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THE LEGACY OF BEVERTON AND HOLT

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Abstract

Beverton and Holt's yield per recruit models provide the rules by which many of the world's greatest fisheries are managed. Despite successes in rebuilding depleted stocks, profitability of fishing enterprises remains low. Efforts now underway to increase the economic efficiency of the fisheries will require new models and analyses.

Quota licensing has been proposed as a means of improving economic performance of the fisheries on Canada's west coast. A simple model for the national economic behaviour of individual fishing enterprises is presented. Analysis of this model suggests that quota licensing will cause excessive reductions in harvesting capacity, producting quota shortfalls.

Fisheries have historically failed to behave as predicted by the simple models used in policy decisions. Thus management organizations must monitor key policy variables. The variables currently available for monitoring are, unfortunately, limited to those which were important for conservation oriented policies. The inability of existing information systems to accomodate change can be traced to constraints imposed by the primitive computational tools available to Beverton and Holt. Change will be slow due both to the

size and complexity of management organizations and to the reluctance to tamper with machinery which has been successful in meeting conservation goals. Future information systems should be designed to satisfy the requirements of a general model.

Introduction

There are few places where mathematical models have a more direct influence on the lives of ordinary men and women than in the fishing communities of Nova Scotia and Newfoundland. These people live by what they can take from the sea, and what they take is, in law if not always in practice, regulated. In Atlantic Canada, as in many jurisdictions, catches are controlled using yield per recruit models.

The acceptance of these models as a basis for management is due, in large part, to a book entitled "On the Dynamics of Exploited Fish Populations" by Beverton and Holt (1957). This remarkable work combines sound ecological principles with a practical framework for generating quantitative results. Where the prescriptions of their theories have been followed, depleted stocks have indeed recovered.

The legacy of Beverton and Holt is an evolving collection of mathematical models and (sometimes heuristic) solution procedures. Over the years many of the specifics supplied by Beverton and Holt have been modified or replaced, but always in concert with the authors' original aims. This may be viewed either as a tribute to their vision or evidence for resistance to change by the institutions which use these models.

Conservation was the dominant concern of fisheries managers in 1957. Today, however, needs of fishermen have come to the forefront.

Canadian fisheries managers are not faced with many of the constraints which prohibit effective management in other jurisdictions. There has been success in obtaining rebuilding of stocks which had become depleted during the 1960's and early 1970's. The goal of economic efficiency, a Canadian policy objective since 1976 (Fisheries and Marine Service 1976), has, however, proven elusive. In 1981 the present Departemnt of Fisheries and Oceans initiated major policy reviews of the fisheries on both the Atlantic and Pacific coasts.

These reviews have concentrated on economic issues. The final report of the Commission on Pacific Fisheries Policy (Pearse 1982) recommends sweeping changes in policies involving licensing and allocation of the harvest, but few changes affecting the way in which harvest levels are determined. The key issues identified by the Task Force on Atlantic Fisheries (1982) are likewise economic in nature, and the policy options being considered do not include changes in mechanisms for determining allowable catches.

The majority of commercial fish species in Atlantic Canada are managed by catch quotas. The fisheries managers who set quotas receive advice on scientific matters from the Canadian Atlantic Fisheries Science Advisory Committee (CAFSAC). In practice the advice of this committee relies heavily on the models and methods of Beverton and Holt.

New policies intended to improve the economic performance of fisheries will place new demands on fisheries management organizations. Fisheries scientists will be required to advise on matters which they have not previously considered. This paper will try to anticipate some of these new concerns and the changes which will be required to meet them.

The body of the paper is divided into two parts. The first part recalls the historical development of theoretical models whch have governed policies for fisheries management. The second part focuses on the demands placed on operational management by policy. The system for determining quota advice will be described in greater detail. A specific proposal for economic rationalization will be examined using a simple microeconomic model. This analysis suggests a fundamental principle: the scales appropriate for the study of different classes of phenomena do not, in general, coincide. In terms of the fisheries, this translates into an urgent need to refine the scales of spatial and temporal aggregation used by current operational models. It is a tribute to the quality Beverton and Holt's vision that this will not require new models.

Policy Models

Fisheries policies are ultimately created by political decisions. While mathematical models seldom play a direct role in such decisions, they are useful in describing the logic which motivates a particular policy.

The key variables which enter into discussions of fisheries policy are the resource biomass, x, a biological measure of effort, E, and a measure of the efficiency of harvesting, q. In the early years, effort was measured in units of time. In order to discuss economic performance, an economic definition of effort is required. When measured in monetary units the symbol for effort will be E', and for the corresponding efficiency, q'.

The basic models employed in discussions of policy are obtained from the following system.

$$\frac{dx}{dt} = x f(x) - H$$

$$\frac{dE}{dt} = g(R - C)$$

$$\frac{dE'}{dt} = g'(R' - C')$$

$$\frac{dg}{dt} = k$$

$$\frac{dg'}{dt} = k'$$

where

H = rate of harvesting

= qEx = q'E'x

R = total revenues = price x H

C = total costs = cE = E'

k = a constant (often 0).

It is further assumed that

$$f(x) \begin{cases} < 0 & 0 < x < x_0 \\ > 0 & x_0 < x \end{cases}$$

$$g(0) = 0$$

$$g'(0) > 0$$

There have been three fundamentally different periods in the development of fisheries policy models (Table 1).

Table 1. Historical periods in the evolution of fisheries policy.

open access (1930-1950)

characterized by efforts to encourage development; research centers on vessels, and catching methods.

conservation (1950-1980)

characterized by efforts to reduce catches; research centers on sampling and parameter estimation.

economic rationalization (1980-?)

characterized by efforts to increase efficiency (q').

