An Indirect Rapid Methods Approach to Assessment

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Strategies and tactics are explored for increasing the usefulness of assessment information obtainable under manpower and budget restrictions. A concept of indirect rapid assessment is gradually emerging based on a collection of rapid methods of varying degrees of accuracy, sophistication, and data requirements. These tactics involve the use of statistics which are functionally related to parameters of interest. Stock composition, growth, mortality, population size, intrinsic rate of increase, and stock production may be efficiently estimated with these methods. Short-term forecasting is also possible. Tactics include group testing, correcting biased estimates, use of comparative studies, using length as a substitute for age, and remote sensing type assessments.

On exploite les stratégies et tactiques afin d'augmenter l'utilité des résultats d'évaluation qu'on peut obtenir sous des restrictions budgétaires et manuelles. Un concepte d'évaluation indirecte et rapide se développe à partir d'un ensemble de méthodes rapides dont le degré d'exactitude ainsi que les exigences de données varient. Ces tactiques engagent l'emploi de statistiques qui sont liées de façon fonctionnelle aux paramètres en question. Par ces méthodes on peut ainsi estimer de façon efficace la composition de stock, la croissance, la mortalité, la taille de la population, le taux intrinsique de croissance et la production de stock. On peut également faire des prévisions à terme court. Les tactiques comprennent les examens en groupe, la correction des estimateurs biaisés, l'emploi d'études comparatoires, la substitution de l'âge par la longueur ainsi que les données reçues par satelites et avions.

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Fishery biologists around the world must face the realities of assessing fisheries under budget and manpower constraints. In this paper, we examine indirect rapid assessment techniques which involve the use of easily obtained statistics that are functionally related to the assessment parameters of ultimate concern. We attempt to develop a general concept of indirect rapid assessment methodology by cataloging and reviewing diverse approaches which can be used by fishery biologists. These approaches include group testing, sampling with two measuring devices of different accuracy, using comparative studies, etc. Several approaches presented are new to fishery biology.

Historically, there have been a number of rapid assessment techniques available but these techniques were generally quite crude. Hence, the term "quick and dirty" was an accurate description in many cases. Many of these techniques have evolved into sophisticated methods.

The variety of strategies available to fishery scientists for dealing with budget and manpower limitations can be contrasted by considering a simple example: suppose one wants to estimate the natural mortality rate in an unexploited fish stock. A traditional approach is catch curve analysis. The technologically oriented fishery biologist may try to develop a faster, automated system for preparing hard parts for examination, or to automate the process of measuring ring radii with a digitizer pad. The statistically oriented biologist might try to determine the minimum sample size which will provide the needed information and might advocate a sequential approach to collecting data. Both types of biologist may combine their general approach with the use of an age–length key. The key, which substitutes easily collected length frequency data for some of the harder to obtain age data, was one of the first "indirect rapid" techniques to be developed. The indirect assessment biologist has other options: age just enough fish to be confident of finding the oldest age in the sample and utilize the relationship between longevity and

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mortality rate to estimate mortality; or age enough fish to estimate the growth parameters — and then estimate the mortality rate from the mean size in the population or from the relationship between growth parameters and mortality rate. These ideas and a variety of other approaches to assessment are explored in the following sections.

Group Testing

Suppose one wants to estimate the prevalence of a certain trait which is known to be rare. Then most units (e.g. animals) tested will show negative results, i.e. the absence of the trait. In this case, one may wish to look for a method of testing randomly formed groups of units.

For example, the parasitic copepod *Mytilicola intestinalis* occurs in the blue mussel *Mytilus edulis* throughout much of western Europe's coastal waters. Detecting the presence of the parasite by dissection is a slow and tedious procedure. Dare (1977) devised a rapid procedure based on treating batches of mussels with the proteolytic enzyme papain and then sifting through the residue under a low-power dissecting microscope to detect the undigested chitinous exoskeletons of *Mytilicola*. If mussels are randomly assigned to jars, then the number of jars showing the parasite must be related to the proportion of animals having the parasite.

The maximum likelihood estimator is given by

$$(1) \quad \hat{p} = 1 - \left(1 - \frac{X}{n}\right)^{1/k}$$

with asymptotic variance given by

$$(2) \quad V(\hat{p}) = (1 - q^k)q^{2-k}/nk^2$$

where $\hat{p}$ is the estimate of the proportion p of animals with the trait (parasite), $q = 1 - p$, X is the number of groups (jars) showing the trait, n is the number of groups, and k is the number of units per group (mussels per jar) (Gibbs and Gower 1960; Thompson 1962; Sobel and Elashoff 1975).

Suppose one only has time to do 50 tests and one wishes to estimate the proportion of animals that are infected when the infection rate is actually 4%. If animals are tested in groups of one (i.e. 50 animals are individually tested), the standard error of the estimate would be $\sqrt{p(1-p)/n} = \sqrt{(0.04)(0.96)/50} = 0.03$. If animals are tested in groups of two (i.e. 100 animals tested in 50 tests), the standard error would be (approximately) 0.02.

Thus, it is clear that when dealing with rare traits, increased efficiency over ordinary binomial testing (one animal per test) can be obtained by testing randomly formed groups. This gain in efficiency can make it possible for a researcher to conduct larger, more detailed studies, e.g. of the importance of spatial or temporal pattern.

Care must be taken, however, not to place too many units in a group. Otherwise, all tests may turn out positive which leads to a maximum likelihood estimate of 1.0 even though the actual proportion could be much less. The statistical theory behind group testing has been described by Hoenig (1981) and Loyer (1983).

For group testing to be worthwhile, it must be almost as easy to test a group as it is to test an individual. This generally means it must be possible to physically combine tissue or body waste samples. For example, in testing for whirling spore disease (*Myxosoma*), one could macerate several fish heads simultaneously in a blender and stain the spores in the pooled sample provided there is no loss in sensitivity caused by dilution with uninfected fish (Markiw and Wolf 1980). A procedure that involves histological examination of tissues would not be suitable for group testing as there is no way to scan several samples simultaneously under a microscope. A variety of applications are suggested in Table 1. To date, only Worlund and Taylor (1984) appear to have used group testing for fisheries work.

An extension of group testing is the estimation of multinomial proportions. Suppose there are three stocks or species whose spatial and temporal distributions need delineation. A simple procedure would be to process samples by electrophoresis from a large number of individuals from various areas, depths, habitats, and times. But consider the results of testing groups of two fish at a time. If the banding pattern of each taxon has at least one unique identifier, then there is no loss of information in testing groups of two. Thus, if just pattern B is seen, both animals must have been from stock B; if A and B are seen, one must have been from A and the other from B.

If group size is greater than two, the results become equivocal. For example, if group size is three and A and B are seen, there could have been two from stock A and one from B or one from A and two from B. It then becomes a statistical problem to estimate the stock proportions in a sample. Unfortunately, little theoretical work appears to have been done in this area. As processing at sea becomes more common it may become more imperative to develop rapid biochemical tests for identifying processed foods so that landing statistics can be compiled on shore. Biochemical means of identifying taxa are discussed in Suzuki et al. (1981) and Ekaratne et al. (1982).

Group testing procedures can also be developed for other multivariate studies. For example, suppose one wants to study the co-occurrence of two rare parasites in a host species. The usual procedure is to record the presence/absence of the parasites in each individual host. However, by pooling samples of blood, feces, etc., one could test in groups. Estimation of the prevalence rates for each parasite proceeds as for the univariate case (i.e. ignoring the information on the "other" parasite). However, it now becomes of interest to estimate and test the degree of association of the parasites (Hoenig and Lawing 1984).

In general group testing situations, less information is obtained per item (animal) tested than if the items were tested individually. However, for suitably chosen group sizes, the information gained per test can be considerably higher than when units are tested in groups of size one.

Further developments include estimation when retesting is possible (Sobel and Elashoff 1975), group testing with a continuous variable (Sobel and Tong 1976), and development of a general theory of composite sampling (Rohde 1979).

Correcting Error-Prone (Biased) Surveys

Suppose one has the choice of using an inexpensive but error-prone technique to estimate the relative abundance of certain traits or using a time-consuming or high-priced technique which is (more) exact. The logical choice of a single technique would depend on a number of factors and thus is not easily specified. However, it is possible to use the inexpensive technique to conduct an extensive survey and use both techniques on a small sample to derive correction factors (Hoenig and Heisey 1984, 1986, 1987).

