RISK ANALYSIS AND BIOLOGICAL KNOWLEDGE

by

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ABSTRACT

The paper adresses the question whether we fully utilize the growth in biological knowledge in fish stock assessments and risk analyses. For illustrative purposes, repeated references are made to the assessment of the Northeast Arctic cod stock. In many cases existing knowledge may allow us to establish relationships for predicting short or medium term changes in vital population parameters determining mortality, growth and recruitment. Independent variables in such relationships, with a priori justification for being chosen, could be parameters describing the state of the fish stock in question or the state of its biological or physical environment. Long time series of biological data exist for several stocks, and these data series should be properly worked up and used for testing proposed relationships. Utilizing information on the state of the system, parts of the range of variation in vital parameters can be excluded in short and medium term predictions. This would increase the empirical or informative content of our risk assessments.

1. Introduction

The main problem dealt with in this paper is the question whether we are fully recognizing and utilizing the growth in biological knowledge in standard stock assessment procedures. The title refers to risk analysis, which in some form ought to be an integral part of stock assessments, but the problem can generally be formulated by the questions: When specifying our population models and assigning values to their biological parameters, do we make the best use of biological knowledge for predicting, with incorporated estimates of uncertainty, what will happen in coming years? What kind of knowledge is required and to what extent does it exist or can it be gained?

The surplus production in a fish stock is determined by natural mortality, growth and recruitment parameters. Natural mortality is seldom estimated but assumed constant at an agreed level from year to year. Growth can be continuously observed, but when projecting stock size and catches assumptions have to be made about its value. Also recruitment can be observed and estimated at the time it occurs, although usually with larger errors than for growth. For long lived species, assumptions on strength of year classes not yet observed in the fishery are usually not of critical importance for short term projections. However, for medium and long term projections, assumptions on recruitment functions are usually the most critical part of the assessment. For short lived species they are also critical for short term projections.

How critical assumptions on the value of these biological parameters are can be studied by sensitivity analysis, and such analysis should more often be done. However, sensitivity analysis does not solve the problem of assessing risks, it shows only what parameters are most critical. For realistic risk assessments *knowledge* on likely values of biological parameters and their variations and causes of such variations, is required.

I fully agree with the Report of the Working Group on Methods of Fish Stock Assessment (Anon., 1993a) when it discusses the different types of uncertainties to be considered and notes that at present, few analyses include all sources of uncertainty, but many are available which describe only measurement error or recruitment uncertainty, and that these should be regarded as an important step forward and are to be encouraged rather than criticized for leaving some factors out.

That being said, it should also be encouraged to try to do more with respect to model parameters which often just have been assigned an assumed value or (more seldomly) an assumed range of variation with an a priori statistical distribution. It should especially be encouraged to investigate whether information on changes in the biological and physical environment of the stock in question can be used for predictive purposes.

2. Example for illustration: Recruitment of the Northeast Arctic cod stock.

I will try to illustrate some of my main points by an example from the assessment of the Northeast Arctic cod stock.

The Arctic Fisheries Working Group uses a lot of survey indices for 1, 2, and 3 years old cod in addition to the 0-group index to estimate recruitment utilizing since 1987 ICES recruitment computer programmes (see e.g. Anon., 1993b).

In Fig. 1 is shown a plot of the 0-group index of cod from the International 0-group survey (INTOGP) against VPA estimated number of three years old cod for the 1966-1986 year classes, based on data given in Anon. (1993b). I am aware that the ICES recruitment computer program uses log transformed

values, but I prefered to use untransformed values in the figure. The index for the 1984-86 year classes indicated much stronger year classes than later estimated by VPA as 3 years old, and contributed to overoptimistic expectations, especially in 1986, of stock development.

In recent years the discrepancy for 1984-86 has led to lower correlation between VPA and the INTOGP index for the time series as a whole. The working group has not discussed in any detail this discrepancy, and although certainly being aware of complicating biological factors, it has treated the 1984-86 indices in the same way as indices from the other years to predict recruitment.

