
PERSPECTIVES

An Alternative Perspective on Recruitment Overfishing and Biological Reference Points

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Sissenwine, M. P., and J. G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Can. J. Fish. Aquat. Sci.* 44: 913–918.

Biological reference points are used to guide fisheries management decisions. The reference points most often used are expressed in terms of fishing mortality rate (F). F_{msy} relates to the maximization of sustainable yield. In principle, it is a most useful reference point, but in practice it is difficult to estimate. F_{max} and $F_{0.1}$ relate to certain levels of yield per recruit and are easily estimated, but they ignore conservation of the resource. Recruitment overfishing has usually been understood to occur when a population has been fished down to a point where recruitment is substantially reduced or fails. It has not been used as a basis for a biological reference point because the definition is vague and cannot be readily related to fishing mortality. Levels of spawning biomass below which recruitment seems to be reduced have been used, but their determination from available data is usually difficult and controversial. We propose an alternative definition of recruitment overfishing in terms of the level of fishing pressure that reduces the spawning biomass of a year class over its lifetime below the spawning biomass of its parents on average. Conventional models and types of data can be used to determine this level of F , denoted as F_{rep} , which clearly relates to the replacement of spawning biomass and thus to sustainability of a population and yield in the long term.

Les gestionnaires utilisent des points de référence biologique pour prendre des décisions sur la gestion des pêches. Les points de référence les plus souvent utilisés sont exprimés en taux de mortalité par pêche (F). Le F_{msy} exprime la maximalisation du rendement soutenu. En principe, c'est un point de référence très utile mais en pratique, il est difficile à estimer. Les F_{max} et $F_{0.1}$ expriment certains niveaux de rendement par recrue et sont facilement déterminés quoiqu'ils ne tiennent pas compte de la conservation de la ressource. Une surpêche au détriment du recrutement a généralement lieu quand une population est exploitée jusqu'au point où le recrutement est nettement réduit ou inexistant. Ce facteur n'a pas été utilisé comme base pour un point de référence biologique parce que sa définition est vague et qu'il ne peut pas être facilement transformé en niveau de mortalité par pêche. On s'est servi des niveaux de la biomasse génitrice au-dessous desquels le recrutement semble être réduit, mais la détermination de tels niveaux à partir des données disponibles est généralement difficile et sujet à controverse. Les auteurs proposent une autre définition de la surpêche au détriment du recrutement comme le niveau de pression par pêche qui réduit la biomasse génitrice d'une classe d'âge au cours de son cycle vital à un niveau inférieur à la biomasse génitrice parentale moyenne. Les modèles et données ordinaires peuvent être utilisés pour déterminer ce niveau de F , représenté par F_{rep} , qui explique clairement le remplacement de la biomasse génitrice et donc la permanence d'une population et le rendement à long terme.

Received June 18, 1986

Accepted December 15, 1986
(J8830)

Reçu le 18 juin 1986

Accepté le 15 décembre 1986

The terms "recruitment overfishing" and "biological reference points" are familiar to fishery scientists concerned with the conservation and management of fishery resources. In fact, they are related to each other although it is rare that the relationship is made explicit. The purpose of this paper is to offer an alternative perspective on recruitment overfishing and biological reference points. This is achieved by redefining recruitment overfishing.

Fisheries are managed to achieve certain socioeconomic benefits while conserving the production potential of the fish-

ery resource. Since the goals of fisheries management are usually complex and difficult to quantify, it is necessary to establish operational objectives to guide the decision process. These operational objectives (referred to as proximate goals by Pope (1983)) usually address conservation and yield implications of fisheries management explicitly, but not economic and social considerations. They are referred to as biological reference points by institutions (e.g. International Council for the Exploration of the Sea (ICES)) concerned with fisheries management.

It would be useful to have biological reference points which take account of recruitment overfishing. The concept of recruitment overfishing was introduced by Petersen (1894) according to Cushing (1976). Yet, its definition is vague. Recruitment overfishing is usually understood to occur when a population has been fished down to a point where recruitment is substantially reduced, or perhaps fails altogether. Unfortunately, the definition places the emphasis on the results of overfishing instead of on the act of fishing. It presumes a compensatory relationship between recruitment and spawning biomass.

Traditional Derivation of Biological Reference Points

Biological reference points are derived from models characterizing fish population dynamics. The most frequently applied models are of three types: spawner-recruit, dynamic pool, and production models.