Modelling of fisheries policy during the open access era was concerned primarily with the decline of stocks as effort expanded. The discussion of bionomic equilibria presented by Clark (1978) summarizes the essential concerns of this period. Changes in q and q' were generally ignored. In fact, both q and q' probably increased (k and k'> 0) during this period, thus accelerating the decline of the resource (Figure 1a).

Recovery of North Sea stocks which had not been fished during the war provided convincing evidence that controls on fishing could reverse the decline. This marked the beginning of the conservation era. In terms of the general policy models being considered here, quota management simplifies the model by making effort a function of Q, x, and q:

$$E = \frac{Q}{xq}$$

$$E' = \frac{Q}{xq'}$$

Again, it was assumed initially that q and q' would not change. It is clear that the expected increase in the resource could be harvested with a much reduced biological effort, E. In retrospect, however, it was politically impossible to reduce participation in the fishery while stocks were increasing. A more realistic model for quota management would allow E' to change, while assuming that q' satisifies

$$q' = \frac{Q}{xE'}$$

(Figure 1b). Then

$$(1) \qquad \frac{dq'}{dt} = -\frac{Q}{(xE')^2}\left(E'\frac{dx}{dt} + x\frac{dE'}{dt}\right)$$

Suppose the system was initially at a bionomic equilibrium $(\bar{x}, \bar{E}')$, where

$$\bar{E}' = \frac{f(\bar{x})}{q'}$$

$$\bar{x} = \frac{1}{pq'}$$

and Q is chosen somewhat smaller than $\bar{H} = q'\,\bar{x}\,\bar{E}'$. Then the right side of (1) involves the sum of a positive term representing the growth of the stock and a negative term representing the decline of effort due to reduced revenue. Events have shown that introduction of restrictive quotas resulted in a decline in revenue to individuals and organizations involved in fishing. This created political pressure for compensatory measures. The result was that E' tended to remain constant, and q' declined, as the stocks rebuilt.

Policy debates in recent years have concentrated on ways to reverse the decline in economic efficiency. The expected behaviour is illustrated by Figure 2c.

The preceding discussion has, for the sake of brevity, omitted much of the debate concerning the criteria used to determine the quota Q. These discussions (Roedel, ed. 1975; Larkin 1977; Cunningham 1981) are important because they expose the issues with which policy makers were concerned. For our purposes, however, it is important to note that fisheries have shown a perverse disregard for models and that policies do not respond quickly to unexpected behaviour.

Scientific Advice

Yield per recruit models are used by CAFSAC scientists to provide quantitative recommendations for quota levels. The primary mandate of CAFSAC, as given in its terms of reference, reads:

> CAFSAC is responsible for providing scientific advice to the Atlantic Directors-General Committee on the management, including the full range of conservation measures taking into account economic objectives, of all stocks of interest or potential interest to Atlantic coast fishermen. Resource management advice will be provided in accordance with specific fisheries management objectives and strategies and will normally be published as a matter of routine. (CAFSAC 1982).

The specific objective of management has, in recent years, been a gradual rebuilding of fish stocks. The strategy involves, among other measures, catch quotas. CAFSAC has been asked to estimate the catch which would produce an $F_{0.1}$ (Gulland and Boerema 1973) level of fishing mortality. By definition, $F_{0.1}$ satisfies

$$\left.\frac{dY}{dF}\right|_{F_{0.1}} = 0.1 \left.\frac{dY}{dF}\right|_{0}$$

where Y(F) is the yield per recruit. For most stocks $F_{0.1}$ is comparable to estimates for M, the natural mortality. When a stock is very low CAFSAC will advise a smaller quota, but quotas are generally set at the $F_{0.1}$ catch. In practice, then, this strategy is remarkably like that suggested by Goh (   ).

Despite the economic rationale provided by Gulland and Boerema, the decision to use $F_{0.1}$ as a reference level of fishing mortality was make on pragmatic grounds. An important advantage of the $F_{0.1}$ criterion is its nearly linear response to parameter variation, in sharp contrast to the nonlinear response of F_{MAX} (White 1983a).

Beverton and Holt were writing for an audience with limited mathematical ability and rudimentary calculating machines. These constraints forced them to make many compromises in their analyses (S.J. Holt, personal communication). In describing yield per recruit modelling as it is used today it will be useful to start with a formulation of the model in terms of a conservation law:

$$(2) \quad \frac{\partial N}{\partial t} + \frac{\partial N}{\partial a} + \frac{\partial\, g(w) N}{\partial w} = -MN - \frac{dC}{dt}$$

where N(t,a,w) is the population density at time T, age a, and weight w, g is the growth rate, M the per capita rate of natural mortality, and $\frac{dC}{dt}$ the rate of death due to fishing. Recruitment at age a_0 is specified through a boundary condition:

$$N(t,a_0,w) = N_0(t,w)$$

In practice it is assumed that recruitment is concentrated at one year intervals and, after a certain stage in the analysis, that weight is a function of age. An important innovation since 1957 is the use of age-length keys. An age-length key is a double frequency:

$$n(t,a,w) = \frac{N(t,a,w)}{\int_0^\infty \int_0^\infty N(t,a,w)\,da\,dw}$$

These may be constructed directly from sampling data, and are used at a variety of steps in the development of quota advice.