As a simple example, consider a survey to estimate the stock

TABLE 1. Biological applications of group testing (after Hoenig 1981).

Detect	In	By	Reference
Helminth eggs	Feces	Physical separation	Weller and Dammin 1945
Whirling disease spores	Fish heads	Maceration and flotation	Markiw and Wolf 1980
Kidney disease bacteria	Salmonid kidneys	Fluorescent antibody	Bullock and Stuckey 1975
Parasitic copepods	Bivalve mollusks	Enzyme digestion	Dare 1977
Ticks, fleas, mites	Mammal pelts	Chemical digestion	Zumpt 1961
Protozoa, bacteria, fungi, etc.	Blood, urine, feces, sputum, mucus	Microbial culture	
Virus	Pancreas, kidney, liver, etc.	Culture; antiserum neutralization	Cone and Moore 1981
Identify species	Mollusks and crustaceans	Latex agglutination test	Suzuki et al. 1981
Proteins (indicative of race or genetic makeup)	Muscle or other tissue	Electrophoresis	
Plant viruses	Insect vectors	Multiple transfer of insects to plants	Gibbs and Gower 1960

composition in a fishery exploiting two stocks. The inexpensive, rapid technique might consist of assigning fish to stocks on the basis of meristic or morphometric characteristics. A more precise but expensive technique would be to use electrophoretic results to classify animals.

The extensive survey using the error-prone technique results in a vector of estimates denoted by

$$E = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} \text{proportion stock X} \\ \text{proportion stock Y} \end{bmatrix}$$

The use of both techniques on a sample, *not necessarily random*, results in correction data of the form

	Classified as:		
Actually	stock X	stock Y	sum
Stock X	*a*	*b*	*m*
Stock Y	*c*	*d*	*n*
sum	*r*	*s*	*N*

Placing the tabled values in a matrix and dividing by the corresponding row totals gives the matrix

$$(3)\quad P = \begin{bmatrix} a/m & b/m \\ c/n & d/n \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$$

which estimates the probabilities of classification. It follows, then, deterministically, that the actual stock composition, denoted by the vector A, is related to E by

$$E = P^T A.$$

In words, this says that the observed number of stock X animals (e_1) is equal to the true number in stock X times the probability that an animal from X is classified as X (p_{11}) plus the number in Y times the probability that an animal from Y is classified as X (p_{21}).

The vector A can be estimated from

$$(4)\quad \hat{A} = (P^T)^{-1}E$$

with variance estimated by the jackknife method (Hoenig and Heisey 1984) or the delta method (Pella and Robertson 1979). The approach generalizes easily to the case where animals can be classified into one of k categories (e.g. stocks). It is then necessary to invert a $k \times k$ matrix in equation (4).

This method is intuitive but no claims for statistical efficiency have been advanced for it. Furthermore, the method sometimes produces unfeasible (negative) estimates. Cook (1983) developed an intuitive method for correcting the corrected estimates, but the statistical properties induced by this modification are poorly known. Recently, Hoenig and Heisey (1987) developed the maximum likelihood (ML) estimators for the correction problem which are always feasible and are asymptotically of minimum variance, unbiased, and normally distributed. Further, they showed that when the estimates obtained by equation (4) are feasible they are also the ML estimates; Cook's method produces ML estimates only for the binomial case (two classes in the population).

Estimates of stock composition are frequently obtained by using a discriminant function to classify animals. The results are unbiased only if the assumptions are fully met. However, the results can be corrected if animals of known identity are used to develop a correction matrix. This correction procedure is nonparametric since traits are not assumed to follow any particular distribution.

Another use of the correction method might be to make estimates of age composition obtained from scales comparable with estimates obtained from spines or otoliths. Although there are a number of other potential uses (Table 2), this technique has only been used a few times in fishery work to correct estimates of stock composition (see Hoenig and Heisey (1984) and Cook (1983) for reviews).

It is important to note that the same set of correction data can be used to correct estimates from different times, locations, etc., provided only that the probabilities of misclassification (as defined by (4)) do not change. That is, the researcher's skills must not change over time and the biological characteristics used to classify the animals (e.g. color, shape) must not change between samples. The relative abundances of the traits can, and in general will, vary between samples.

TABLE 2. Applications of correction matrices in fishery surveys (from Hoenig and Heisey 1984).

Objective	Error-prone method	"Exact" method
Sex determination in fish	(1) Hematocrit[a] (2) Probe[b] (3) External characteristic[c]	(1) Otoscope (2) Surgical examination
Species identification	Morphometrics, meristics, anatomy	(1) Electrophoresis[d] (2) Latex agglutination[e]
Stock identification	(1) Morphometrics, meristics (2) Scale pattern[f] (3) Elemental composition[g]	(1) Electrophoresis (2) Sample known stocks
Age determination in pinnepeds	Tooth wear	Dentinal growth rings
Maturity stage	(1) External characteristics (2) Gross internal examination	Internal/histological examination
Composition of catch	Industry reports	Spot-checking by biologists

[a] Steucke and Atherton (1965).
[b] Glass et al. (1962).
[c] Parker (1971).
[d] Ekaratne et al. (1982).
[e] Suzuki et al. (1981).
[f] Cook (1982).
[g] Mulligan et al. (1983).

Comparative Studies

Comparative life history studies have been used to study problems in physiology, ecology, and evolution by exploring relationships in compendia of life history parameter estimates. In its simplest form, the comparative study consists of plotting one parameter against another to visually check for possible relationships. In its most sophisticated form, it can involve any of the exploratory data techniques, including classification and discrimination methods and regression and correlation analysis.

Applied ecologists have used comparative studies to seek easier ways to estimate parameters. That is, if a parameter which is difficult to estimate is functionally related to parameters which are easier to measure (or estimate), then these easily obtained parameters can be used to estimate the parameter of ultimate concern. This use of comparative studies is in contrast with studies which seek clues to basic physiological principles or taxonomic hierarchies.

One of the first comparative studies of life history parameters in fishery biology was the study of natural mortality rates by Beverton and Holt (1959) based on a compendium of mortality, growth, and longevity estimates. They showed that natural mortality is closely related to growth parameters within taxonomic orders, but failed to detect a general relationship. Taylor (1958, 1959, 1960) noted that subtle differences in temperature among stocks of a single species are correlated with growth and mortality rates. Putting these pieces together, Pauly (1980) was able to derive a multiple regression equation using data from 175 fish stocks to predict the natural mortality rate from growth parameters and mean water temperature. Using analysis of residuals, he found that only two groups, polar fishes and clupeoids, departed significantly from the relationship. Physiological considerations accounted for the departure of the polar group; a satisfactory explanation for the clupeoids is not currently available.

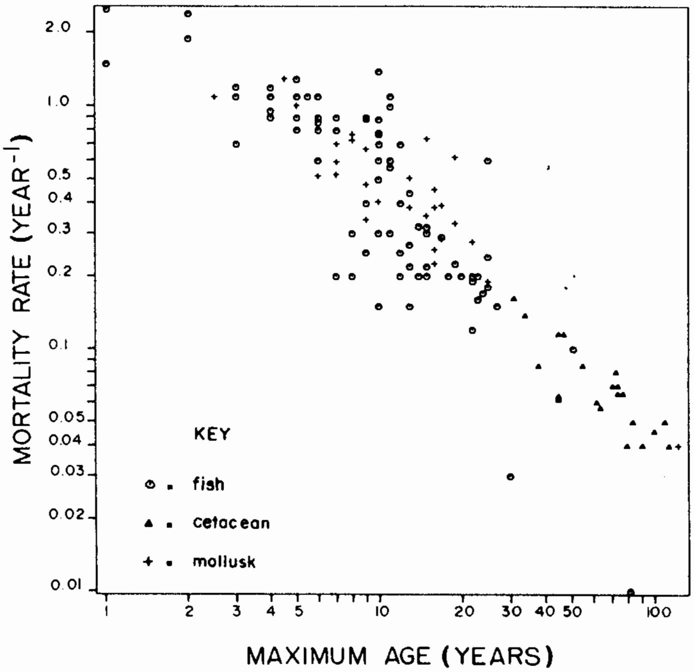

FIG. 1. Relationship between the instantaneous mortality rate and the maximum age known for 125 stocks of fish, mollusks, and cetaceans (from Hoenig 1983).