Spawner-recruit models describe the relationship between generations (e.g. Ricker 1954; Beverton and Holt 1957). Most models assume that the per capita recruitment rate (R/S) decreases as S increases, i.e. compensation. Compensation, during at least one life stage, is necessary if there is to be a sustained yield.

Dynamic pool models (e.g. Beverton and Holt 1957; Thompson and Bell 1934) describe the change in year class (or cohort of fish of the same age) biomass following recruitment. The number of individuals in the year class is reduced by fishing and natural mortality. The biomass of the year class is the product of its size in numbers and the mean weight of individuals. In general, unexploited or lightly exploited year classes increase in biomass following recruitment (when growth rate is relatively high) to a peak, and then biomass declines (as growth rate moderates). The yield of a year class is determined by the age at which fishing begins (t_c) and fishing mortality rate (F). If fishing begins too soon or if the fishing mortality rate is too high, then the fish are harvested before the year class has had a chance to achieve its maximum biomass and some potential yield is lost, and vice versa.

Fishing also affects the spawning biomass produced by a year class over its lifetime. The lifetime spawning biomass of a year class is the sum (over ages, indexed by i) of the biomass at each age (B_i) times the fraction mature at age (x_i), $\sum_i x_i B_i$. Fishing pressure (F and t_c) reduces lifetime spawning biomass of a year class.

Yield and spawning biomass are usually normalized to the number of recruits. The methods are also known as yield per recruit (Y/R) analysis or spawning biomass per recruit (S/R) analysis.

The production of a population (in biomass) is the sum of the weight of recruitment and the weight gain (i.e. growth) of individuals in the population minus the weight loss due to natural mortality. Production models (e.g. Schaefer 1957) describe production as a function of biomass, or equilibrium production as a function of fishing pressure. They are usually heuristic models of the aggregate effect of recruitment, growth, and natural mortality. They assume that per capita production decreases as biomass increases or fishing pressure decreases, i.e. compensation. Production models need not be heuristic. They can be derived by combining a spawner-recruit model and dynamic pool model (Shepherd 1982).

A graphic representation of spawner-recruit, dynamic pool,

and production models is given in Fig. 1. The control variables are F and t_c . Together they characterize the intensity of fishing pressure. Superimposed on the graph of the spawner-recruit function is a line with a slope equal to the inverse of S/R from the dynamic pool model. This line is referred to as a "replacement line." Its intersection with the spawner-recruit function determines the equilibrium values of S and R for a specific level of fishing pressure. The corresponding equilibrium production is the product of the equilibrium R and the Y/R . By varying fishing pressure, a production model can be constructed.

Several biological reference points are defined in Fig. 1. F_{\max} is the fishing mortality rate that maximizes yield per recruit. While F_{\max} has obvious merit relative to short-term yield (for recruits already vulnerable to the fishery), it ignores the effects of fishing on future generations. $F_{0.1}$ is often proposed as an alternative, since it produces nearly as much yield without reducing spawning biomass so severely. The yield per unit of fishing mortality is higher as well. $F_{0.1}$ is defined as the fishing mortality rate that corresponds to a point on the yield per recruit function with a slope of 10% of the slope through the origin (Gulland and Boerema 1973). While the effect of fishing on the future recruitment is one of the considerations behind $F_{0.1}$, the relationship is speculative at best.

Biological reference points based on a production model (Fig. 1e) incorporate the effect of fishing on future generations. MSY is a biological reference point specified in terms of yield. It corresponds to a fishing mortality of F_{msy} at equilibrium. A biological reference point in terms of equilibrium biomass can also be specified.

Recruitment overfishing is usually understood to occur when spawning biomass is so low that recruitment decreases substantially and perhaps precipitously. While this vague definition does not lend itself to exact specification of a biological reference point, a fishing mortality rate of F_0 and the corresponding spawning biomass of S_0 in Fig. 1 are good candidates. The specific value labeled as F_0 is arbitrary, but it is clear that an increase in fishing mortality will result in a sharp reduction in equilibrium recruitment. A more extreme choice of a biological reference point would be the level of fishing mortality that corresponds to a replacement line that is so steep that it only intersects the spawner-recruit function at the origin. This implies that the population will be fished to extinction. In theory, a population can persist with a very low level of equilibrium recruitment so long as F corresponds to a replacement line with slope less than the slope of the spawner-recruit function at the origin. If a spawner-recruit function is known, the definition of recruitment overfishing can be quantified in terms of the slope of the function, e.g. fishing mortality rate that corresponds to an equilibrium point on the spawner-recruit function with slope of 10% of the slope at the origin.