Solving (2) by the method of characteristics yields, for each cohort defined by the time of recruitment:

$$\frac{dN}{ds} = -MN - \frac{dC}{ds}$$

$$(3) \qquad \frac{dw}{ds} = g(w)$$

with initial conditions at s = 0 given by

$$N(0) = N_0(t_0, w_0)$$
$$w(0) = w_0$$

It should be noted that the forcing term $\frac{dC}{ds}$ presents serious technical problems because it cannot be observed. In practice it is estimated from the model:

$$\frac{dC}{ds} = FN$$

where F is assumed precewise constant and the observable is an accumulation:

$$C[a;b] = \int_a^b \frac{dC}{ds}\,ds$$

The interval for accumulation is generally one year. This choice was necessary in the days of manual calculation, but introduces errors which are not tolerable now that the calculations can be automated (White 1982b).

From the practical standpoint, the characteristic solutions (3) have the important advantage that processes of growth, mortality, and recruitment can each be analyzed separately.

The system required to make this model work can be divided into four main activities. These do not necessarily correspond to organizational boundaries. Each activity involves a different academic discipline, as shown in Table 1, and in more detail in Figures 2 a-d. Beyer and Sparre (1982) discuss some of the procedures which have been developed since 1957, but many have not been published except as working papers.

Space does not permit a complete discussion of Figure 4. It is, however, important to note that many classes of data are used for non-scientific purposes such as quota monitoring and enforcement, and may be inaccurate or incomplete if fishermen are concealing illegal fishing activities. The presence of a biological observer may alter fishing patterns. Each data item passes through many hands, so there are many opportunities for error and misunderstanding. It is difficult, in such a system, even to ensure that basic quantities are defined in a consistent way by all individuals involved.

The procedures of the synthesis (Figure 4d) are descended directly from those of Beverton and Holt (1957). Some of the most important changes to the original theory are:

1. the use of sequential population analysis to estimate historical abundance,
2. the $F_{0.1}$ criterion, and
3. the calculation of the catch which would produce an $F_{0.1}$ fishing mortality.

This final step goes part way towards overcoming Beverton and Holt's reliance on steady-state solutions of their models, but may be inappropriate for some stocks (Sinclair and O'Boyle 1983).

Less apparent are the increasing use of statistical tools and automatic computing machinery. The size and complexity of this system makes it inevitable that irregularities will occur. Traditional statistical procedures are not appropriate for the analysis of many of the errors and distortions which occur in such systems (White 1983a,b,c).

The models used by CAFSAC bear little relation to the models used in policy analysis. The data requirements of a system which generates quantitative management advice have produced a complex and expensive apparatus which cannot respond quickly to changes in policies. Many aspects of the design of this system were dictated by the limited data management and calculating tools available to Beverton and Holt. In particular, aggregation in time and space reduces the volume of data which must be processed. This minimizes computational work and simplifies data transfers between different parts of the organization.

Table 2. Activities of the systems defined by the legacy of Beverton and Holt.

Activity	Discipline	Role
Sampling	Field Biology	collection of data
Data Management	Information Science	organize, edit, store and retrieve data
Analysis	Statistics	estimation of fundamental parameters from sampling data
Synthesis	Mathematics	calculation of results

Economic Rationalization

Usufructuary rights schemes are seen by many as an answer to the economic problems of the fisheries (Scott and Neher, eds. 1981). Pearse (1982) has proposed that a system of quota licenses be adopted for west coast stocks currently managed by quota. Under this system each license entitles the holder to harvest a predetermined quantity of a particular species in a specified area. The licenses are to be sold using a system of competitive bids so that their cost will be determined by the market.

A key tenet of microeconomics holds that a free market economy produces the same result as one which is perfectly managed. From this it can be argued that free markets are preferable because they place few demands on the management organization. Pearse (1982) proposes that the quota license system be administered by an independent board with no capability for data collection or analysis.

Implementation of a quota license policy requires that the fishing grounds be partitioned into licensing areas. Since most stocks are defined on an area basis for the purpose of determining quotas, these areas should be a refinement of stock boundaries. It can be argued that many stocks should be split into several quota license areas. If this is not done fishing effort will be concentrated in the most profitable areas, leading to overcrowding of port and processing facilities while similar facilities in other areas lie idle.

To understand the implications of this quota license policy it is necessary to model the behaviour of an individual fishing enterprise. The analysis presented in this paper is designed to explore the kinds of information that will be needed from biological models. Although the actions of fishermen may not always be rational, a model for rational decision making would be expected to involve more

kinds of relevant information than are actually used, and is therefore suitable to the task at hand. Furthermore, constrained decisions can ignore information which is irrelevant in the face of a constraint. Thus many constraints which might be important in practice can safely be omitted from the following discussion.

A standard model for rational decision making in the presence of uncertainity is the maximization of expected utility (Luce and Raiffa 1957). In this model a decision, $\underline{\delta}$, produces a net return, $r(\underline{\delta}, \omega)$, where ω is a random variable representing the state of nature. In the case at hand, $\underline{\delta}$ will be a vector of fishing efforts, $\underline{\delta} = (E_1, \ldots, E_n)$, and

$$r(\underline{\delta}, \omega) = \sum E_i \rho_i(\omega)$$

where ρ_i is the net rate of return. This depends on the market price of rights in category i as well as many uncertain elements, including weather, equipment failure, catch rates, availability of labour, fuel prices, markets, and others.