Another example is the prediction of the mortality rate from the maximum observed age. Ohsumi (1979) found a functional relationship between these parameters in the Cetacea. Hoenig (1983) generalized the relationship to include mollusks and fishes (Fig. 1). However, the realization that maximum observed age depends on sample size led Hoenig and Lawing (1983) to treat the maximum ages in a sample as order statistics from an exponential distribution. They thus developed an estimator based on the k oldest ages in a sample which requires a minimal amount of aging, since the oldest fishes can be found by

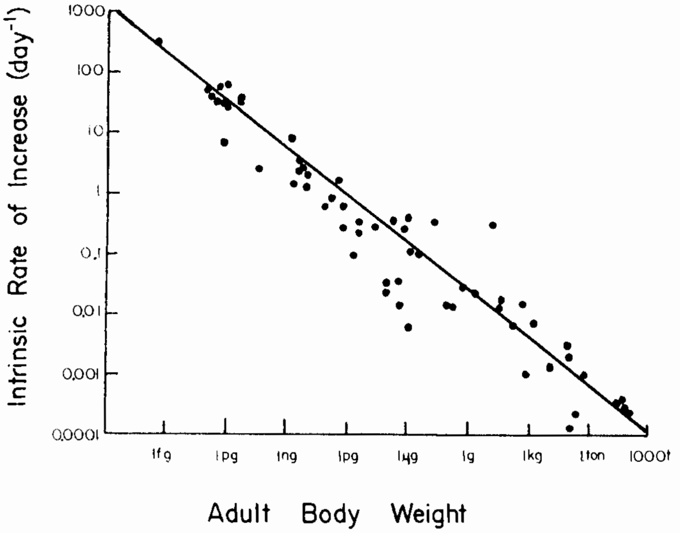

FIG. 2. Relationship between the intrinsic rate of increase of various organisms and their adult body weight (modified from Blueweiss et al. 1978 by Pauly 1982).

aging just the largest ones. Alverson and Carney (1975) developed a method for estimating the natural mortality rate from estimates of maximum age and the parameter K of the von Bertalanffy growth equation.

A well-known comparative study in fishery biology is Ryder's (1965) development of the morphoedaphic index (MEI) to estimate total potential yield from lake depth and dissolved solids. This approach has received much attention and is still the object of much interest (Jenkins 1977; Toews and Griffith 1979; Schlesinger and Regier 1983; SPOF 1982; Hanson and Leggett 1982; Oglesby et al. 1987; and references in these works). Jenkins (1977) also empirically studied the numerical relationship between predators and prey. Simple physical models for predicting potential fish yield from rivers were described by Kölbing (1978) and Welcomme (1975, 1979, 1983). Garcia and LeReste (1981) discussed use of physical variables concerning rainfall and heat flux data for short-term forecasting of shrimp yields.

A tantalizing possibility is to estimate the intrinsic rate of increase, r_m, of a population from the adult body weight. Blueweiss et al. (1978), based on work by Fenchel (1974), showed these two parameters to be highly correlated in organisms ranging in size from viruses to elephants (22 orders of magnitude). Pauly (1982) added whales and more fishes to the preceding compilation (Fig. 2) and pointed out that if further study confirms the strength of the relationship, it will be possible to employ Schaefer models without recourse to long series of catch and effort data.

Intrinsic rate of increase might be expected to be related to other life history parameters according to r–K selection theory. Heron (1972) showed that r_m is related to generation time and reproduction per generation (Fig. 3). Thus we have two independent estimates of r_m derived from life history considerations. Another compilation of life history parameters, which includes values of r_m, can be found in Caddy and Csirke (1983). One hopes that some useful generalizations will emerge as more observations are compiled and analyzed and the resulting theories are evaluated. Adams (1980) found that five other life history parameters, maximum size, growth rate, longevity, size at maturity, and natural mortality, varied in marine fishes in ways consistent with r–K selection theory. The recent volume by Calder (1984) provides a thorough examination of comparative studies and should be a useful source of ideas for further research.

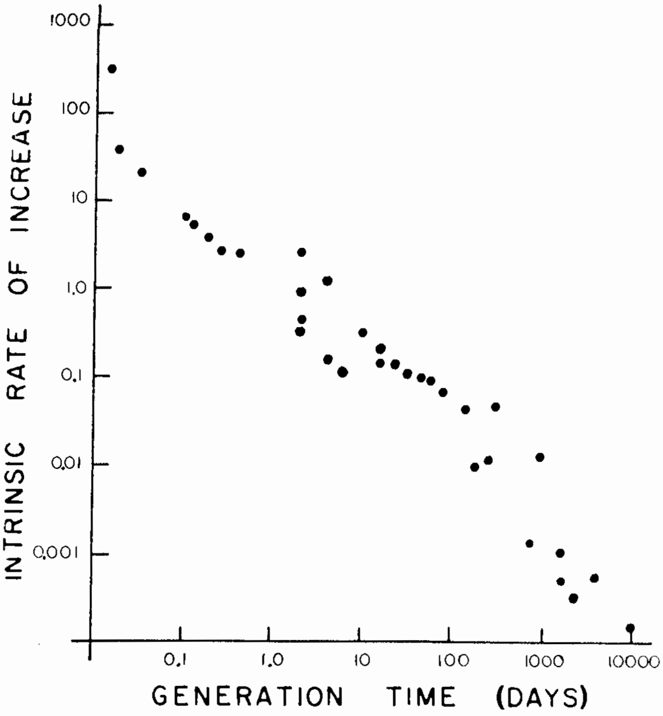

FIG. 3. Relationship between the intrinsic rate of natural increase of various organisms and the generation time (modified from Heron 1972).

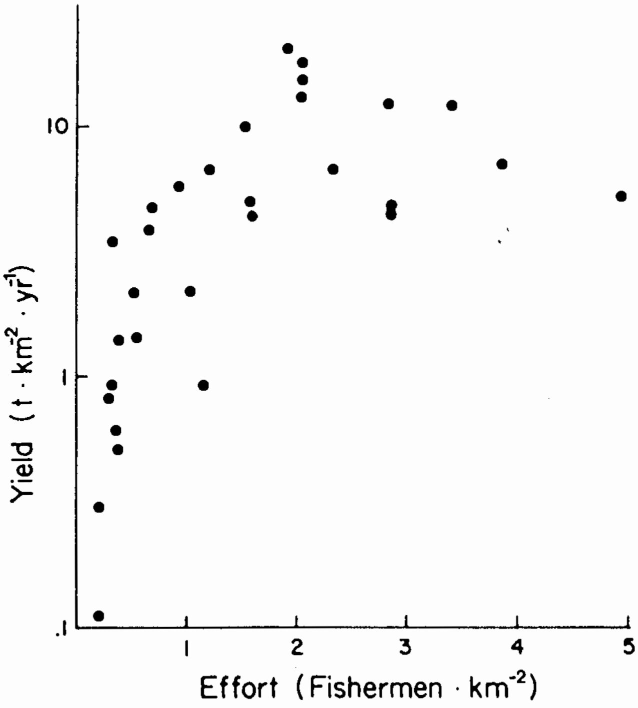

FIG. 4. Fish yields from African lakes as a function of fishing effort (from Marten and Polovina 1982).