Based on the theory, there are ample choices of biological reference points, including some that correspond in some way to recruitment overfishing. But to apply the theory, there must be sufficient information to estimate a compensatory spawner-recruit function. More often than not, the data provide little support for the models (see review by Sissenwine et al. 1984). It should be apparent from Fig. 1 that unless a spawner-recruit model can be fitted to the data with a reasonable level of confidence, then only $F_{0.1}$ and F_{\max} are available as biological reference points. In fact, that is why they are applied most often.

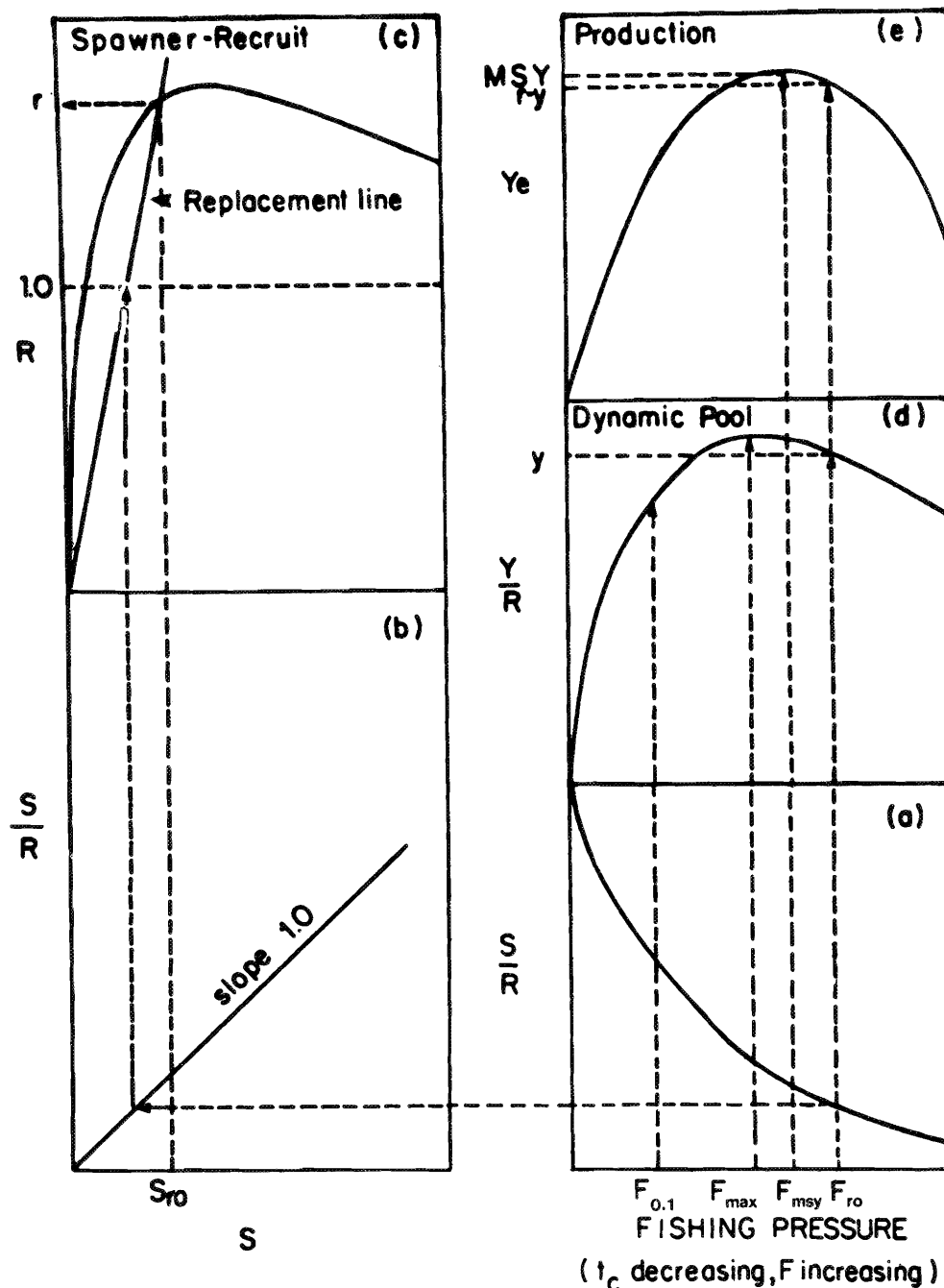


FIG. 1. Single species theory of fishing. A dynamic pool model (Fig. 1a and 1d) describes the effect of fishing mortality rate (F) and age at first capture (t_c) on spawning biomass (S) per recruit (R) and yield (Y) per recruit. A spawner-recruit model (Fig. 1c) relates the number of recruits to spawning biomass; a "replacement line" with slope equal to the inverse of S/R is mapped by a graphic procedure (Fig. 1b). S and R must be scaled to appropriate units (e.g. thousands of tons and millions of fish, respectively) in order for the graphic procedure to be practical. The intersection of the replacement line with the spawner-recruit function determines equilibrium recruitment. The product of equilibrium recruitment (from Fig. 1c) and yield per recruit (from Fig. 1d) is the equilibrium production (Fig. 1e). The method is demonstrated for a fishing mortality rate of F_{ro} (conditional on an unspecified value of t_c). F_{msy} is indicated based on the production model of Fig. 1c; $F_{0.1}$ and F_{max} are indicated in Fig. 1d.

There are three explanations for the poor fit of spawner-recruit models: (1) the models may be too simple biologically, (2) variability caused by abiotic factors obscures biotic relationships, and (3) measurement error (Walters and Ludwig 1981). Undoubtedly, all three contribute to the problem.

It can be argued that S_{ro} , MSY , and F_{msy} can be estimated

without a spawner-recruit model. One argument is that it is not necessary to be able to fit a compensatory spawner-recruit model in order to detect a level of S below which the magnitude of R declines precipitously. But the formal statistical interpretation of not being able to fit a compensatory spawner-recruit model to a data set is that the null hypothesis

of a constant per capita recruitment rate (R/S) cannot be rejected. R is lower for low values of S , but the data do not usually indicate a specific level of S where a marked change in the pattern occurs. The traditional concept of recruitment overfishing implies compensation; if the hypothesis of compensation cannot be supported by the data, then there is no basis for a biological reference point corresponding to recruitment overfishing.

Another argument is that a production model can be fitted to catch and fishing effort data directly without considering the spawner–recruit relationship. Therefore, it may be possible to estimate MSY and F_{msy} from a production model even if the spawner–recruit model does not fit the available data.