The utility of a particular net rate of return will be denoted by $u(r)$. The decision rule stated above implies that a decision $\underline{\delta}_1$ is prefered to $\underline{\delta}_2$ if

$$E[u(r(\underline{\delta}_1, \omega))] > E[u(r(\underline{\delta}_2, \omega))]$$

It will be assumed that $u(r)$ is monotonic increasing and concave. Then, by Jensen's inequality,

$$(4) \qquad E[u(r)] \leq u(E[r])$$

Equality holds in (4) if the return is certain. Thus, no other decision with the same expected rate of return can improve upon a decision with a sure return. This raises the possibilty that fishing enterprises may adopt strategic behaviour involving trade offs between uncertainty and expected returns.

One possibility for strategic behaviour under a system of quota licenses is purchase of a portfolio including rights to a variety of species and areas. Since profitability is likely to vary with species and area, this requires a sacrifice of expected returns for a gain in expected utility.

The advantage of spreading harvesting effort over a number of units stems from the reduced level of uncertainity and the concave shape of the utility function. In particular, if the units correspond to different geographic areas occupied by a single population with unpredictable distribution, declines in abundance in one area must be accompanied by increases in other areas. By fishing in all areas that may be occupied, a fisherman is assured of finding fish. This idea is illustrated in the following example.

Example

It is assumed that a stock has been divided into two quota license areas, but in any given year is abundant in only one of these areas. Let x_i be the return from harvesting operations (price received less cost of capture) and h_i the number of quota units purchased by a particular enterprise for the ith license area (i = 1,2). $x_1 = 1-x_2$ is assumed to be a coin-tossing game with values 0 or 1,

and the enterprise is assumed to have a maximum capacity of $H \leq 2$ units. The net return is:

$$r = x_1 h_1 + x_2 h_2 - p(h_1 + h_2) - cH$$

where p is the price established by the market for a quota unit and c the cost of harvesting capacity. The decision vectors $\delta = (h_1, h_2, H)$ and associated returns are listed in Table 3.

Since $x_1 + x_2 \equiv 1$,

$$E[u(r(1,1,2))] = u(1-2p-2c)$$

Suppose that this zero risk decision is optimal. Since the fishery cannot exist with negative net return, the market price p must satisfy

$$0 < 1-2p-2c$$

Recalling (4), the other decisions yield

$$E[u(r(0,1,1))] \leq u(\tfrac{1}{2}-p-c)$$

$$E[u(r(0,2,2))] \leq u(1-2p-2c)$$

Since the decision (0,2,2) can do no better than the decision (1,1,2), it (together with (2,0,2)) may be rejected. The decision (0,1,1) might

Table 3. Decision vectors and returns for an enterprise fishing a stock with two quota license areas. Brackets enclose decisions having identical expected returns.

Decision	Return
h_1 h_2 H	$r(h_1,h_2,H)$
0 1 1	x_2-p-c
1 0 1	x_1-p-c
1 1 2	$x_1+x_2-2p-2c$
⋮	⋮

Decision	Return
0 2 2	$2x_2-p-2c$
2 0 2	$2x_1-p-2c$

be considered when $0 > 1-2p-2c$, but this contradicts the assumption of profitability. Thus the decision (1,1,2) is an expected utility maximum. Actually, it is possible to improve profitability if harvesting capacity can be reduced to the single unit which yields a positive return. This analysis appears to contradict a statement of Pearse (1982, p. 91) to the effect that investment in the purchase of quota rights is an incentive to exercise these rights, and points out a serious weakness in the proposal for quota licensing. It should, however, be noted that Pearse (1982) has recommended that consideration be given to an insurance system. By reducing uncertainties this could encourage fulfillment of quotas.

Failure to modify the quota licensing system so that quotas are fulfilled could have disastrous consequences. Rationalization necessarily implies loss of jobs. As the example shows, quota licensing may go beyond rationalization and cause excessive reductions in harvesting capacity. Furthermore, treaty obligations may require that unused quota allocations be made available to other countries.

The preceding analysis shows one way in which a quota license market may have undesirable consequences for a fishery. If the management apparatus is unable to monitor the quota license market, problems which arise may be recognized late and their causes misunderstood.

This managment function will require data from the information processing portion of the advisory system. The preceding example suggests that these data must describe the distribution of a resource in space and time. This requires a reduced level of aggregation from that currently used in providing quota advice.

Discussion

Beverton and Holt have exerted a profound influence in the development of fisheries management. Their contribution was two-fold. Firstly, their yield per recruit models provided a practical basis for rational management towards conservation goals. Their second contribution was explicit procedures for estimating the model's parameters.

The strength of their first contribution lies in its sound theoretical foundations. Beverton and Holt were keenly aware that the limitations of the information processing machinery available in 1957 placed severe constraints on their analyses. Their second contribution suffers, consequently, from limited use of statistical procedures and, due to high levels of aggregation, cannot accomodate change.

Reductions in levels of aggregation are required not only to understand interactions between man and the fishery, but also between other components of marine ecosystems. The fundamental factor preventing reduced levels of aggregation is the need to transfer data between different parts of the management organization.

Today's technology makes possible a data processing system which is dedicated not to the requirements of a particular model, but to those of a generalized model. Such a system will not discard information, but be able to provide it at many levels of aggregation. It will include new kinds of information and will have the flexibility to accept change.

The impetus for the creation of such a system can come only from theory, for this will provide the foundation for future models. Theoreticians must work to establish generality and flexibility as goals ranking in importance with the requirements of current operational models.

Figure Legends

Figure 1. Expected (solid line) and observed (dashed line) trajectories for policy variables. Upper coordinate axes are biological coordinates, lower axes are economic.

a. open access (1930-1950)

b. quota management (1960-1980)

c. economic rationalization (1983-?)