A very different approach to modeling stock production without a long time series of data was developed by Munro and Thompson (1973), Munro (1980), Henderson and Welcomme (1974), Welcomme (1976), and Marten (1979). Munro showed

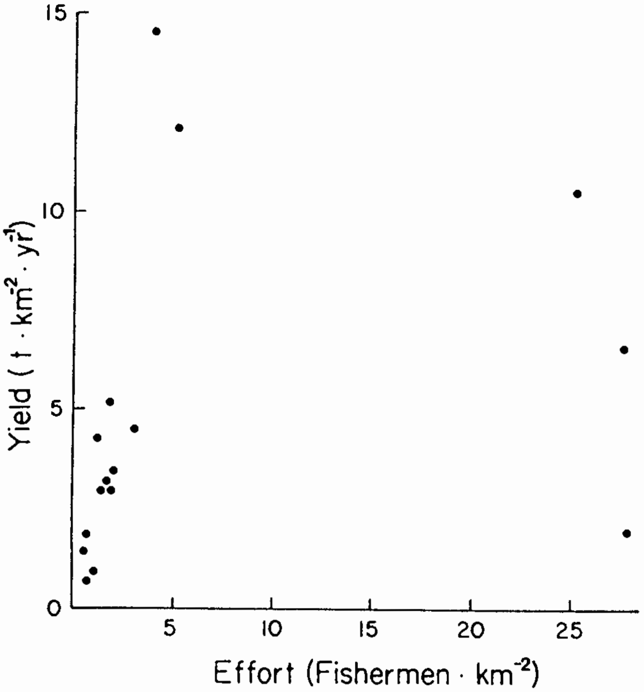

FIG. 5. Fish yields from tropical rivers as a function of fishing effort (from Marten and Polovina 1982).

that catch–effort data from ecologically similar regions in Jamaica experiencing different fishing pressures could be plotted on one graph and used to fit a production model with data from only one or two years (see Fig. 4, 5). The procedure was clarified by Caddy and Garcia (1982) and applied to a Mediterranean fishery by Garcia (1984). Goddard et al. (1987) applied the method to sport fisheries.

Csirke and Caddy (1983) presented another variation of stock production modeling in which catch per effort is plotted against total instantaneous mortality rate (Z). The method is of interest, in the context of indirect rapid assessment methodology, because the considerable problems in estimating total fishing effort are circumvented by substituting more easily obtained estimates of total mortality. Furthermore, Z can be estimated from mean length data using, for example, Beverton and Holt's (1956) equation

$$(5) \quad Z = K(L_\infty - \bar{L})/(\bar{L} - L_c)$$

where K and L_∞ are von Bertalanffy growth parameters and $\bar{L}$ is the mean length of those fish above the length L_c. If all the mortality estimates are derived from this equation, then K need not be known, since arbitrarily setting K equal to 1.0 would only serve to shift the location of the parabola along the x-axis and not change the shape. Also, L_∞ can be approximated by dividing the average length of the three largest fish known from the stock (or a similar stock) by 0.95 provided the stock is not too heavily exploited (Pauly 1984b). Another possibility is to estimate mortality from the mean weight by solving the following expression iteratively for Z (Hoenig et al. 1987):

$$(6) \quad \bar{W} = ZW_\infty \sum_{n=0}^{3} \frac{U_n(1 - (W_c/W_\infty)^{1/3})^n}{Z + nK}$$

where $\bar{W}$ is the mean weight of animals above the weight W_c, W_∞ and K are the asymptotic weight and growth coefficient, respectively, in the von Bertalanffy growth in weight curve, and $U_n = 1, -3, 3, -1$.

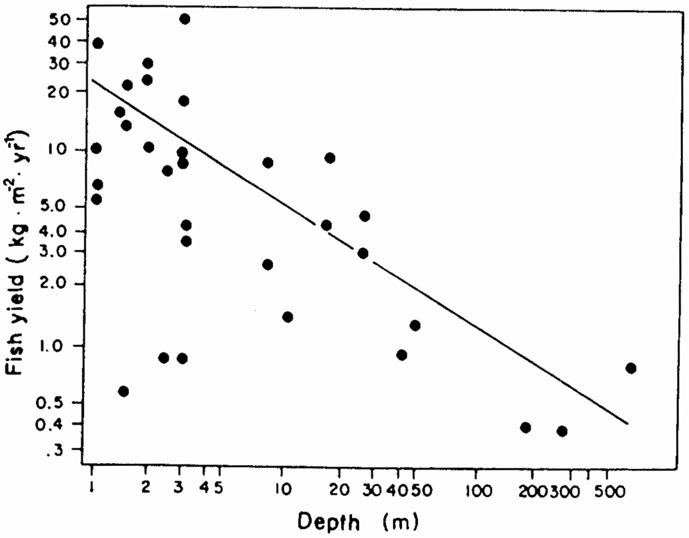

FIG. 6. Fish yields from African lakes as a function of lake depth (from Jones 1982).

Further developments are possible. For example, if only a few data points are available for a freshwater system, or if the data are too noisy for fitting a parabola, one can use an independent estimate of maximum sustainable yield (MSY) (e.g. from the MEI or other empirical relationship) as a constraint in estimating the parameters of the parabola (Hoenig and Hoenig 1986). The constraint can be introduced into the normal equations using a Lagrange multiplier. The model of interest is

$$Y_{\text{eq}} = b_1X^2 + b_2X + b_3 + \text{error}$$

where Y_{eq} is the observed equilibrium yield, the b_i are regression coefficients, and X can be either total mortality rate or fishing effort (with $b_3 = 0$ in the latter case). The predicted equilibrium yield has a maximum value of $-b_2^2/4b_1 + b_3$ which is constrained to be equal to some value "M." Then instead of

$$\text{Minimize } \Sigma(Y_{\text{eq}} - b_1X^2 - b_2X - b_3)^2,$$

the constrained least squares estimates consist of

$$\text{Minimize } [\Sigma(Y_{\text{eq}} - b_1X^2 - b_2X - b_3)^2 + \lambda(-b_2^2/4b_1 + b_3 - M)]$$

where λ is the Lagrange multiplier. The nonlinear regression routines in some of the major statistical packages allow regression with constraints.

Similarly, in Csirke and Caddy's (1983) version of the stock production model based on mortality estimates, the left x-axis intercept can be constrained to the value of an independent estimate of natural mortality rate.

Other examples of comparative studies include relating yield and community structure to physical parameters (Fig. 6–9) and relating yield to primary productivity (Fig. 10–11; also Jones and Hoyer 1982; Oglesby et al. 1987). Pauly (1984b, chap. 3) showed that comparative anatomy studies could be used to determine approximate trawl selectivity factors for soft-rayed fishes, e.g. by examining the relationship between selectivity and girth to depth ratio. A review of data compilations and comparative studies can be found in Hoenig (1982).

A conceptual framework for comparative studies was presented by Anderson et al. (1980) (Fig. 12). The different types of studies they identified can be contrasted using a simple example. Suppose one wishes to determine what factors account

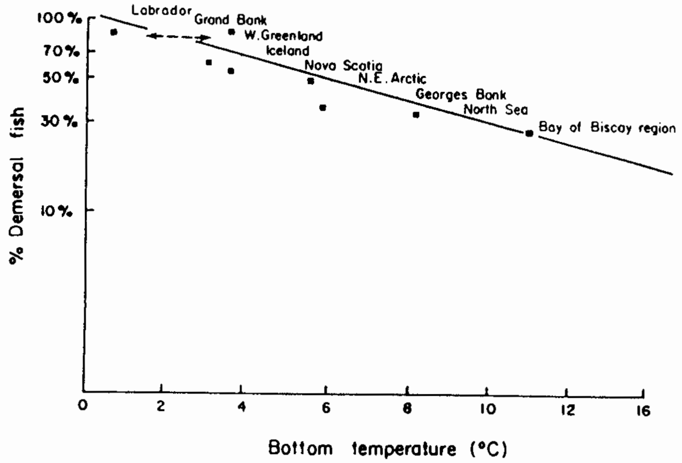

FIG. 7. Relationship between the percentage of demersal fish in the commercial landings and the bottom temperature (from Jones 1982).