There is now rather firm evidence that the discrepancy for the 1984-86 year classes in Fig. 1 is not primarily a problem of erroneous survey results but a problem of mortality. When using a relationship as in Fig. 1 to predict year class strength, one (usually unstated) assumption is that natural mortality (M) from time of survey to recruitment to the fishery is constant between year classes (or, rather, survival exhibits a random variation around a constant mean value). No value of M is assumed, but as in many other cases it is more the assumption of constant M rather than an assumed value which is the problem. It is now known (Mehl, 1989, 1991) that cannibalism increased heavily in the cod stock in 1985-87, reducing the number of recruiting fish from the 1984-1986 year classes. The 1983 year class, i.e. the year class immediately preceding the 1984-1986 year classes, was also strong. The increase in cannibalism must be seen as a direct result of increased food demands from an increasing cod stock and severely reduced shrimp and especially capelin stocks (Mehl, 1991). Also the 1984 and 1985 year classes of herring, which appeared strong as 0-group, almost completely disappeared (Anon., 1987). The cod stock's comsumption of these year classes in 1984-86 was probably one of the main factors causing this depletion (Mehl, 1989). In addition to reduced recruitment due to cannibalism, reduced growth of cod contributed to the downward amendments of predicted cod stock biomass and catch (Mehl and Sunnanå, 1991). Increased discarding of small slow-growing cod not taken account of in the stock assessment further contributed to the failure of the stock predictions (Anon., 1990).

There are some important lessons to learn from the history given above:

a)   The gross error in predicted development in the cod stock, as given by ACFM in for example its report from November 1986 (ICES, 1987), could not have been avoided by for example using more sophisticated statistical techniques for VPA tuning or recruitment predictions from survey data.

b)   The predictions could have been modified by utilizing the knowledge available on the development in the Barents Sea ecosystem together with bold scientific conjectures (scientific hypothesis or theories).

Item b) needs some elaboration. It was in autumn 1986 known that the capelin stock was severely depleted and the Working Group on Atlanto-Scandian Herring and Capelin (Anon., 1987) also foresaw that the stock might suffer from recruitment failure in the years to come. It was also known that the relatively strong 1983 year class of herring had left the Barents Sea in summer 1986 and that the 1984 and 1985 year classes had disappeared almost completely (Anon., 1987). The first data on increased cannibalism in the cod stock were also reported (Mehl, 1986). These facts together with background knowledge on the cod's diet and the assumption of four successive strong year classes (1983-86) in the cod stock prediction should make it more likely than not that cannibalism would reduce recruiting year classes of cod and that reduced food availability might result in reduced cod growth. This would be the "bold scientific conjectures". The fact that in the known history of the stock it has only twice been observed two successive strong year classes in the fishery (1918-19 and 1963-64 year classes, see Sætersdal and Loeng (1984, 1987)), and never more than two, should have strengthened the suspicion that "something might go wrong".

Having said this, it should be added that in view of the general *problem situation* or *the state of the discussion* (readers interested in epistemology are refered to for example Popper (1972)) in ICES in 1986, it would have been surprising if at that time the information refered to above had been effectively used. Historically, the main problem has been the overexploitation of the cod stock. During the late 1970s and early 1980s, severe worries were repeatedly expressed by ICES in relation to the rate and pattern of exploitation of the Northeast Arctic cod stock. When the stronger year classes from 1982 onwards were observed, it was pointed out to the managers that "The present situation offers the possibility to rebuild the spawning stock while increasing catch quotas and, at the same time, reducing fishing mortality gradually towards F_{max}" (ICES, 1986). The attention was almost totally concentrated on the effects of the *cod* fishery on the stock and the necessity, and potential gains, of reducing the fishing pressure (Ulltang, 1987), putting to a large extent aside other conditions which had to be fullfiled in order to achieve the predicted rebuilding of the stock.

The experience from the Barents Sea and the multispecies research carried out since 1986 have contributed to change this situation. The experience has shown the importance of utilizing information about food requirements of the stock and the state of the rest of the ecosystem in cod stock predictions for the Barents Sea. Such information can not easily be put into the ICES standard assessment machinery, but it may be of more critical importance than some of the information being used. The multispecies research has made it possible to start to quantify some of the important multispecies effects (see for example Tjelmeland and Bogstad (1993)).

3. How can biological knowledge be utilized better?

3.1. Possibilities and limitations.

Rothschild (1986) states that the problem of predicting fish-population variability does not at present rest on our understanding of the behaviour and physiology of any particular group of fish. Rather, it rests on our ability to identify, define, and measure the fish's ambient environment, and the complexity of such a task is rooted in the virtually infinite dimensionality of the marine ecosystem. A typical approach is to select some time sequence of annual fish-stock abundance and some time sequence of abiotic or biotic environmental variable(s) and analyze the relationships between sequences. If a statistically promising relationship is not found, then the process is repeated. As noted by Rothschild, it is not surprising that many correlations are found with such a procedure. However, it is most difficult to distinguish between relations that are causal or predictive and relations that are simply correlative, because typically there is no a priori theoretical justification for the choice of independent variables.

