of the modelled data to the actual observations. In practice, some restrictions on the parameters are needed in order to get a unique solution.

One way is to find the Fs and the Ns, given M, that give a perfect fit to the reported catches, which renders one parameter (F or N) undetermined for each cohort. This is the VPA in this broader perspective.

Alternatively, some relationships between parameters can be assumed, thus reducing the number of unknowns. The common approach is to assume that the fishing mortalities are separable, i.e., the fishing mortality F(a,y) at age a in year y is a product of a year factor f_y and an age factor S_a:

$$F(a,y) = S_a(a)\, f_y(y). \qquad (1)$$

The component S_a is the relative fishing mortality at age or selection at age and the overall fishing mortality f_y is a scaling of the selection which relates to how intensively the fleet operates in that year.

In order to estimate the remaining parameters as those that give the best fit of the model to the data, a measure of the fit (objective function) is needed, as well as some method to find the set of parameters that gives the best fit. The likelihood function is a statistical objective function which can be optimized by non-linear optimization. This was the basic idea underlying the crucial work in 1982 by Fournier and Archibald which, since then, has influenced the world's fisheries science community to a large extent. Their new concept for assessment methods was to gather all auxiliary information in one *statistical* model which constitutes the basis for formulating the measure of fit of the model to the data. They claim that this theory is the first to address itself properly to the stochastic nature of the errors in the catch-at-age data (Fournier and Archibald, 1982). As part of the minimization, the Hessian matrix (the mixed second derivatives of the objective function with respect to the parameters) is computed, which can derive approximations for variance estimates for the parameter estimates. This strategy (Fournier and Archibald, 1982; Deriso *et al.*, 1985) is sometimes termed "statistical catch-at-age methods" (Hilborn and Walters, 1992).

While the work by Fournier and Archibald inspired assessment modellers several places in the world in their development of methods, the ICES community kept the tuned VPA models (see below) almost exclusively until the mid-1990s. The exception was the separable VPA (see below) which was introduced in the early 1980s (Pope and Shepherd, 1982). In the late 1990s, ICA (integrated catch-at-age analysis, Patterson and Melvin, 1996), which is a "statistical catch-at-age" method, took over as the standard tool for assessing many pelagic stocks.

Tuning of the VPA

As pointed out above, applying the VPA algorithm to catch-at-age data leaves one parameter undetermined for each year-class cohort: either the F in the last year, for which there are observations from the cohort (terminal F), or the numbers remaining in the cohort at the end of the last observation year (survivors). This implies that the VPA can tell about the stock backwards in time, but to assess its present state, more information is needed. This information will most often be in terms of relative measures of the stock abundance at age or the overall fishing mortality. The former can be catch per unit of effort (cpue) at age, or survey indices which can be treated as cpue with a standardized effort. Effort in its own is a relative measure of the fishing mortality.

Let I represent an index of the cpue type. Being a relative measure of abundance, it is related to the stock numbers by a catchability q:

$$I = q\,N. \qquad (2)$$

This basic concept can be varied in several ways. Most often, q is assumed to be constant over years, but dependent on age. Other methods assume a linear trend in q over time, while still others assume a power relation:

$$I = q\,N^p. \qquad (3)$$

When I represents catch C, per unit of effort E, and

$$C = F\,N_{mean} \qquad (4)$$

[see Equation (A4) in the Appendix], effort and F will be related through

$$F = q\,E. \qquad (5)$$

Thus, one may either attempt to find the relationship between I and N or between E and F.

In the first years, even up to the late 1980s, the common procedure in ICES working groups was to consider possible changes in fishing mortality, taking various kinds of information into account. The working groups then agreed on terminal fishing mortalities at age, and the VPA was run according to these values.

The following citation from the Arctic Fisheries Working Group (ICES, 1976) is illustrative of the kind of deliberations that led to the decision on terminal fishing mortalities:

> In deciding on the input F values for 1976 the following points were considered:
> Year class strength from pre-recruit surveys;
> The expected exploitation pattern allowing for some concentration of fishing on the 1970 year class;
> The overall level of fishing mortality that would be expected in relation to the reported catches;
> The changes in estimated fishing effort.

A decision was made based on a discussion where these points were compared. An obvious alternative to such subjective deliberations would be to obtain a formal estimate of q and apply this to the indices for the present year. In ICES, this approach developed quite slowly, and throughout the 1980s, it was largely in terms of *ad hoc* methods. In these methods, catchabilities are computed by comparing indices with VPA-derived stock numbers in an iterative process instead of making least-squares estimates or other statistical estimates of the catchabilities.