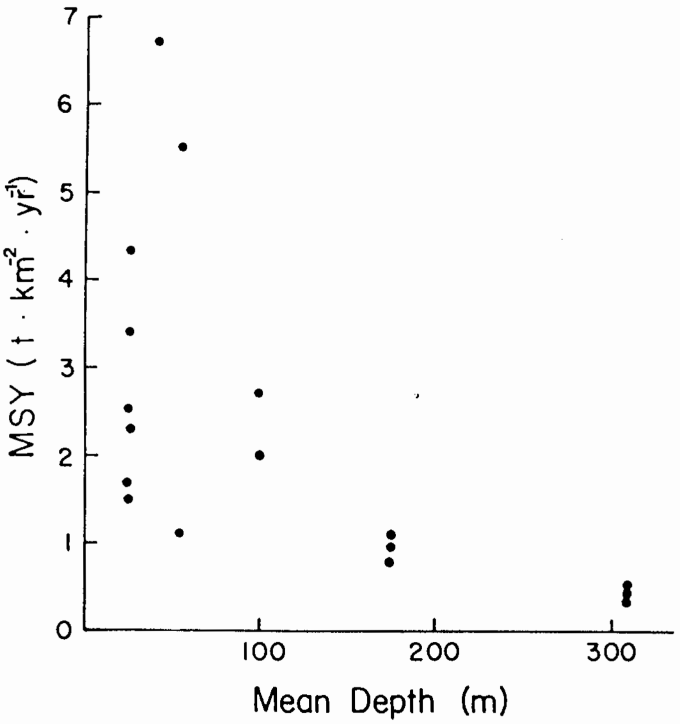

FIG. 8. Maximum sustainable yield as a function of depth for tropical continental shelf demersal fisheries (r = −0.86) (from Marten and Polovina 1982).

for the occurrence of undesirable events, such as winterkills or epizootics, in the lakes of a region. Suppose further that a potential "causal" factor (risk factor) has been identified such as shallow water depth. In a cohort study, a group of lakes with the factor (i.e. with shallow depth) and another group without the factor would be identified. Then the incidence of the response (winterkill or epizootic) would be contrasted in the two groups. This type of study can be conducted prospectively (identify lakes and then wait for the response) or retrospectively (identify lakes and then check the historical record to see if the response occurred). In a case control study, a group of lakes is identified in which the response is known to have occurred and, similarly, another group is identified in which the response has been absent. The occurrence of the potential causal (risk) factor is then compared in the two groups. Case control studies can only

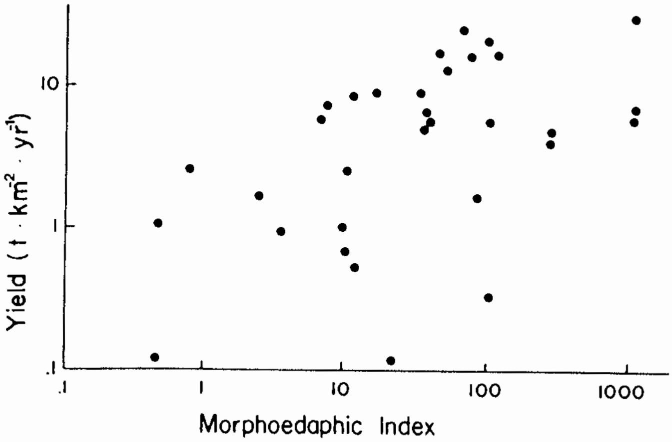

FIG. 9. Fish yields in African lakes as a function of the morphoedaphic index (from Marten and Polovina 1982).

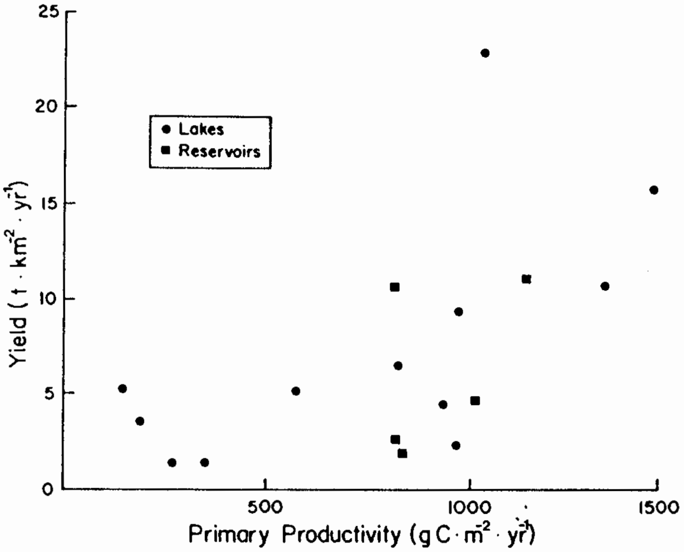

FIG. 10. Fish yields from tropical lakes and reservoirs as a function of the primary productivity (from Marten and Polovina 1982).

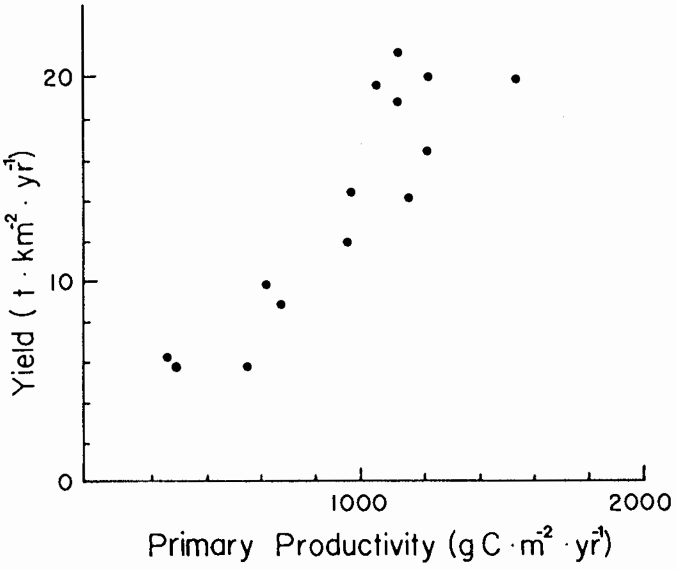

FIG. 11. Fish yields from tropical tilapia ponds as a function of the primary productivity (r = 0.89) (from Marten and Polovina 1982).

TABLE 3. Examples of indices in fishery science and their conversion to totals by ratio estimation.

Index	For parameter	Ratio estimator
Catch per unit effort (CPUE)	Fish population size (N)	—
Total effort (f)	Fishing mortality (F)	F = (catchability) × f
Total effort (f)	Catch (C)	C = (catch per unit effort) × f
Diesel fuel sales (S)	Effort (f)	f = (effort per liter) × S
Garbage left at boating facilities (g)	Effort (f)	f = (trips·kg garbage^{-1}) × g
Total catch (C)	Effort (f)	f = (catch per unit effort)$^{-1}$ × C
Total effort reported (rf)	Total effort (f)	f = (ratio of actual effort/reported effort) × rf
Total catch reported (rc)	Total catch (C)	C = (ratio of actual catch/reported catch) × rc
Uncalibrated measure (U)	Actual total (A)	A = (correction factor) × U where correction factor = change in A per unit of U

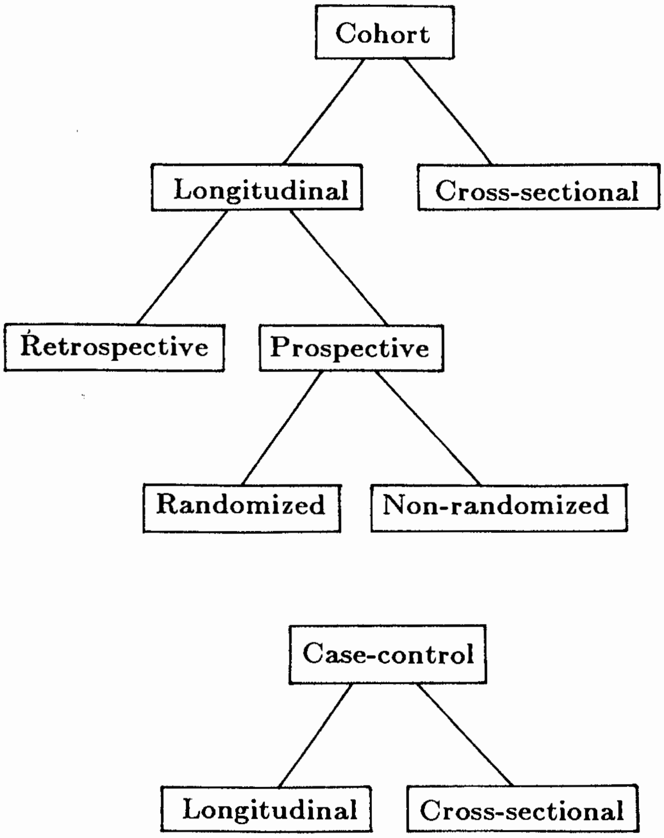

FIG. 12. A conceptual framework for comparative studies (redrawn from Anderson et al. 1980).

be conducted retrospectively. In a cross-sectional study, lakes would be simultaneously classified for the presence of the risk factor and the occurrence of the response. The type of study selected will depend on the availability of historical data and also the relative prevalences of the risk factor and the response. For example, if winterkills are uncommon, then a case control study may be preferable to guarantee adequate sample sizes in each group.