Although agreeing with Rothschild concerning the complexity of the task, my conjecture is that in the context of improving our short and medium term predictions of fish stock development, the background knowledge allows us in many cases to give a priori justification for choice of independent variable for predicting short or medium term changes in vital parameters. If for example it is known that species A is a dominating item in the diet of species B, it should be investigated whether there exists a relationship between individual growth of species B and the abundance of species A, or the ratio between the abundance of species A and species B, in the stock area.Although not solving the problem of fish stock variability, small steps could be taken in the right direction by making use of such relationships, and these small steps could be rather large jumps with respect to the quality of traditional fish stock predictions.

Independent variables to be used in predictive relationships could be
     a)   variables describing the state of the fish stock in question,

b) variables describing the state of other fish stocks,other parts of the biological environment
or the physical environment.

For several fish stocks in the ICES area, time series of biological data exist for periods covering 40-50
years or more. These series contain potentially important information not yet being fully utilized,
since data in many cases are not available in a useful form. The perhaps most important single step
which could be taken to ensure the maximum utilization of biological knowledge would be to make
these series available in a form which makes it possible for the international scientific community to
draw pertinent data from them.

Beverton and Holt (1957) made a tremendous work in assembling the different, and at that time "best",
biological theories into one comprehensive fish population dynamics model. The development in ICES
stock assessment since that time has largely consisted of computerization of the calculations and
statistical/mathematical refinements of their basic model, including development of VPA models.
Smaller attention has been given to the problem of predicting changes in biological parameters. Use
of computers made it possible to develop invaluable new techniques in abundance estimation
procedures (e.g. VPA tuning programs). However, it also made it possible to replace simple
mathematical functions with large data matrices with the (unintended) side effect of putting smaller
attention to the biological processes which the original mathematical functions were supposed to
describe (e.g. von Bertalanffy's growth equation replaced by matrices of weight-at-age data). It is now
time to put more emphasis of the biological part of the theory, using basic biological knowledge to
suggest a priori predictive relationships and test these by data from biological time series and possibly
especially designed experiments.

For illustrating the kind of knowledge which could be better utilized and how it could be done I will
below give some comments on three groups of problems, namely the problem of predicting
recruitment, the problem of predicting natural mortality and the problem of predicting growth and
maturation. These short comments should not in any sense be regarded as an attempt to give an
extensive review of the problems.

3.2 The problem of predicting recruitment

This problem has traditionally been treated by trying to establish a relationship between spawning
stock and recruitment, recruitment being measured as the number of fish at a defined age usually close
to the age of recruitment to the fishery. Different types of stock-recruitment relationships have been
suggested (e.g. Beverton and Holt type, Ricker type and many variations on these). Like Rothschild
(1986) I believe that further insight into the problem requires a more detaild look at mechanisms
operating at the different life stages. As pointed out by Paulik (1973) and Rothschild (1986), a stock-
recruitment function R=f(S) can be written in the form $R = f_3\{f_2 [f_1(S)]\}$ where f_1 might be the egg
production as function of spawning biomass, f_2 larval production as function of egg production and
f_3 number of recruits as function of larval production. Ulltang (1984), in a simulation model
developed to describe a cod population, decomposed the recruitment function into two parts, the first
part represented by a Berverton and Holt type transition from spawning biomass to number of 0-group
and the second part by a Ricker type survival function ae^{-bP} from 0-group to recuitment, letting P be
the part of the recruited stock feeding on juveniles (which generally will be different from the
spawning stock) to take account of cannibalism.

Splitting Rothschilds (1986) 3rd transition (larvae → recruitment) into two parts, the following major
problems can be separated:

a)   What determines population fecundity (total egg production)?
b)   What are the size and causes of variations in survival from
      - eggs to larvae
      - larvae to 0-group
      - 0-group to recruitment age