Various *ad hoc* methods from this period differ in their use of log-transformed data, whether they assume a somewhat more elaborate catchability model than the simple proportionality in Equation (2), in the way they combine the information from different fleets, and by various procedures for down-weighting less relevant data (e.g., from very distant years).

The method that came into common use was proposed by Laurec and Shepherd (1983). This method used logarithmic transformed catch and cpue data, down-weighted old data with a "tricubic taper", and assumed constant catchabilities over time. The F at the oldest age was set to the average of the five next youngest ages. Catchabilities were estimated using data for all years except the last one, and the terminal F was derived by applying the catchabilities to the last year's indices.

Accordingly, this tuning method not only treats the catches as exact, but also takes the cpue indices in the last year literally, while the indices in the past are assumed to have errors. The XSA (extended survivors analysis; Shepherd, 1999), which was the next (and hitherto last) step in the development of VPA tuning methodology in ICES, can be regarded as an attempt to get away from this paradox. In the XSA, the VPA algorithm is used to reconstruct the population as before, but now starting with the numbers in each cohort at the end of the last year (survivors). The catchabilities [as defined by Equation (2)] are estimated by comparing the stock numbers derived from the indices, i.e., $N_I = I/q$, with those derived from the VPA by minimizing the overall log sum of squares over all years (y), ages (a), and fleets (f):

$$SSQ=\Sigma_{y,a,f}\{\log[N_I(y,a,f)]-\log[N_{VPA}(y,a)]\}^2 w(y,a,f) \quad (6)$$

where w is a weighting factor for each term and $N_I(y,a,f) = I(y,a,f)/q(a,f)$.

Here, all indices are treated as having errors, and Equation (6) is the objective function to be minimized. In XSA, the weighting is the inverse variance computed from the residuals for each age and fleet. Down-weighting of data from the distant past is also included. With this objective function, the minimization can be done iteratively, and this is the procedure in XSA. This is computationally much faster than ordinary non-linear minimization, but the variance estimates from the Hessian are not obtained.

XSA has the option to shrink recent F values towards the mean. Shrinkage implies that the terminal F values become a compromise between what the recent data tell and a hypothesis of a stable mortality. If there apparently are rapid changes in the mortality, shrinkage implies that they are interpreted largely as noise. Thus, the effect of noise in recent data is reduced, but true changes are, to some extent, concealed.

Separable VPA

The separable VPA (Pope and Shepherd, 1982) is somewhere between a statistical model and a VPA model. It uses a separable model to estimate mortalities, fits population numbers with these mortalities to the catches, and uses these stock numbers for the final year to initiate a VPA. It was introduced at a stage where decisions on terminal F values were still made "by hand", often looking for consistency in the selection pattern over the last years. It is designed for the situation where there are only catch-at-age data, and has been used both for assessments in that situation [see ICES (1999) for a recent example] and for obtaining a smooth selection pattern for use in predictions. However, the parameter is not estimated by minimizing a sum of squares, although it represents a fair approximation, and the solution by simple iteration does not provide any formal measure of the variances.

ICA

The ICA method (Patterson and Melvin, 1996) is, so far, the only statistical catch-at-age model used as a standard tool within ICES. Since it was introduced, it has taken over as the standard tool for many pelagic stocks. One motive for developing this method was the need to utilize data that could not be directly used in the tuning methods in a formally consistent way, particularly measurements of the spawning stock biomass (SSB). Furthermore, it can give estimates of the variances of the parameter estimates.

The method assumes a parametric population model with separable fishing mortalities and terminal stock numbers as parameters and derives modelled catches according to the parameter values. Furthermore, it assumes catchability models as Equation (2) both for cpue data and for measurements of SSB. The objective function is a weighted sum of terms comparing observed and modelled values, and is of the form:

$$w \ \log\left({x_{obs}}/{x_{model}} \right)^2 \quad (7)$$

where w are the weights, and the errors are assumed to have a log-normal distribution. The parameters are estimated by non-linear minimization of the objective function. The weighting factors are, in principle, subjective input values, although iterative reweighting according to estimates of the inverse variance is possible. As part of the standard output, variance estimates for the parameter estimates, derived from the Hessian matrix, are presented.

Background for the methodological development in ICES

The development of methods in ICES has taken somewhat different directions from that in other communities, and ICES has sometimes been criticized for being too conservative and unwilling to follow trends in modern methodological development. Although the development within ICES has been a gradual process, some crossroads can be identified where strategic decisions were made. We here try to elucidate how and why these decisions were made.