These examples demonstrate several important aspects of comparative studies: (1) comparative studies are relatively new, yet they have already produced some spectacular results; (2) vitally important parameters, which are difficult to estimate or measure directly, may be easily estimated indirectly from other parameters; (3) with time, the data bases become better, the analyses become more sophisticated, and the inferences become more insightful; (4) the empirical comparative studies can lead to better theoretical models and understanding of the systems by suggesting structural relationships which require explanation; (5) results from comparative studies can be used as preliminary estimates for traditional assessment analyses, thus providing a transition between empirical "seat of the pants" management and state of the art modeling.

A drawback of comparative studies based on literature data is that one may not have control over the quality of the data used. It may be difficult to develop objective criteria for deciding which published studies will be rejected for lack of adequate supporting information. Also, it may be difficult to obtain a complete list of pertinent studies or to obtain an unbiased sample of studies.

Holt (1962) called for more comparative studies. Recently, Banerji and Krishnan (1973) and Bakun et al. (1982) renewed the call. An international symposium held in Pallanza, Italy, in 1978 sought to review the bases for comparative studies of freshwater fisheries to promote this general approach (FAO 1980).

Indices and Ratio Estimators

Sometimes a comparative study establishes that one quantity can be used as an "index" of another quantity. For example, fishing effort is commonly used as an index of fishing mortality and catch rate as an index of population size (Table 3). The ideal index is one that is directly proportional to the quantity it replaces.

In certain situations, an index can be converted into an estimate of population total. For example, diesel fuel sales (Levi 1976) and fish landings (Ricker 1975, p. 19) are both indicators of fishing effort. The following estimators of total effort can be used:

Total effort = effort per litre × total sales
Total effort = (catch per unit effort)$^{-1}$ × total catch.

The effort per gallon and catch per unit effort ratios are determined by sampling a portion of the fleet. These procedures avoid the difficult problems of estimating relative fishing power of various types of boats and gears.

Of course, if both auxiliary variables (catch and fuel sales) are known, it is possible to use a multivariate ratio estimator for increased efficiency as follows (Sukhatme et al. 1984):

$$\text{Total effort} = wf_c + (1 - w)f_s$$

where f_c and f_s are the estimates derived from catch data and fuel sales, respectively, and w is a weighting factor for combining the estimates. If the two estimates are independent, then the optimal weight would be given by

$$w = \text{MSE}(f_s)/[\text{MSE}(f_c) + \text{MSE}(f_s)]$$

where MSE is the mean squared error. Otherwise, if catch rate and fuel consumption data are obtained from the same boats, one would need to incorporate the covariance of the auxiliary variables in the weighting calculations (Sukhatme et al. 1984).

It should be noted that only the population totals, not the individual values, are needed for the auxiliary variables when the relationship between the variables and fishing effort is linear. In the above example, if the relationship between fishing effort and fuel consumption is nonlinear, then one would have to accept added bias in the estimated total effort. However, if each individual sale of fuel is known, instead of just total sales, then a regression of effort on sales can be used to estimate the total effort for each boat. This model-building approach is discussed in more detail below under Aerial and Remote Assessments.

Williams (1978) described how auxiliary variables can be obtained almost "out of thin air." For example, to estimate the total landings in a port in a given day, one could guess at the landings for each boat and use the sum of the guesses as the population total for the auxiliary variable. Then one randomly samples some boats to estimate the ratio of actual landings to guessed landings. The observer's lack of objectivity does not cause bias in the estimate per se. However, the ratio estimation method is in general statistically biased for small samples. This bias will depend on the extent to which the relationship between guesses and actual landings violates the assumptions of the method (i.e. a linear relationship through the origin with minimal deviation from this relationship).

The variance, small sample bias, and use of the jackknife method for reducing bias is discussed for ratio estimation and related techniques in most sampling texts. Unfortunately, scant attention is usually paid to the statistical aspects of ratio estimation in fishery courses and texts despite the prevalence and importance of the method in practice.

Length as a Substitute for Age

Length frequency data contain much of the information contained in age frequency data. Thus, there has been a long history of trying to extract useful information from length frequency distributions since Petersen (1892) associated modes with age classes. Various approaches were tried over the years to improve upon Petersen's basic idea (see review by Brothers 1980), but a dependable procedure seemed elusive. Recently, Pauly developed and implemented an algorithm (in Basic) called ELEFAN I which promises to be a significant improvement (Pauly and David 1981; Pauly, 1987). The algorithm defines a set of peaks and troughs in one or more length frequency samples and then tries to maximize the goodness of fit of a growth curve by passing the curve through as many peaks and avoiding as many troughs as possible. A host of further algorithms for estimating mortality, selectivity, and population size from suitable length data have been developed for use with the original ELEFAN program. ELEFAN occupied a prominent position during the recent International Conference on the Theory and Application of Length-based Assessment (Pauly and Morgan 1987). Morgan (1987) modified the ELEFAN algorithm so that supplemental growth information, e.g. from a limited number of tag returns or age determinations, could be incorporated into the estimation procedure. Shepherd (1987a) and Pauly and Caddy (1985) described alternative algorithms to the ELEFAN method.

Estimation of mortality rates from length frequency data has proceeded along two lines. Fridriksson (1934) developed the age–length key in which an aged subsample is used to estimate the age composition in each length interval of a length frequency distribution. The method relies on the statistical concept of stratified random sampling. It qualifies as an indirect rapid assessment tool since easy to collect length data are substituted for some costly age data. Properties and modifications of the age–length key are presented in Kimura (1977), Westrheim and Ricker (1978), Clark (1981), Bartoo and Parker (1983), and Hoenig and Heisey (1987).

A classical age–length key can only be validly applied to a population with the same composition as the one from which the key was derived. Clark's method looks at the variability in length about age instead of age about length. As a consequence, his procedure can be applied to any number of populations, with varying age compositions, provided the growth rate and gear selectivity are constant. However, Clark's method assumes that the age–length key data are known without error so that the only uncertainty lies in the estimate of the length frequency of the population for which the estimate of age composition is desired. In general, age–length key data are based on small samples, since age determinations are tedious and expensive to obtain, whereas length frequency estimates are based on large samples, since measuring fish is easy. It would therefore be more reasonable to assume that most of the uncertainty lies in the age–length key part of the data. Hoenig and Heisey (1987) pointed out the similarity between the age–length key problem and the correction matrix procedure for stock composition described earlier. Their ML estimation procedure allows for stochastic error in both the length frequency sample and the age–length key data with the amounts of error depending on the sample sizes.

Beverton and Holt (1956, 1957, p. 22) pioneered the other approach of estimating the total mortality rate directly from length statistics when growth rates are known (see equations (5) and (6)). A number of extensions have been developed over the years which are reviewed by Hoenig et al. (1983) and Pauly and Morgan (1987).