Rothschild (1986) used the coordinate system of diagrams suggested by Paulik (1973) for discussing the dynamic behaviour of a multiple-life-history-stage model:
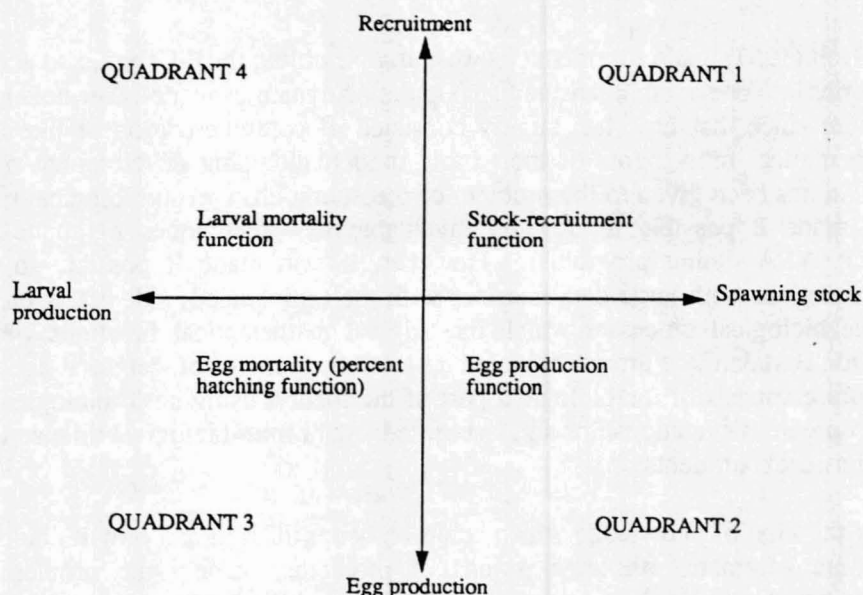
If the functions in quadrants 2, 3 and 4 can be drawn, one can start with the size of the spawning stock and get the resulting egg production, larval production and finally recruitment. The starting point (spawning stock) and end point (recruitment) determine the stock-recruitment function in quadrant 1.

For the purpose of the present paper, I will use this diagram in a slightly different way. Let all quadrants, including quadrant 1, represent transitions in a clockwise direction. Quadrant 1 then represents the transition from recruits to spawners, and the life cycle is completed. Further, let us no longer be bounded by a coordinate system for numerical representation, but look on the quadrants or more generally sectors of a circle as parts of the life cycle with their different processes (with very different time scales).
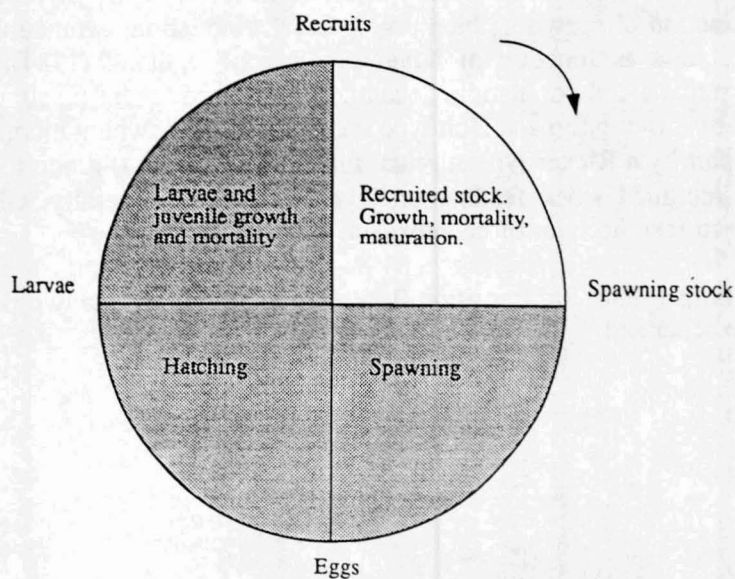
ICES stock assessments as basis for management advice have to a large extent been concentrated on the processes in quadrant 1. The discussion of the large shaded area (quadrants 2-4), if discussed at all, usually has been limited to give a stock-recruitment plot with some (usually inconclusive) comments. I propose to attack the stock-recruitment problem in the stock assessment process by gradually trying to expand the white (or rather "enlightened") area in both directions utilizing existing or attainable knowledge.

As noted by Rothschild (1986), egg production is largely a property of the fish, whereas egg-and-larval mortality is largely a property of the oceanic environment. Further, the "environment" of the adults is quite different from the "environment" of eggs and larvae. These facts, with the addition that

a)   egg-and-larval mortality may to some extent be influenced by maternal effects,

b)   the "environment" of juvenile fish is quite different from the "environment" larvae are exposed to, and juvenile fish growth and mortality could preferably be assessed in an expanded model for the recruited stock in cases where the "conventional" age of recruitment is high,

could be a useful starting point for considering such an expansion of the "enlightened" area or reduction of the shaded area.