But why should a heuristic production model which aggregates recruitment with growth and natural mortality be able to explain the dynamics of a fishery if the spawner–recruit data are so variable that a relationship cannot be fitted? Even though the spawner–recruit relationship is not treated explicitly in the heuristic production model, it is still a component of production. It is frequently the largest component (e.g. southern New England yellowtail flounder; Sissenwine 1974) and the component where compensation is usually assumed to occur.

In fact, there are more examples of the “successful” application of production models than spawner–recruit models. In part, this is because the data used to fit the former are more often available than the data to fit the latter. But, we wonder if some of the apparent success of production models might reflect the frequent use of an inappropriate method for fitting. The procedure for fitting production models is often simplified by assuming that data are drawn from a fishery at equilibrium. The assumption is virtually always invalid. Even if it were not, the linearized equilibrium version of the most frequently applied production model (i.e. Schaefer, 1957) may indicate a spurious fit to data (even random numbers) when none exists (Knights and Pope, unpublished, see Sissenwine 1978; Kenney 1982). There are methods for fitting production models (Rivard and Bledsoe 1978) that do not suffer from this problem, but their application is not as common. It should be noted that the same type of spurious correlation that can result when fitting linearized equilibrium production models can result from the linearized version of some spawner–recruit models.

An Alternative Approach when the Spawner–Recruit Relationship is Indeterminate

The spawner–recruit relationship is indeterminate when there is no statistical evidence of a trend in R/S over the observed range of S . But, the observed values of R/S can be used as a basis of an alternative definition of recruitment overfishing and a biological reference point.

A priori, persistence of a population requires that each year class replace the spawning biomass of its parents on average. We have already shown that a dynamic pool model can be used to calculate the effect of fishing on the lifetime spawning biomass, and that these values of S/R correspond to replacement lines on a spawner–recruit plot (i.e. $L = S/R = H(F, t_c)$). Data points that lie on a replacement ($R/S = L^{-1}$) line correspond to year classes that are the exact size to replace the spawning biomass of their parents when subjected to a level of fishing pressure that corresponds to the line. Points above the replacement line ($R/S > L^{-1}$) are year classes that produce a

surplus spawning biomass; points below the line ($R/S < L^{-1}$) are year classes that do not produce enough. For a population to persist, the points below the line must be balanced by the points above it.