A problem with using simple statistics such as mean or median length to estimate the total mortality rate is that one cannot judge the validity of the basic assumptions. As Powell (1979) has shown, even a cursory examination of a length frequency distribution can give useful insights into the population dynamics of a stock (Fig. 13). Thus, it is significant that Jones (1981) developed a regression technique for length frequency data which allows one to visually inspect the goodness of fit. Jones' technique consists of plotting the cumulative catch above a length L against $\log_e (L_\infty - L)$. The resulting slope (except at the ends of the line segment) estimates Z/K. If L_∞ is not known, it can be estimated by iteratively seeking the value of L_∞ which maximizes the coefficient of determination. Pauly

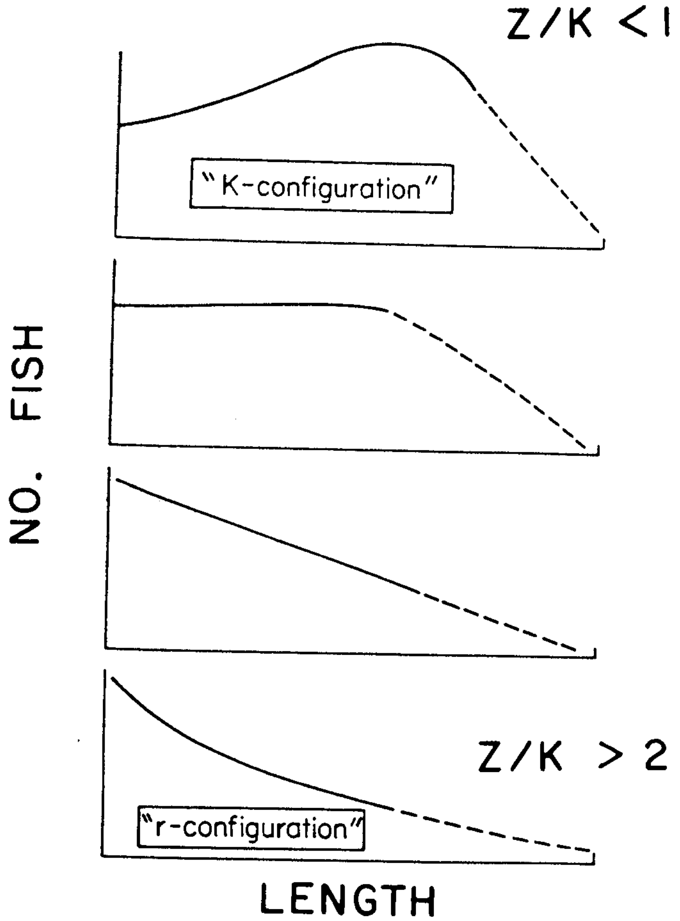

FIG. 13. Relationship between the ratio of Z/K (mortality to growth coefficient) and the shape of a length frequency distribution (from Pauly 1982).

(1983, 1984a, 1984b) advocated the slightly different approach of analyzing a catch curve based on relative ages derived from a length frequency sample (Fig. 14). Since Jones' method uses cumulative catch, which is a monotonic function of $\log_e (L_\infty - L)$, the slope will always be significant. Thus, Pauly's method seems to be on sounder statistical footing, but further work is necessary to study the properties of these techniques.

It is now feasible to think in terms of length-based virtual population analysis (VPA). The approach has been pioneered in papers by Jones (1974, 1979, 1981, 1984) and Pauly (1984b). Pope and Jiming (1987) developed a length-based multispecies cohort analysis. Holt (1977) proceeded in a different direction and considered the estimation of population size of sperm whales from changes in the mean size in the catches.

It is clear that there is now considerable interest in the development of length-based assessment techniques. The estimation of growth parameters from length data is mainly of interest in tropical regions and for use on crustaceans, since direct age determinations are difficult in these situations. Short-term forecasting (Shepherd 1987b), mortality estimation, and estimation of population size are almost universally of interest.

Assessment by Analogy

Intuitive judgments about the fisheries in a lake can be sharpened by defining empirical indices that can be used for comparing ecologically similar lakes. The basic idea is that if easily measured statistics for a given lake, such as test netting data, are similar to lakes known to be in acceptable condition, then the lake is probably also in good condition. Mean length might be plotted against standard deviation to develop empirical probability densities as a basis for comparison, and to try to cluster similar lake communities. Predatory–prey ratios and other indicators of community structure could be tabulated. These statistics can be used to "flag" lakes potentially in need of further study.

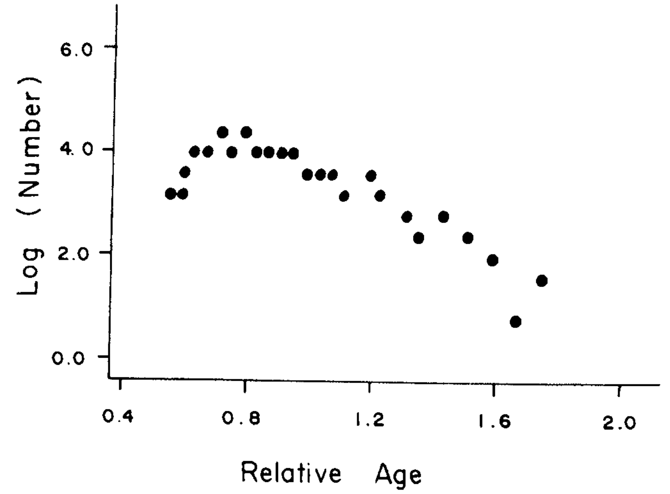

FIG. 14. A length-converted catch curve for Lake Minnetonka, Minnesota, largemouth bass (*Micropterus salmoides*). Ordinate is the logarithm of the number of fish in a length interval; abscissa is the relative age at the midpoint of the length interval defined as $t' = -\log_e (1 - L/L_\infty)$ where L_∞ is the asymptotic size. The slope of a regression line fitted to the descending right limb estimates $1 - Z/K$. (Data courtesy of M. Ebbers, Minnesota Department of Natural Resources.)

As an example, mean lengths and standard deviations of bluegill (*Lepomis macrochirus*) and northern pike (*Esox lucius*) were obtained from routine survey files for 41 lakes in central Minnesota with permanent fish populations (Fig. 15). Mean length appeared to be unrelated to standard deviation among pike populations ($r^2 = 0.015$, $p = 0.550$). Hence, unusual occurrences were taken to be indicated by extreme values of either variable. Among bluegill populations, mean length appeared to be negatively correlated with standard deviation ($r^2 = 0.161$, $p = 0.002$). Unusual populations were considered indicated by extreme outlier scores (Cook 1977) of data points about a linear regression line (e.g. those points with p values less than 0.10). This procedure is intended as an exploratory tool, not as a formal test of hypothesis, and is at any rate tentative.

An alternative approach was developed by Tonn et al. (1983) who used various multivariate statistical techniques to classify lakes and relate community structure to habitat variables. They used these results as a basis for developing management strategies.

Ryder and Edwards (1985) recommended a holistic approach to ecosystem quality and suggested that key indicator species be monitored as guides to the rest of the system. The evaluation of impacts on key species, known as Representative Important Species (RIS), is a standard approach to meeting the assessment provisions of sections 316a and 316b of the *United States Federal Water Pollution Control Act of 1972* (see EPA 1977a, 1977b). Regardless of what one thinks of this strategy, it is likely to play a prominent role in ecological impact assessment for many years for want of a better approach. It is also clear that

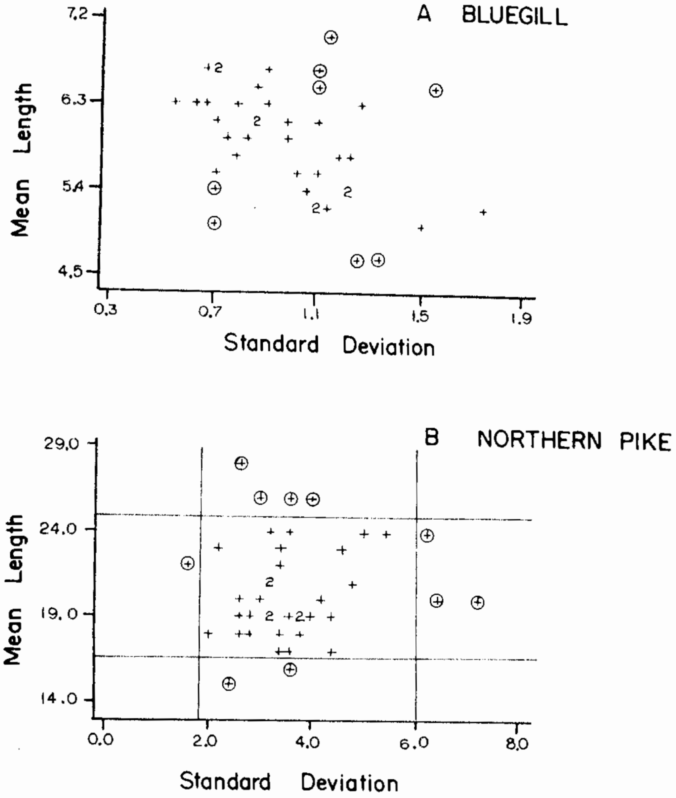

FIG. 15. Plot of mean length versus standard deviation for 41 populations of (A) bluegill and (B) northern pike. Lines and circles indicate "unusual" conditions (see text).