I will illustrate this by returning to the Northeast Arctic cod. It should first be noted that for this stock even the estimation of spawning biomass for the years covered by VPA creates large problems (lack of maturity ogives, resulting age compositions and mean weights), and further insight into the stock-recruitment relationship is dependent on the success of getting the lacking data from a new look on the biological time series.

Concerning the spawning stock-egg production problem, substantial work has been done on the problem of estimating fecundity as function of age, size and condition of the cod (Kjesbu, 1988; Kjesbu et. al., 1991). If agreed as an important task, it should be possible both to estimate egg production for part of the historical time series and to establish relationships for predicting egg production for coming years, thus expanding the assessment model to include quadrant 2.

For this stock, work has also been conducted on possible maternal effects on egg quality influencing egg- and larval survival (Kjesbu et. al., 1992; Solemdal et. al., 1992; Solemdal et. al., 1992; Solemdal and Kjesbu, 1992). This puts on the agenda the possibility of elucidating some processes in quadrants 3 and 4 as function of the composition of the spawning stock.

Let us now move to the possibility of expanding the "enlightened" area in the figure above in the other direction. The recruitment age of cod in the assessment model presently applied is 3 years. Survival of age groups 2 and 1 should not be mixed into the stock-recruitment problem but included in the model for the recruited stock, modelling to the extent possible the different components of mortality (cannibalism, predation from others, discards etc.). Also survival of 0-group may be considered to be removed from the general stock-recruitment problem.

The figures below illustrate the suggested expansion of the assessment model ("enlightened" area) and reduction of the stock-recruitment problem (lightly shaded or partly "enlightened" area).

Present situation
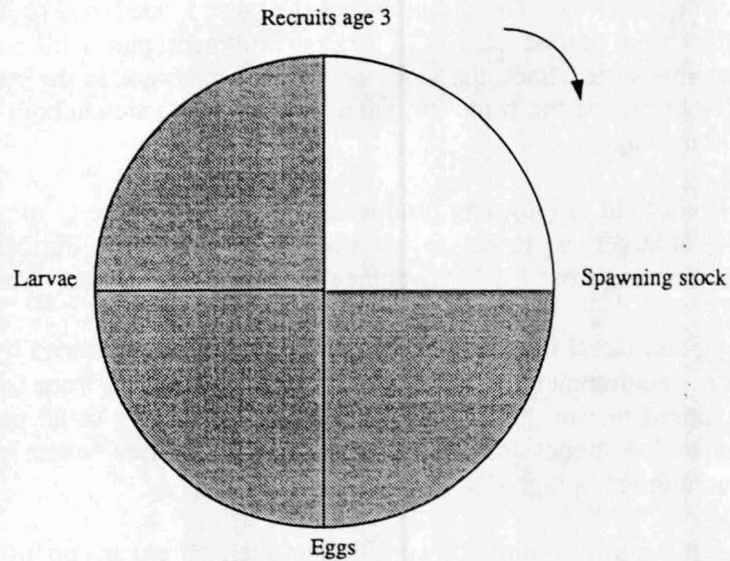
Expanded assessment model
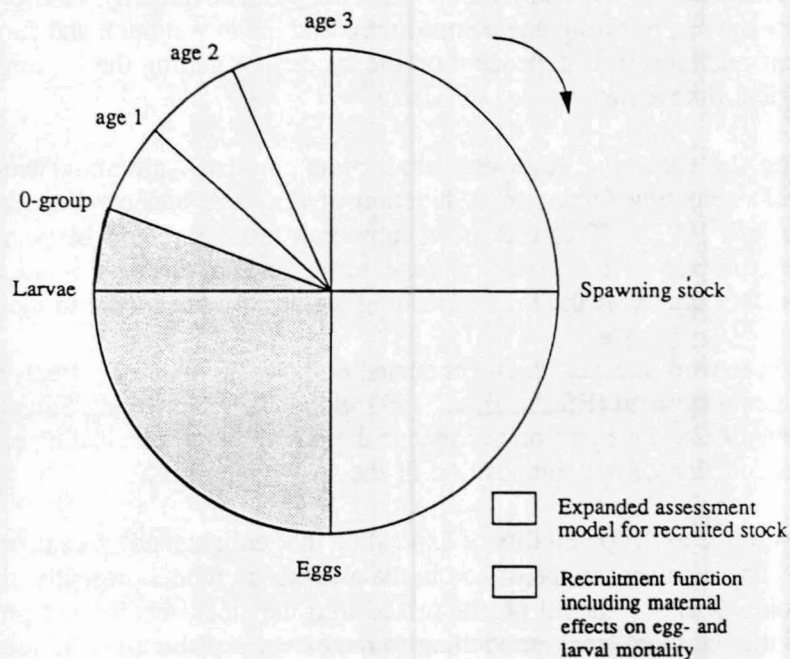
If successful, this procedure would isolate the most difficult part of the stock-recruitment problem, i.e. egg-and-larval mortality as mainly a function of the oceanic environment, modelling to the maximum possible extent processes directly connected with properties of the parent stock and processes more connected with the "environment" of the recruited stock than "environment" of eggs and larvae. A plot of number of 1-group (or 0-group) against egg production will certainly show a considerable scatter and estimates of 1-group (or 0-group) and egg production will have errors. However, a part of the scatter in traditional plots of number of 3-years old cod versus parent stock may be explained and the rest of the scatter will be more informative with respect to the size of the effects of variations in oceanic environment on egg-and larval mortality. This would prepare the ground for refinements