Age-structured models vs. production models

In the 1930s, the way of thinking population dynamics by Hjort, Graham, and others (Ulltang, 2002) was in terms of production models. Such models describe the variations in population size in terms of biomass without considering age. In particular, a regeneration term that included both mortality and recruitment was used to describe population growth as a function of population size. Age composition studies were carried out as well, motivated by the idea that year-class variation was important for explaining variations in resource abundance. Hjort had argued during the previous several decades that age sampling of the commercial catches should be done regularly (Sætersdal, 2002). Eventually, in the 1930s, it was accepted within the ICES community that age reading of scales and otoliths was reliable enough to produce valuable data. Age composition studies were then considered more reliable than size-class studies for predicting the future development in the stock. Hjort's breakthrough was, of course, of crucial importance to the development of the VPA later on since this method utilizes the information in catch-at-age data.

Another important idea for the later development of assessment tools was the notion of expressing the loss in a stock as a relative rate. This concept is attributed to Baranov as early as 1918 (described in Megrey, 1989), although his contribution was recognized much later. The next important idea was to work with numbers instead of biomass, and to work with year classes where the only loss was due to mortality. This enabled separate computation of the recruitment and the exploitation rate directly from data with very few assumptions about the population dynamics. This is basically different from general population dynamics theory where gain (growth and reproduction) and loss are modelled as functions of stock biomass and the abundance of other stocks. As explained by others (e.g., Ulltang, 2002), one background for the route of development in ICES may be the controversy about the importance of recruitment variation and about the appropriateness of age determinations.

In the 1960s, when the first VPA assessments were made, the emphasis was on estimating the mortality due to the fishery rather than to the natural mortality. It can be illustrative to have a closer look at the background for these assessments.

The first VPA on Arctic cod

In 1957, the scientists expected the strong 1950 year class to increase the catches of Arctic cod in the Lofoten fishery. But the fishery failed, and for the first time, Norwegian scientists suggested that overfishing could be a problem in Norwegian waters (Schwach, 2000). On behalf of the Institute of Marine Research in Bergen, Norway, Sætersdal and Hylen (1957) prepared the report "The state of the Arctic cod" for the Permanent Commission meeting in 1957 [the predecessor of the North-East Atlantic Fisheries Commission (NEAFC)]. The report discussed whether the failed fishery was due to natural variation or to the fishery itself. The conclusion was that the shift to more efficient fishing gears had contributed to the decrease in the catches and that more rigorous conservation measures should be considered in the northern area. At this time, the stock was regulated by mesh size, like the other ICES stocks that were regulated at that time. Mesh size experiments were thus an important activity and continued to be so to see whether the small fish could be protected more effectively. The concern for the cod stock led ICES to establish the Working Group on Arctic Fisheries. Previously, this cod stock was handled in the Gadoid Fish Committee. The Working Group had its first meetings in 1959 (ICES, 1959). The first objective for this meeting was to examine, interpret, and quantify the changes in the fisheries for cod and haddock and to distinguish between changes due to the fisheries and to natural fluctuations. The second objective was to make some preliminary assessments of the effects of increasing the mesh size of trawls. The cpue had decreased and also the average cod length in the catches. The assessment on Arctic cod that was produced during this meeting was based on the work by Beverton and Holt (1957) from Lowestoft. This methodology enjoyed great confidence within the ICES scientific community and made quite an impact on the scientists' understanding of stock dynamics, and still does. The theory is built on several stability assumptions and is based on deterministic relations only. Beverton was a member of the Working Group in 1959 and presented the Working Group report to the following Gadoid Fish Committee meeting. The methodology used in this Working Group was, in short, the following. The total mortality rate Z was defined to be

$$\frac{dN}{dt} = -ZN \tag{8}$$

where N was cohort number, t time, and Z the sum of the different mortality rates. The total mortality rate was estimated by comparing relative cohort numbers from the age data in successive years. But in order to say whether fishing or natural fluctuations caused the observed lower stock abundance, the fishing mortality rate F needed to be separated from Z.

This was done by fishing effort considerations. The conclusion was that the fishery and not natural fluctuations was the reason for the stock decline. The relation between F and natural mortality M was estimated to be of the order 4:1. Supported by the age data, the Working Group suggested that the mesh size in the trawl fleet should increase.

However, these calculations were based on several shaky assumptions: 1) recruitment to the exploitable part of the stock must be fairly constant for a period of years, 2) total fishing effort must remain steady, and 3) fishing mortality would be constant over all ages. Since the main fishery on Arctic cod was on the spawning area, the fishing mortality rate could not be the same for both the mature cod and the immature part of the exploited stock. The estimates were considered to be extremely uncertain.