"key indicator" lakes and streams will be used to monitor regional problems such as acid precipitation. There is a trade-off between studying more lakes and studying lakes in more detail. The importance of this trade-off diminishes when quicker study techniques become available. It is hoped that a spectrum of approaches with varying data requirements can be developed to suit individual needs based on cost, data availability, and political considerations.

Volunteered Data

Fishermen can be enlisted to provide a variety of types of information. The trick is to estimate the reliability of the data and to deal with systematic errors.

One of the earliest uses of volunteer sportsmen was in the analysis of banding and tagging data. A highly sophisticated set of models and procedures, developed largely for bird banding studies, are now available to fishery biologists (Otis et al. 1978; White et al. 1982; White 1983; Brownie et al. 1985). Unknown and changing reporting rates are handled by marking animals at two or more times. Then, differences in return rates for the cohorts in a given year can reasonably be attributed to mortality (provided tag shedding and other factors can be accounted for).

Under suitable supervision, fishermen can provide quality information on catch rates, fish size frequencies, geographic distribution, etc., as well as quantitative tag return rates and biological samples. Ebbers (1987) enlisted anglers to keep detailed diaries and also collected data at sport fishing tournaments. The data collected from both sources were comparable with data collected on biological surveys but entailed less manpower on the biologists' part.

In Yellowstone Park, fishermen are asked to voluntarily submit reports on their fishing trips. A creel clerk makes spot checks so that inverse regression (calibration) can be used to adjust the estimates for reporting bias (R. Gresswell, pers. comm.). Further consideration of creel survey methods is given in the next section.

Aerial and Remote Assessments

The use of aircraft and remote sensing satellites may seem inconsistent with the rapid assessment goal of stretching the research budget. However, in many cases, assessments from the air can be highly cost effective. Some useful remote sensing data, generated as a by-product of other projects, can be obtained for a nominal charge. (Use of inexpensive kites has also been tried (Scoffin 1982).)

Aircraft can cover in a few hours what a team of biologists on the water might take several days to visit. Aerial observers can count fishing vessels by size and gear (and other boat types), count fixed location gear, count and estimate the size of fish schools and identify them to varying degrees, count salmonid nests (redds) in streams, map reefs and marshes, etc. (Squire 1983; Parrack 1976; Heggberget et al. 1986). Biotic and abiotic environmental conditions such as chlorophyll, phytoplankton taxa, riparian vegetation, surface temperature, wave height, and current characteristics can be quantified (Klemas et al. 1980; Brahma et al. 1983; Crouse and Findley 1984; Feldman et al. 1984; Fu and Chelton 1984). In addition, the observers can provide public services such as relaying the locations of fish schools and basking tunas and billfish, reporting mariners in distress, hazardous obstructions, etc.

These methods enter the realm of indirect rapid assessment methodology when there is visibility bias which must be corrected (e.g. Cook and Jacobson 1979), when raw counts from the air must be apportioned to various categories based on surface studies of relative abundances (ratio estimation), or when remote sensing signals need calibration.

When the study area is too large to be completely observed, one can use line transect methods to count boats and fixed gear (see Burnham et al. (1980) for a review). Statistical and practical aspects of aerial sampling are discussed by Jolly (1979) and Jolly and Watson (1979).

An alternative is to make two (or more) independent counts in which each object is uniquely identified (e.g. by noting its location on a map or recording its license number). The results can then be analyzed using mark–recapture methods. That is, one survey "marks" the boats by uniquely identifying them; the other survey "recaptures" a boat when a previously identified boat is spotted (Magnusson et al. 1978). If the whole area is not censused, then the boats must mix randomly between observation periods or the observation trips must follow random paths. Mark–recapture methods have been tried (without the use of airplanes) on Liverpool taxicabs (Bishop and Bradley 1972) and creeled fish (Regier 1971).

Another strategy that can be applied to catch and effort surveys is to correlate observations at one time (of day, of the week) with the total over a longer interval. For example, Parker (1956) found that sport fishing effort at noon was highly correlated with the total daily fishing effort. This aspect has also been investigated by Powell and Bowden (1981). This suggests the use of a model-based approach to sampling whereby observed count or effort data can be fitted to a model by regression techniques. Total effort can then be estimated by integrating the regression equation over the appropriate time interval (e.g. season). Variance, bias, and design considerations were discussed by Hoenig et al. (1986).

Hydroacoustic surveys and use of resistivity fish counters in streams (Dunkley and Shearer 1982) are conceptually similar to aerial surveys in that the recorded signals must be calibrated with biomass or numbers and apportioned to species or size groups. The use of automatic traffic counters at fishing access points also generates data which need calibration.

Perspective

Does the foregoing constitute the basis of a general strategy for managing aquatic resources? Or have we simply presented a collection of more or less unrelated techniques?

Implicit behind the use of all of these techniques is the idea that a biologist, faced with a choice of methods, may choose a less accurate method if the savings over using a more accurate method are substantial. The lower cost may allow one to process a large enough sample so that better results can be obtained over the use of a more accurate/precise (and more expensive) technique applied to a smaller sample. But even if the less expensive technique necessarily gives inferior estimates, its use may still be warranted so that a greater number of samples (of species, geographical areas, etc.) can be processed. Greater detail in the assessment of a fishery may be preferable to greater accuracy for a segment and no information for the rest of the fishery. This may be particularly important to consider in multispecies stock assessments.

Of course, indirect rapid assessment methods do not have to be crude. In many instances, "quick and dirty" techniques have evolved into "quick and sophisticated" procedures. The use of length-based assessment and hydroacoustics has already been mentioned. Even "rules of thumb" can be improved or expanded. For instance, Beddington and Cooke (1983) evaluated Gulland's suggestion that MSY may be approximated by $0.5MB_0$ (where M is the instantaneous natural mortality rate and B_0 is the virgin biomass). They proposed simple modifications to protect against recruitment problems.

It is reasonable to expect that ecological theory will benefit from the routine use of rapid assessment methodology for fisheries management. The benefits will accrue from the compilation of comparative data, the search for functional relationships, and the increasingly detailed studies possible with some rapid methods.

It is difficult to combine these ideas into a definition of indirect rapid assessment methodology. But one cannot propose a concept without attempting to define it. Perhaps the following will serve as a working definition:

> Rapid assessment methodology aims to increase the amount of assessment work that can be accomplished under fixed manpower and budget constraints by seeking faster and less expensive methods. Indirect rapid assessment methodology seeks to exploit the functional relationship between easily measured or estimated quantitites and the parameters of ultimate concern. Indirect methods may sometimes be chosen for their ability to provide greater detail in assessments (even though this may sometimes be at the expense of less accuracy or precision).

The rapid assessment approach is almost universally applicable. In tropical waters, a single trawl haul may contain more than 100 species for which basic life history parameters are largely unknown. This led Pauly (1980, 1982, 1984b) to advocate a set of rapid assessment techniques for tropical fish stocks. His procedures should also find use in other regions. In the major groundish fisheries of the North Atlantic, basic parameters have long been known for the most important species, yet stock identification is still a large problem, and attempts to develop working multispecies models are hindered by lack of information on the minor species. In the State of Minnesota, there are some 10 000 lakes; hence, it is not an exaggeration to say that there are more than 10 000 stocks to manage. Most of the managers of these fisheries would probably agree that some information is better than no information. Presumably, rapid assessment techniques could go a long way in filling their needs.

In the universities, students are taught to use state-of-the-art technology and are counseled to learn statistics in order to increase the quality and quantity of assessments. Perhaps it is time to counsel them to also look to where the "quick and dirty" approach can lead. We may develop a well-stocked toolbox of rapid assessment techniques ranging from crude to highly sophisticated. Perhaps the dictum "correlate, calibrate, and compare" is worth remembering.

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