Figure 2. Data flows for quota advice (as of November, 1982). Only major data flows are shown.

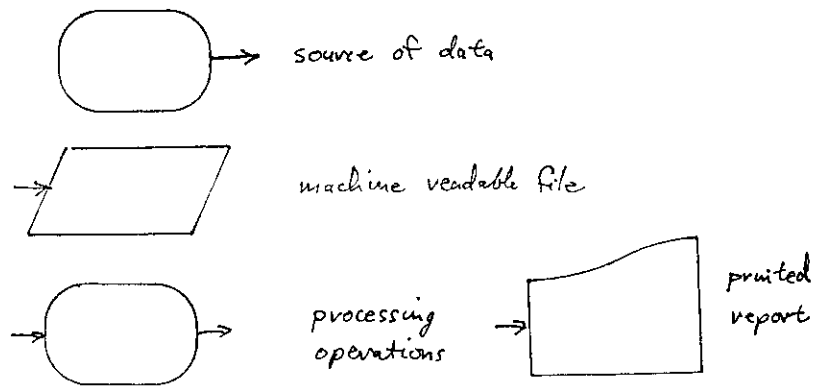
a. data collection (for details see O'Boyle and McMillan ms)

b. information storage and retrieval

c. analysis

d. synthesis (for details see White 1983b,c; Rivard 1982)

symbols for data flow diagrams:



(a)

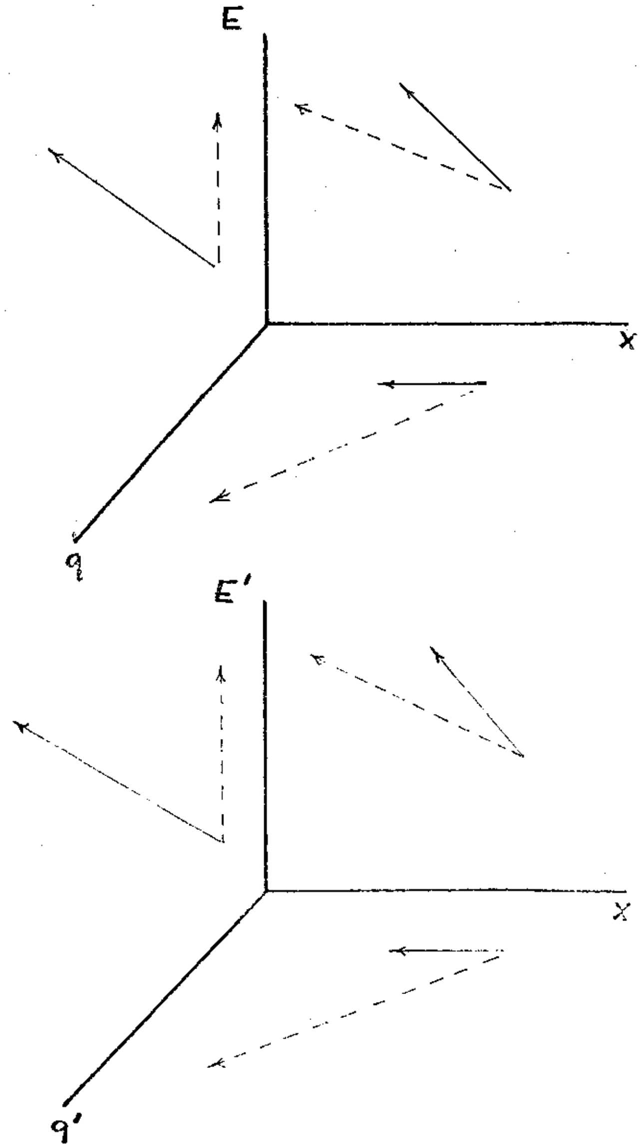


Figure 1

(b)

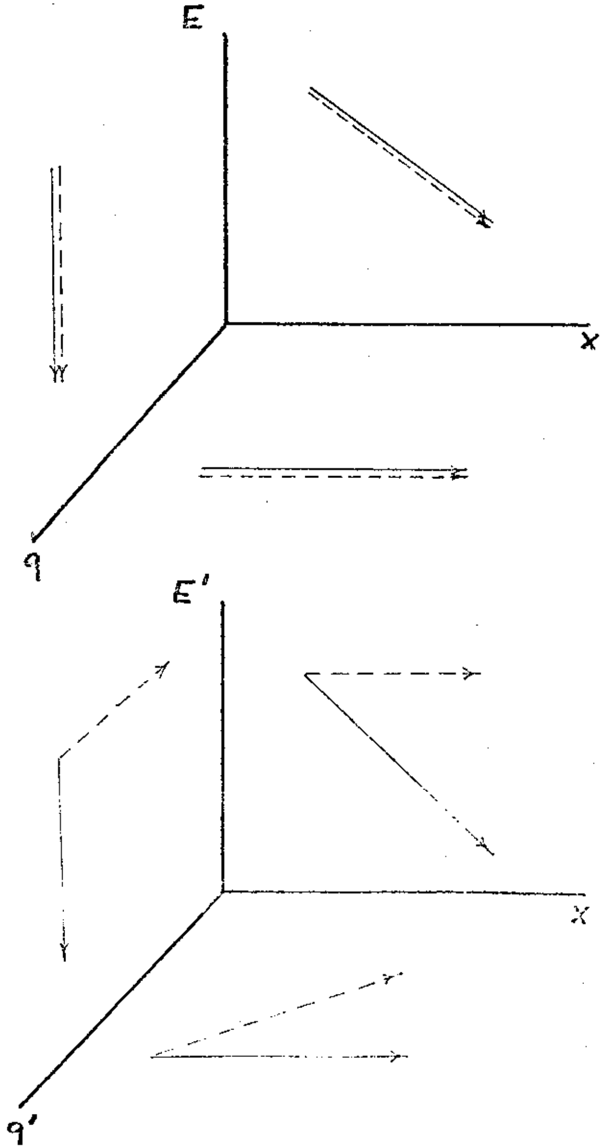


Figure 2

(c)