of studies of possible causal relationships between egg- and larval mortality and environmental factors, i.e. studies like the ones reported in Sætersdal and Loeng (1987) and Ellertsen *et. al.* (1989). The role of maternal effects on egg- and larval mortality may be approached by splitting the egg production by age groups and/or first time spawners - repeat spawners. The research effort needed for modelling this system would be considerable, but small compared to the effort already used for establishing the basic biological knowledge. In the context of risk analysis, risks assosiated with high exploitation rates would be more realistically estimated when incorporating maternal effects if recruit spawners are "low quality" spawners.

3.3 The problem of predicting natural mortality.

For one component of natural mortality, namely predation mortality, there are in many cases possibilities for getting estimates of likely values or indications of whether it will increase or decrease from an assumed average level the first coming years. This could be of critical importance for assessing short lived species where predation mortality is high or recruitment to the fishable stock of more long lived species where cannibalism or predation from other stocks generate a variable and, in at least some years, high mortality.

Predation mortalities are best assessed in multispecies models. However, this does not imply that improvements in our assessments can not be achieved before a multispecies model has reached a stage where it is tested and documented to an extent which has made it generally accepted as basis for managment advice.

One simple approach is to utilize the analogy between the relation of fishing mortality (F) to fishing effort (f), $F = qf$, and the natural mortality M^* generated by a predator stock P^* on a prey stock P as function of P^*, $M^* = q^*P^*$, as discussed by Beverton (1985) in the context of marine mammals predation on fish. Considerations which have been made on the formulation $F = qf$ apply to a very large extent to $M^* = q^*P^*$. As noted by Beverton, over a moderate range of relative abundance of P^* and P, $q^* = M^*/P^*$ can probably be treated as effectively constant. At for example low levels of prey, or of the prey-predator ratio, two alternative responses may appear: Specialist feeders, trying to maintain their daily ration, may generate a higher mortality (increasing q^*), analogous to the relation $q = kN^{-b}$, $N =$ fish stock abundance, which has been demonstrated for some purse seine fisheries on pelagic stocks (Ulltang, 1980), whereas opportunistic feeders may turn to a more abundant prey stock (decreasing q^*).

General knowledge on feeding behaviour and diet together with abundance data on alternative prey stocks may in each particular case be used to hypothesize the likely response, and stomach sampling programs may provide test data.

Approaches as the one applied by The Atlanto-Scandian Herring and Capelin Working Group (Anon., 1993c), using the data in a cod stomach data base together with assessment data on cod to predict predation mortality on prespawning capelin, should be encouraged. A further step would be to use cod-capelin models (Tjelmeland and Bogstad, 1993) to calculate mortalities, utilizing results from multispecies modelling work.

With reference to the example in section 2 and the discussion of the problem of predicting recruitment in section 3.2, the possibility of changing the age of recruitment in the ICES assessment model for Northeast Arctic cod to age 1 should be seriously considered. In such a model, predation mortalities on age groups 1 and 2 could be made dependent on predicted abundance of older cod and its alternative prey species.

In the North Sea, application of results of the multispecies VPA model has been limited mainly to undertake an upward adjustment of average mortalities on young fish. There are important differences between the North Sea and Barents Sea situation with respect to both complexity of the ecosystems and data collection programmes. However, the potential information content of the data collected for the North Sea goes probably far beyond their present use and also for this area short term prediction of mortalities for some of the species should be considered.