In this context, we define recruitment overfishing as a level of fishing pressure that reduces the spawning biomass produced by a year class over its lifetime below the spawning biomass of its parents on average, i.e. recruitment overfishing corresponds to $L^{-1} > E(R/S)$ which is the expected value of R/S . We denote the fishing mortality rate that corresponds to average replacement as F_{rep} (conditional on t_c). F_{rep} is a useful biological reference point. If F exceeds F_{rep} for an extended period of time, population size will decline, and vice versa, assuming that the pattern of R/S does not change (i.e. assuming a stationary distribution).

This alternative definition of recruitment overfishing is illustrated for Georges Bank haddock in Fig. 2. The observed values of recruitment and spawning biomass are so variable that a spawner–recruit function was not fitted. Three replacement lines, corresponding to $F = 0.0, 0.5$, and 1.0 , for $t_c = 2.0$ yr, are superimposed on the spawner–recruit data. Most of the points are below the replacement line for $F = 1.0$, indicating that the population will decline in size, on average, at this level of fishing mortality. On the other hand, the figure indicates that the population will grow if fishing ended, but it is noteworthy that some year classes are too small to replace their parents even with no fishing. The replacement line of $F = 0.5$ is the median (i.e. equal number of points above and below). For a value of $F = 0.5$, the population will fluctuate in size without trend.

For this illustration, we estimate F_{rep} as 0.5 . It is approximately equal to F_{max} which is about 0.55 and much higher than $F_{0.1}$ which is about 0.25 . Technically, MSY and F_{msy} are indeterminate because there is no statistical evidence of compensation. Nevertheless, it is possible to get some idea of the outlook for long-term average yield (quasi- MSY) from Fig. 2. The average recruitment, over the observed range of spawning biomass, is about 50 million fish. The product of the average recruitment and the Y/R corresponding to F_{rep} (about 1 kg) is about 50 000 tons. In fact, the population sustained an average catch of about 50 000 tons for 30 yr when it was fished at a fishing mortality rate of about 0.5 . When the fishing mortality rate increased in the mid-1960's, the population collapsed (Clark et al. 1982). So, for the Georges Bank haddock, it appears that F_{rep} , F_{max} , and F_{msy} are about the same value. Recruitment overfishing occurs when F is greater than 0.5 . Since the data do not support the hypothesis of a compensatory spawner–recruit function, a critical value of spawning biomass that corresponds to recruitment overfishing cannot be specified.

Discussion

This paper provides an alternative perspective on the interpretation of spawner–recruit data and dynamic pool models when the spawner–recruit relationship is indeterminate; it is not an argument against compensation in fish populations. Compensation must exist at some level of population size, since life-sustaining resources (e.g. food, space) are limited. Compensation need not be operative over the range of spawning biomass for which there are quantitative observations. For the population to persist where compensation is inoperative, F should not exceed F_{rep} . If compensation is operative, but