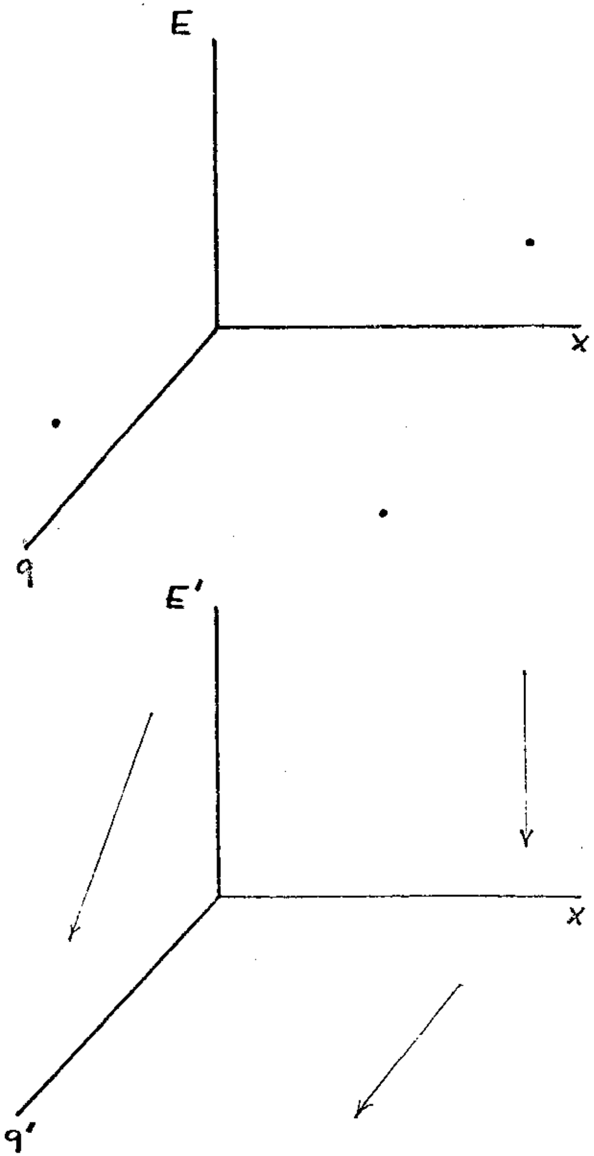


Fig. 3

(a)