3.4 The problem of predicting growth and maturation

The importance of realistic assumptions on fish growth was clearly illustrated by the situation in the Northeast Arctic cod in the latter half of the 1980s. The failure of the stock projections was due to a combination of overestimating both the strength of recruiting year classes and the individual growth. Mehl and Sunnanå (1991) show that the unexpected low growth was closely correlated with decreased individual food consumption following the collapse of the capelin stock.

Also for Icelandic waters (Magnusson and Palsson, 1991; Steinarsson and Stefansson, 1991) strong indications have been found that capelin biomass affects cod growth. Of special interest in the present context are the results given by Steinarsson and Stefansson (1991), indicating from a formal statistical analysis of the basic effects the possibility of using capelin biomass as an explanatory variable for predicting cod growth. This is an excellent example of what kind of relationships one should look for, giving if established a prediction with associated error distribution which is conditional on the (predictable) state of some other parts of the ecosystem or (partly predictable) abiotic factors (e.g. temperature).

Another example of studies which should be followed up is found in Skjoldal et al (1992), where the complex and intricate relationships which exist between ocean climate variability as a primary driving force, zooplankton stocks, and growth rate and population dynamics of capelin are discussed for the Barents Sea, concluding that "only through insight into the basic mechanisms can such relationships be properly described and used for predictive purposes".

Maturation is closely linked to growth, which can affect both age and size at maturity (Rothschild, 1986). The relationship between growth and age and size at maturity has to be established for each stock separately. The extent to which the relationship between feeding conditions, growth rate and maturation may vary between species and even between stocks of the same species was illustrated by the results of Oosthuizen and Daan (1974), indicating that for North Sea cod better feeding conditions had resulted in maturation at a smaller length but with no change in growth rate, contrary to the usually expected mechanism of increased growth rate. Both mechanisms, however, result in maturation at an earlier age.

Data for undertaking an analysis of possible relationships are probably available for a lot of fish stocks in the ICES area. That the number of cases where a relationship has been established and used is relatively small does probably not reflect that relationships do not exist.

4. Predictive relationships and empirical content of risk analysis. Concluding remarks.

Our aim is to give true statements about future events with as high *empirical content* as possible. The more a statement excludes of possible outcomes, the higher is the empirical content (see Popper, 1959). Going back to the example (Fig. 1), one of the problems with the 1986 assessment of cod was that survey indices and established relationships between such indices and year class strength gave

wrong predictions, since no account was taken of the unusual state of the ecosystem. Having now the observations for the 1984-1986 year classes and including them in the regressions, predictions of future year classes with appropriate confidence limits may include the true (realized) values with very high probability. However, the empirical content of our statements will decrease with wider confidence limits. To be sure that all possibilities are included in our management advice, its empirical or informative content may decrease towards what can be read from a table of historical total catches.

The alternative is to try to use additional information with predictive content. If we for example in 1993 know that the situation is quite different from that in 1986 and that there is no evidence for expecting extraordinary high mortalities on young cod in the immediate future, the 1984-86 points in Fig. 1 should not be included when estimating year class strength and risks or (better), a multivariate analysis including variables characterizing the state of the ecosystem should be attempted.

Generally, when using simple regressions based on historical data series, these give predictions with error distribution valid under the assumption that variables not included but possibly influencing the parameter we try to predict will vary as over the historical time series. Our biological knowledge should be used to establish predictions conditional on the value of such variables if these themselves are known or, at least partly, predictable. This would increase the reliability of our predictions and empirical content of our risk assessments.

Realizing the conjectural character of trying to explain fish stock variability and predicting future events, it is tempting to limit our activity to describe what we observe and refrain from attempts to exclude any part of the range in earlier observed values of vital parameters in our predictions. Progress in science is, however, dependent on a certain amount of boldness in formulating explanatory theories. In our field, the possibility of ourselves designing crucial experiments is limited. The initial conditions of the large scale "experiments" in nature are to a large extent given. But competing theories will as a rule give different results, and some of the results we can observe, and have observed over decades, together with a subset of initial conditions. Our task is to formulate these theories, re-interpret earlier observations, re-design collection of new observations, and gradually progress through conjectures and refutations.

This paper originated from the recognition that a large amount of biological knowledge potentially useful in a stock assessment - management context remains unused. I have offered some thoughts or examples on how this knowledge could be more effectively used, but no detailed recipes can be given. Ample thoughts should also be given to the question of how to organize the assessment work to create conditions for better utilization of such knowledge. The present practice is characterized by a too sharp *de facto* separation of stock assessment experts and experts within various fields of marine biology. For a better understanding of fish population dynamics we need persistingly to look for the mechanisms behind the observations. Stock assessment and management advice could greatly benefit from a closer regular communication with scientists working in more basic projects within marine fish biology.