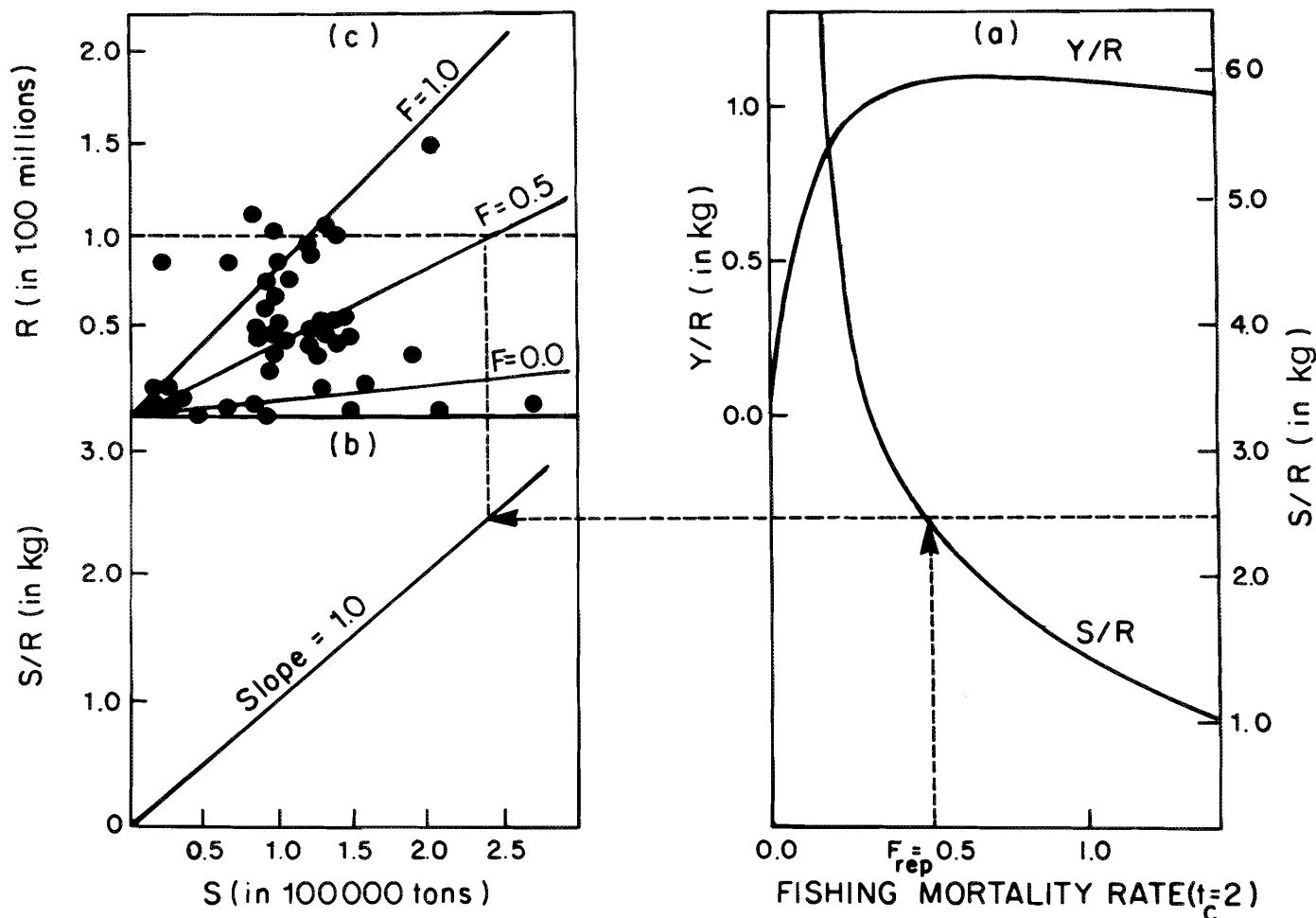


FIG. 2. Population dynamics of Georges Bank haddock (after Sissenwine and Marchesseault 1985; Sissenwine et al. 1984). One data point ($S = 1.94$ and $R = 3.68$) has been omitted. Replacement lines corresponding to several levels of fishing mortality (with $t_c = 2.0$ yr) are derived from the spawning biomass per recruit analysis (Fig. 2a) and superimposed on the spawner–recruit plot (Fig. 2c). For specific level of fishing pressure, points above the replacement line represent year classes that will produce more than enough lifetime spawning biomass to replace their parents; points below will not. The replacement line for $F = 0.5$ is the median, e.g. an equal number of points above and below. If the median is taken as an estimate of the mean, then a fishing mortality rate of 0.5 will allow year classes to replace the spawning biomass of their parents on average. A fishing mortality rate that corresponds to replacement on average is denoted by F_{rep} .

obscured by the effects of a fluctuating environment, then F_{rep} is a conservative biological reference point. This is appropriate in the absence of statistical evidence that can be used to quantify compensation.

Since compensation must be operative at some high level of biomass, F_{rep} is most likely to be conservative for a short data set drawn from a developing fishery. In such cases, it will be necessary to apply an adaptive management strategy in order to discover the nature of the spawner–recruit relationship, i.e. either to fit a spawner–recruit model or to be convinced that F_{rep} is not conservative. If an estimate of F_{rep} is greater than or equal to F_{max} , it is not conservative in terms of yield, if the spawner–recruit relationship is asymptotic. If the spawner–recruit function is dome-shaped, $F_{rep} \geq F_{max}$ may be conservative although we think this is unlikely.