In 1965, NEAFC submitted a request to the ICES Liaison Committee [predecessor of the Advisory Committee on Fishery Management (ACFM)] to have the Arctic Fisheries Working Group produce a report on the state of the Arctic fisheries (ICES, 1965). The next Working Group meeting was held in 1965. With the weak points in the 1959 assessment in mind, a new method was presented (ICES, 1966). Gulland, who was working at Lowestoft together with Beverton and Holt, had developed this method and described it in the annex of the report. He referred to the work done by Fry (1949) and Ricker (1958) where the VPA had been applied. This method provided an opportunity to calculate fishing mortality rates for each age. Pope (1972) gave Gulland credit for being the popularizer of the VPA method, while Megrey (1989) gave both Murphy (1965) and Gulland (1965) the credit.

Thus, it seems that the choice of approach, to a large extent, was driven by the need to estimate the effect of the fishery as precisely as possible and to separate it from other forces influencing the stock dynamics. The fact that the process was triggered by the disappearance of a presumably large year class may also have contributed to the choice and links this development to the previous discussions on the variations in year-class strength.

One may also argue that this kind of approach was taken because the conditions, in terms of the necessary data, were in place. Thus, there were catch data from fisheries statistics, there were age data, and there were effort data, at least from some fleet segments. Furthermore, the conceptual framework was largely in place through Beverton and Holt's work not many years before.

The VPA method gradually became dominant after 1965 in attempts to assess other ICES stocks. The further development of the VPA in subsequent years was not systematically published. Rather, scientists contributed to the working groups with different tables of calculations, which were modifications of Gulland's method. It seems that within the ICES system, the development of methodology did not receive very much attention during this period. A few people, who often had influential positions in ICES committees, were the major actors in this development.

VPA models vs. statistical models

Throughout the 1970s and 1980s, fishing pressure continued to increase on the exploited stocks, and mesh size regulations were not considered sufficiently effective. Several fisheries became effort or quota regulated. Quota regulations rely heavily on precise estimates of the present stock abundance, which is the weaker part of the VPA algorithm, as such.

Such problems in the roundfish assessments led to the establishment in 1981 of an *ad hoc* Working Group on the Use of Fishing Effort Data in Stock Assessments, which was the predecessor of the Working Group on Methods of Fish Stock Assessment, formally established in 1982. The idea of tuning the VPA directed further developments. The Laurec-Shepherd method for tuning VPAs became widely used, with XSA taking over later (see previous section on "Tuning of the VPA"). Simpler methods received some attention (e.g., ICES, 1984), but never replaced age-structured methods except in cases where age data were missing or very unreliable. Production estimates have never been used as a substitute for VPAs as a basis for advice. Apparently, there has always been a strong belief that age-structured models are superior, although this belief is seldom challenged by comparative studies.

As mentioned earlier in this paper, Fournier and Archibald published their pioneer article in 1982 on an assessment method where all auxiliary information could be gathered in one statistical model. It took more than a decade before such models came into use in ICES.

There may be several reasons why relatively little emphasis was put on statistical aspects of the assessments in ICES. One reason may simply be that the development in the 1980s in the ICES system was dominated by non-statisticians, such as Pope and Shepherd (their impact is humorously described in Hilborn, 1992).

But in general, rather than focusing on uncertainty of the results, the dominating goal was to obtain point estimates which were presented as "the best numbers that can be provided". This may perhaps, most of all, reflect the needs of the customers, i.e., various management bodies, who wanted specific numbers as the basis for their decisions or negotiations. But it may also reflect the scientists' lack of confidence in the managers' ability to make rational decisions when faced with uncertainty in the basis for their decisions. It is sometimes claimed (at least in informal fora) that "managers easily understand that there is a 50% chance that the stock is better than the scientists tell them, but never that there is also a 50% chance that it is worse".

Another feature was the still-existing emphasis on standardized tools. This may, to some extent, be a reaction to the previous subjectivity in the VPA tuning and the multitude of tuning variants, but has implied that the various working groups have not been encouraged to go into each assessment and evaluate which assessment strategy would be optimal for just that stock and those data. Rather, they have been requested to adhere to standard software as far as possible. There are many good reasons for this, but it has led to methodological conservatism and an emphasis on consistency which may have hampered the development of methods within this community. On the other hand, even these standard tools have enough flexibility to allow a user with limited insight to apply erroneous assumptions, which easily leads to misleading results. Thus, the element of subjectivity may still be strong, but it is now applied by selecting options and eliminating data (Hauge, 1998).