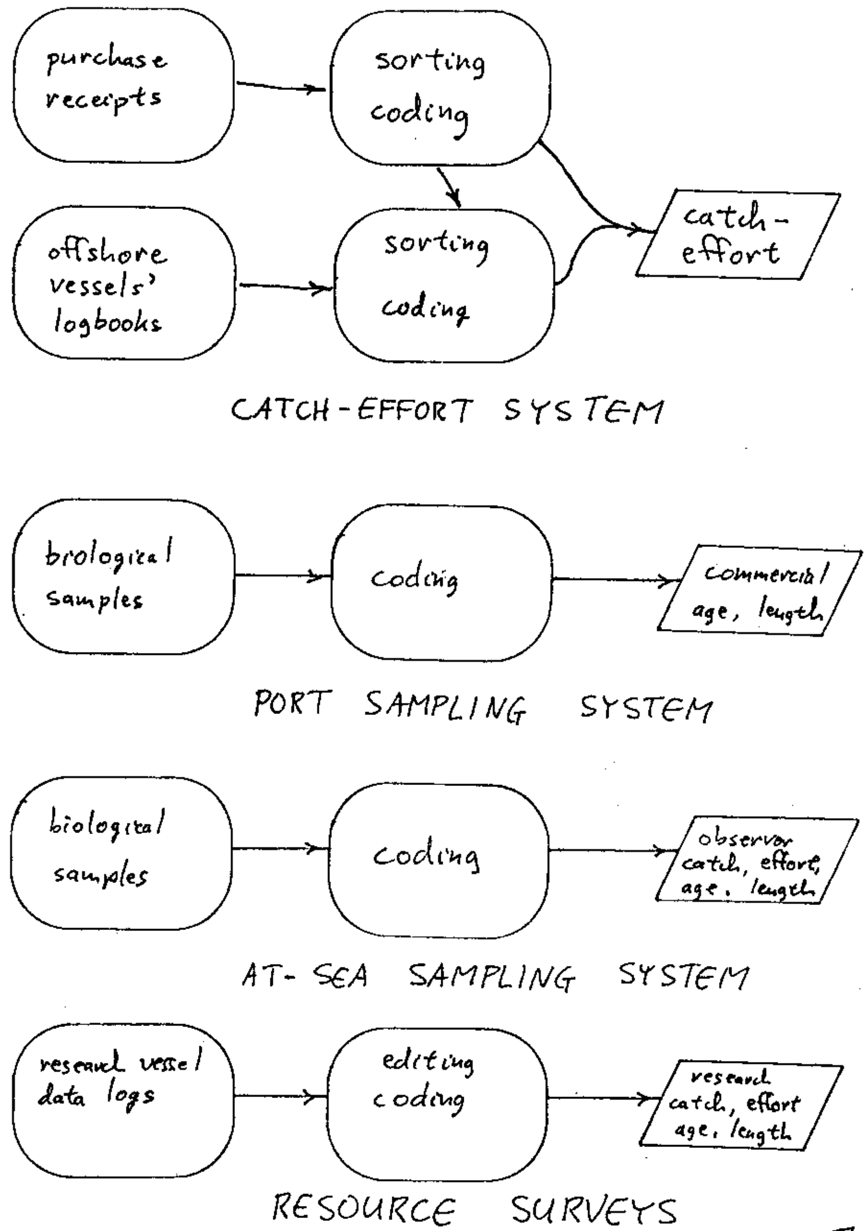
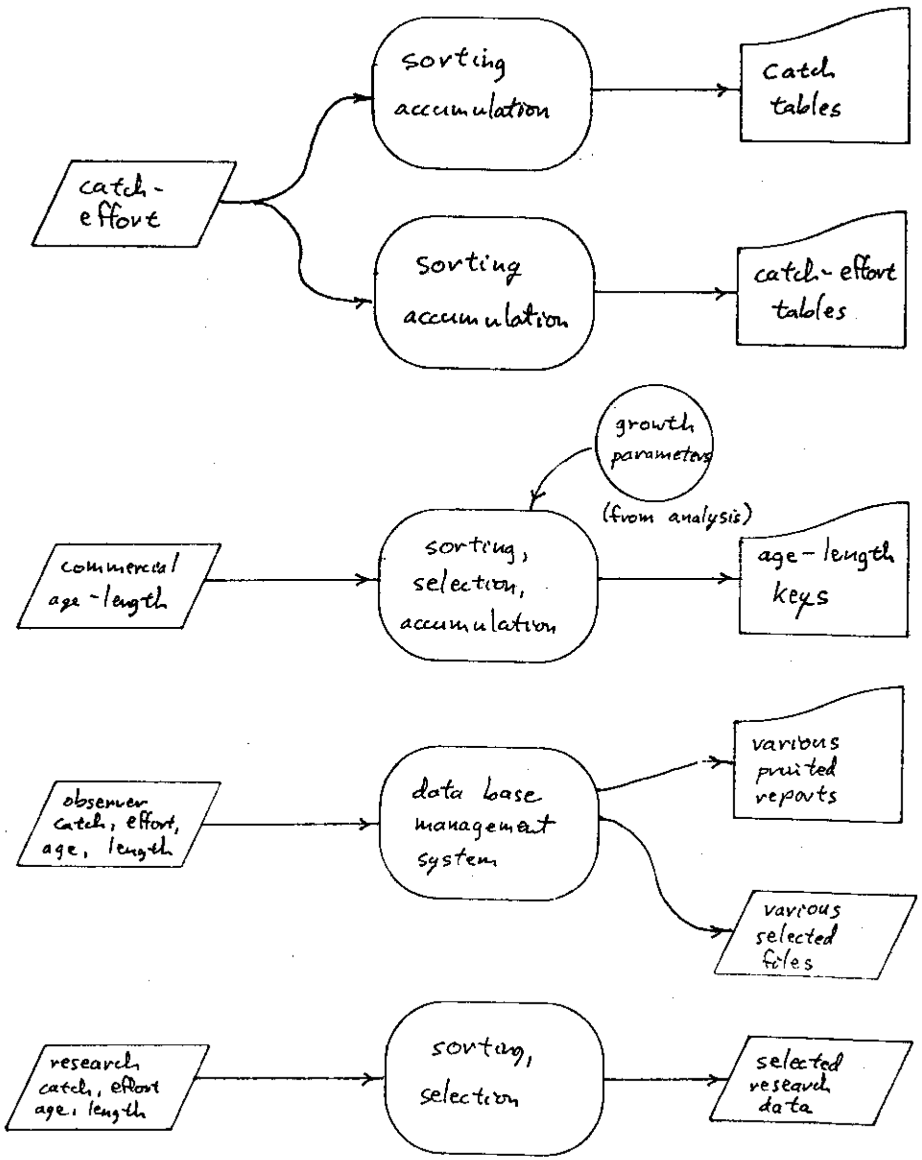
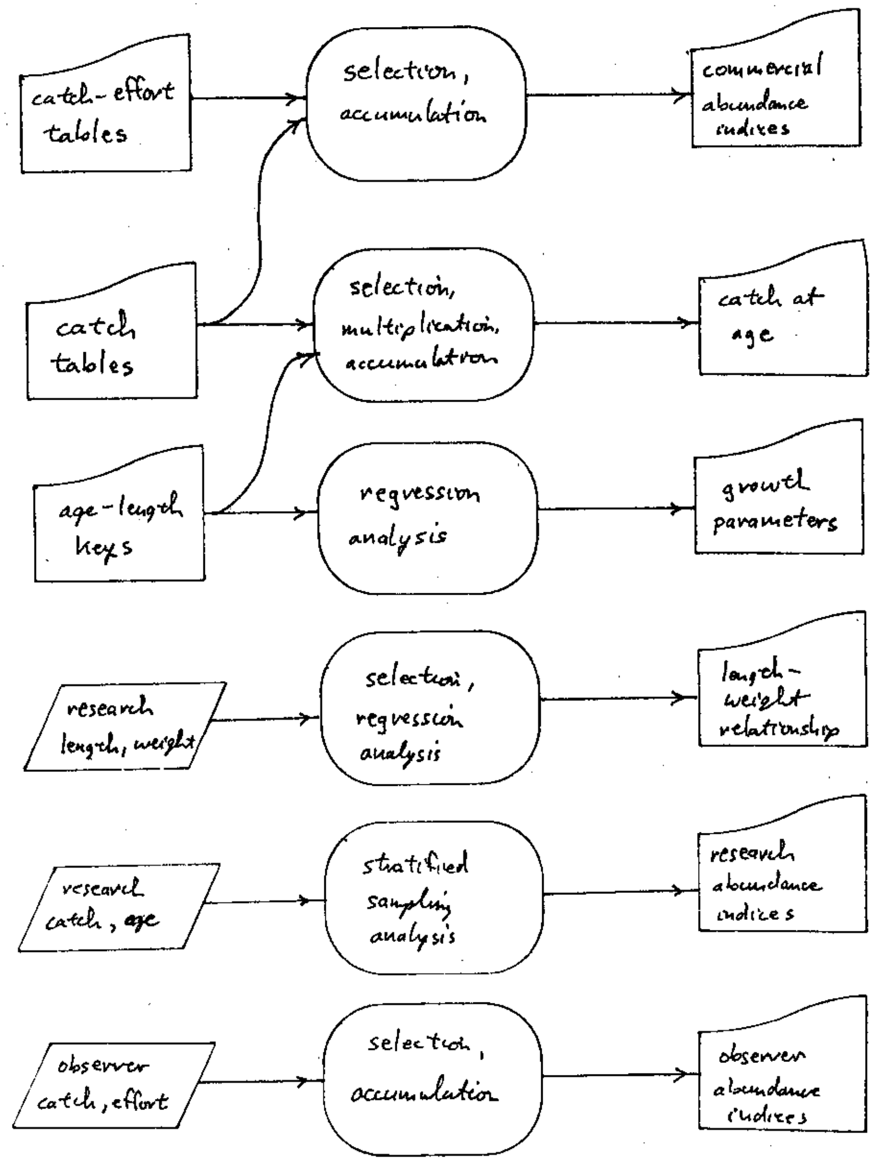