There are several limitations to the approach described herein. First, the method assumes that the observations of S and R are from a stationary distribution, i.e. past events are a useful basis for forming expectations about the future. This assumption can be investigated by examining the data to determine if R/S has a temporal trend. If a trend is suspected, then

the most recent observation should be weighted more heavily.

Second, the approach requires data describing S and R . These data are not available for all fisheries, although they are for a large number. If S and R data are missing, F_{rep} can be inferred from a period during which a fishery was relatively stable. In the case of Georges Bank haddock, observations from a relatively stable period were used to confirm an estimate of F_{rep} .

Third, the approach does not consider the potential effects of depensation, i.e. R/S decreasing as S decreases. If there is depensation, then F_{rep} is not a conservative biological reference point. This problem can be alleviated to some degree by weighting the most recent values of R/S more heavily. In effect, this narrows the range of S over which the mean of R/S is calculated.

Fourth, it requires estimates of biological parameters such as age at maturity (t_m), natural mortality rate (M), and growth rate or size at age (W_i) to calculate S/R from a dynamic pool model. These parameters are also required to estimate R and S by the most popular method (virtual population analysis (VPA), Murphy 1965). If the same values of t_m , M , and W_i are

TABLE 1. Effect of overestimating age at maturity (t_m), natural mortality (M), and weight at age (W_t) on dynamic pool model results and spawner–recruit plots when S and R are derived by virtual population analysis (VPA). Underestimates are indicated by a minus sign, overestimates are indicated by a plus sign, a greater degree of overestimation is indicated by two plus signs, no effect is indicated by zero.

Overestimated parameter	Dynamic pool		Spawner–recruit		
	$L = S/R$	L^{-1}	R	S	R/S
t_m (+)	–	+	0	–	+
M (+)	–	+	++	+	+
W_t (+)	+	–	0	+	–

used to calculate L^{-1} by a dynamic pool model and to estimate R and S by VPA, then estimates of F_{rep} should be robust. Table 1 indicates the effect of overestimating t_m , M , and W_t on L^{-1} from a dynamic pool model and R/S (derived by VPA) on a spawner–recruit plot. In each case, the errors are in the same direction so that the relative position of replacement lines and points on a spawner–recruit plot are not sensitive to errors in the aforementioned biological parameters.

These limitations are not unique to this approach. They apply to the traditional definition of recruitment overfishing and of biological reference points. An advantage of our approach is that it is straightforward to define recruitment overfishing and biological reference points in terms of t_c as well as F . This flexibility is inherent in the coupling of a spawning biomass per recruit analysis (as a function of both F and t_c) and spawner–recruit data.

It is also possible to estimate the slope at the origin of the spawner–recruit plot to find a biological reference point (F_{high} in the terminology used by ICES 1984) more directly indicative of possible stock collapse. Shepherd (1982) suggested that using a value of F corresponding to the upper 90-percentile of the observed R/S values would be conservative because the population might be capable of more compensation at low stock levels than was evident in the data. Sissenwine et al. (1984) pointed out that this was not guaranteed because the effects of environmental variation would cause the observed extreme values of R/S to be inflated. There are, thus, two opposing effects, but what is certain is that there is little evidence in the data to support the idea that the population could support F values as high as F_{high} for any length of time. Thus, it may still serve as a useful indicator of dangerously high fishing mortality, as compared with F_{rep} which indicates a level which probably can be sustained indefinitely.

In this paper, the median is used to estimate the expected value of S/R as a basis to determine F_{rep} . One advantage of the median is that it is a robust estimator if S and R are measured with error. Other estimators should be considered.

The ideas in this paper have evolved over a few years. Shepherd (1982) reviewed the use of spawning biomass per recruit analysis to calculate production models and emphasized the connection between the slope at the origin and stock collapse. ICES (1984) introduced the idea of using spawning biomass per recruit as a basis of biological reference points. Shepherd and Sissenwine (see Beverton et al. 1984) expanded on the approach at a Dahlem Conference on “Exploitation of Marine Communities.” At the same time, Sissenwine was

working directly with fisheries managers to apply the approach (Sissenwine and Marchesseault 1985). The guideline of enough spawning biomass per recruit so that year classes replace the spawning biomass of their parents on average was adopted as an objective of the Multispecies Fisheries Management Plan for New England (NEFMC 1985). This paper was written to expose the approach more broadly to the scientific community.

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