Under these conditions, it may not be surprising that the development has concentrated on VPA methods. VPA methods are, in general, simple, robust, and computationally fast, but depend heavily on the assumption that the reported catches encompass all mortality exactly, apart from the assumed natural mortality. However, statistical methods also fit the population to the observed catches. Since the stock numbers backwards in time are weighted sums of catches (observed or fitted), the result for distant years becomes more or less the same. Thus, the main difference is for the recent years where the statistical methods offer a greater flexibility with respect to the data used and are more tolerant if data are missing. They also offer greater flexibility as to the statistical model assumed for the noise in the data and give formal estimates of the uncertainty in the assessment.

From a purely scientific point of view, it is clearly unsatisfactory to give point estimates without indicating their precision. In many environments, such practice would simply be rejected as non-scientific. There is also a growing demand for estimates of uncertainty in the assessments and predictions, created in particular by the implementation of the precautionary approach.

The uncertainty is computed with coefficients of variation commonly in the order of 10–30% for key measures of the state of the stock. However, these variance estimates cover only parts of the variance and generally not the uncertainty due to catch misreporting, poor survey coverage, assessment model misspecification, variations in natural mortalities, etc. Moreover, the management advice is too often inconsistent from year to year, perhaps more than indicated by the variances [van Beek and Pastoors (1999) give some recent examples]. Therefore, one may question whether the management advice, in the form it is given at present, requires greater precision than what is realistic to achieve with the data and models that are within reach. Even though improvements both in assessment methodology and in supplementary data may be expected, there is also a need to consider alternative kinds of management advice by which future regulations can be more foreseeable. In addition, the safety margins need to be more satisfactory, taking into account that some of the uncertainty cannot be determined. Tools will be required for assessing other aspects of the stock dynamics, with less emphasis on the point estimates of the present stock abundance and more emphasis on probabilities of future productivity and the risk associated with various management regimes, together with tools that are better suited to discover changes in the state of the stock. Still, it is not evident to what extent this can be achieved.

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Appendix

Basic concepts

As an introduction to the methods, a brief outline of some basic definitions and concepts is necessary. These have been developed gradually over many decades, as described by Ulltang (2002), into a standard conceptual framework for assessments.

The measure of exploitation is mortality, which is defined as the relative rate of disappearance of fish. Let N be the number of fish at any time. When all change in N is due to loss by death, the instantaneous mortality is:

$$Z = \frac{-1}{N}\frac{dN}{dt}\,. \qquad \text{(A1a)}$$

In the time span from t=0 to t=1, the number of fish at t=0 and t=1 are denoted by N_0 and N_1, respectively. The mean mortality in the time span then becomes

$$Z = \log\left({}^{N_0}\!/_{N_1}\right). \qquad \text{(A1b)}$$

It also follows that

$$N_0 = N_1 \exp(Z)\,. \qquad \text{(A2)}$$

For the management of the stock, it is of particular interest to consider the exploitation due to the fishery. In general terms, if $Z_1, Z_2 \dots Z_p$ represent mortality related to different causes of death, and $D_1, D_2, .. D_p$ are the number of deaths by each cause in the time span, then:

$$D_i = \frac{Z_i}{Z}(N_0 - N_1)\,. \qquad \text{(A3)}$$

In particular, if C is the number caught in a year, F is the mortality associated with the loss of fish because of this catch, and N_{mean} is the mean value throughout a year:

$$N_{mean} = N_0\left(\frac{1 - e^{-z}}{Z}\right) \qquad \text{(A4)}$$

then:

$$C = F\,N_{mean} = \frac{F}{Z}(N_0 - N_1) = \frac{F}{Z}N_0(1 - e^{-z})\,. \qquad \text{(A5)}$$

All other mortality is denoted by M (natural mortality), thus

$$M = Z - F. \qquad (A6)$$

M can generally not be estimated from the available data, and it is customary to assume a value for M.

It follows from Equations (A2), (A5), and (A6) that if C and N_0 are known, then F and N_1 can be computed, and if C and F are known, N_0 as well as N_1 can be computed. It is not possible to express these quantities as explicit functions of each other, however, because of the mix of plain and exponential terms. This is a purely technical problem, and to solve the equations numerically is straightforward. One may also use approximations, e.g., the so-called cohort equation (Pope, 1972) or Pope's approximation which is derived by assuming that all catch is taken instantaneously in the middle of the year:

$$N_0 = N_1 \exp(M) + C \exp(M/2)\,. \qquad (A7)$$