Fig. 2a

(b)


catch-effort
sorting accumulation
catch tables
sorting accumulation
catch-effort tables
growth parameters
(from analysis)
commercial age-length
sorting, selection, accumulation
age-length keys
observer catch, effort, age, length
data base management system
various printed reports
various selected files
research catch, effort age, length
sorting, selection
selected research data

(c)


catch-effort tables
selection, accumulation
commercial abundance indices
catch tables
selection, multiplication, accumulation
catch at age
age-length keys
regression analysis
growth parameters
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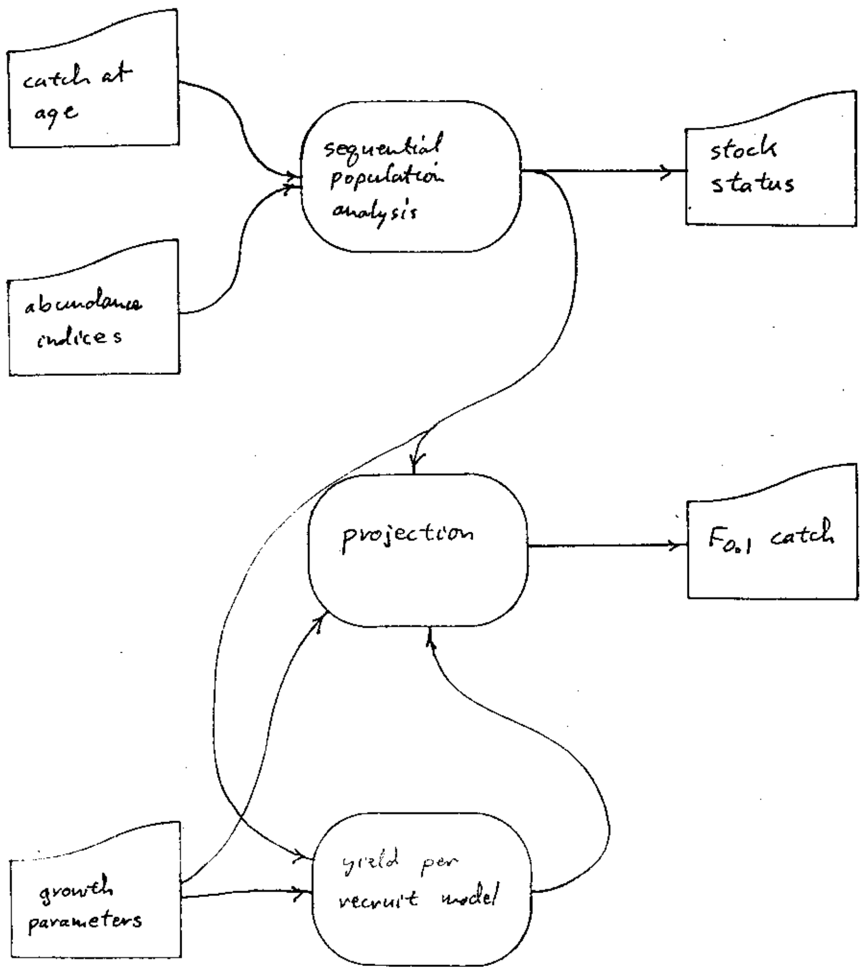
research catch, age
stratified sampling analysis
research abundance indices
observer catch, effort
selection, accumulation
observer abundance indices

(d)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growth parameters
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projection
yield per recruit model
stock status
$F_{0.1}$ catch