"So we can now admit, without becoming essentialists, that in science we always try *to explain the known by the unknown*, the observed (and observable) by the unobserved (and, perhaps, unobservable)" Karl R. Popper.

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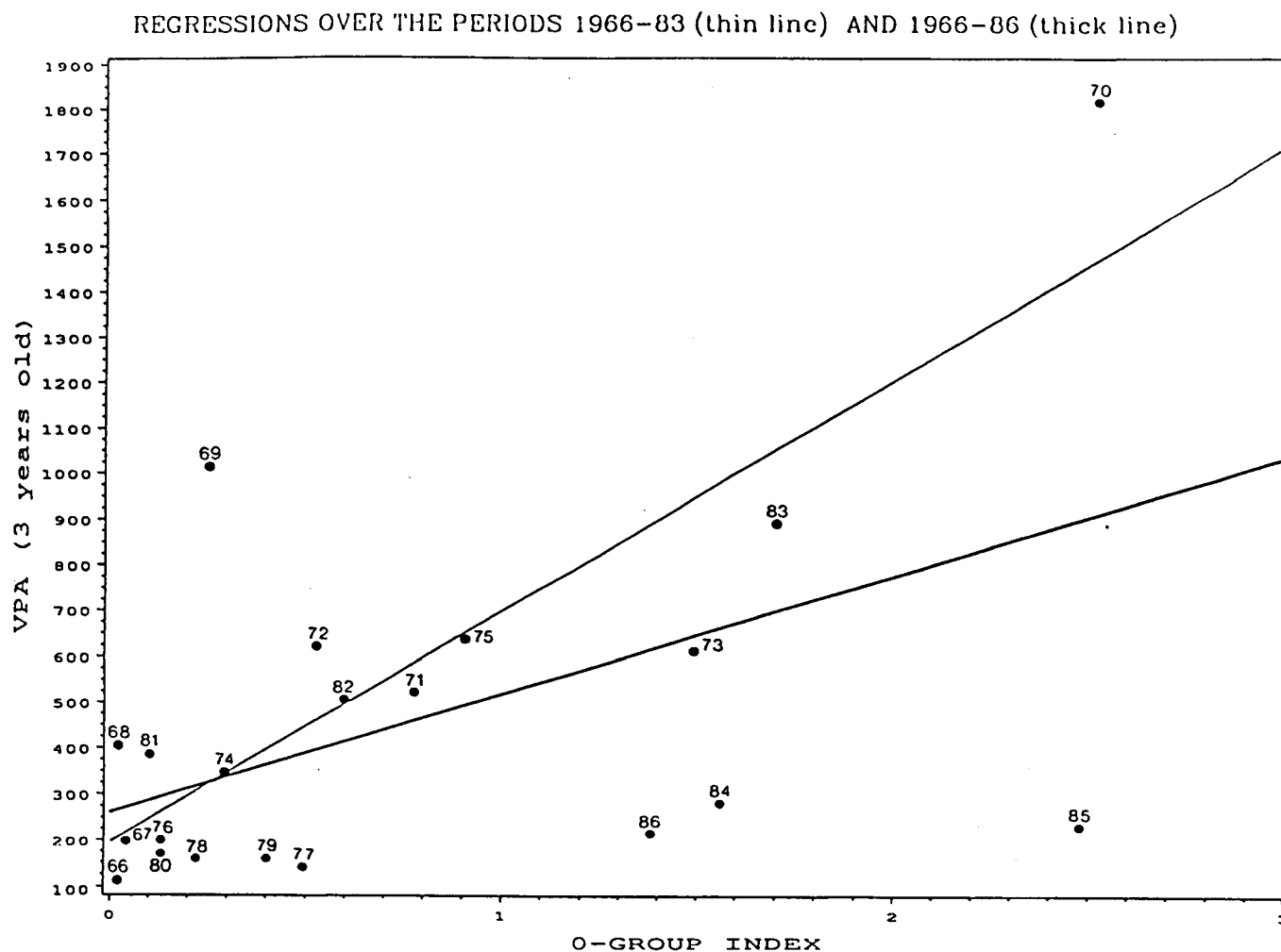
REGRESSIONS OVER THE PERIODS 1966-83 (thin line) AND 1966-86 (thick line)

Figure 1. Northeast Arctic cod. Plot of year class strength estimated by VPA as 3 years old cod (millions) against 0-group index.