

# Groundfish Exploitation Rates Based on Life History Parameters

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The problem considered is how to choose a fixed exploitation rate that will provide a high yield at low risk, when the investigator has no knowledge of the yield curve or the spawner-recruit relationship of the stock. Commonly employed expedients are  $F_{0.1}$ , and  $F = M$ , but these have little empirical or theoretical support. Calculations made with a range of life history parameter values typical of demersal fish and a range of realistic spawner-recruit relationships show that yield will be at least 75% of maximum sustainable yield so long as the spawning biomass is maintained in the range of about 20-60% of the unfished level, regardless of the form of the spawner-recruit relationship. A relative spawning biomass in this range can be achieved by choosing a fishing mortality rate that will reduce the spawning biomass per recruit to about 35% of the unfished level. This is the level of fishing mortality that maximizes the minimum yield among all of the spawner-recruit relationships considered ("maximin" rate,  $F_{mmy}$ ). The actual value so calculated depends on the relative timing of growth, maturity, and recruitment to the fishery. In practice,  $F_{mmy}$  appears to be very close to  $F_{0.1}$  except where recruitment and maturity schedules do not coincide.

Cet article traite du choix d'un taux d'exploitation fixe permettant d'obtenir un rendement élevé tout en minimisant les risques quand on ne connaît pas la courbe de rendement ou la relation reproducteurs-recrues du stock. On utilise souvent les valeurs  $F_{0.1}$  et  $F = M$ , mais les fondements théoriques et empiriques de ces solutions sont faibles. Des calculs fondés sur différentes valeurs typiques des paramètres du cycle vital des poissons de fond et sur différentes relations reproducteurs-recrues réalisistes montrent que le rendement sera d'au moins 75% du rendement maximal soutenu dans la mesure où la biomasse des reproducteurs est maintenue entre 20 et 60% de celle qui existerait si le stock n'était pas exploité et ce, quelle que soit le type de relation reproducteurs-recrues. On peut obtenir une biomasse relative de reproducteurs de cet ordre en choisissant un taux de mortalité due à la pêche réduisant la biomasse de reproducteurs par recrue à environ 35% de celle existante en l'absence d'exploitation. Parmi toutes les relations reproducteurs-recrues considérées, un tel taux de mortalité due à la pêche est celui qui maximise le rendement minimum (taux de "rendement maximin",  $F_{mmy}$ ). La valeur réelle ainsi calculée est fonction des relations temporelles entre la croissance, le moment de l'arrivée à maturité et le recrutement de la pêche. En pratique, la valeur de  $F_{mmy}$  est très près de celle de  $F_{0.1}$ , sauf quand le recrutement et l'arrivée à maturité ne coïncide pas.

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**R**ecommending a groundfish catch quota, or a biological upper limit for one, often consists of two steps: (i) estimating the present stock size and (ii) applying an appropriate rate of exploitation to the estimate, usually meaning a rate that will provide a high average yield in the long term without running the risk of overfishing the stock. Where the management objective is to maximize physical yield, the best approach is to apply the  $F_{MSY}$  rate of fishing mortality, defined here as the constant rate that produces the maximum average yield in the long term. Fishing at  $F_{MSY}$  will provide a yield close to the maximum obtainable by any strategy (Getz et al. 1987; Hall et al. 1988) and at the same time guarantee that on average the catches will be less than the potential yield whenever the stock happens to fall below the maximum sustainable yield (MSY) level of biomass, so that the stock will automatically rebuild from any mishap, whether it be a run of poor year-classes or some inadvertent overharvest.

During the last few decades, major advances have been made in methods of estimating stock size, but little progress has been made on the problem of estimating  $F_{MSY}$ , or any other kind of optimal exploitation rate. The difficulty, of course, is that to determine an optimal rate of exploitation, one needs to know

about the density-dependent behavior of the stock in question, and that knowledge has proved elusive. It appears that for most marine fish, density dependence operates through the spawner-recruit relationship, but spawner-recruit data are typically so few or so variable that it is impossible to estimate the form of the relationship objectively with any confidence (Shepherd 1982; Sissenwine and Shepherd 1987).

Lacking any information on the yield curve (i.e. total yield as a function of fishing mortality) or, equivalently, the spawner-recruit relationship, assessment scientists have usually not been able to determine  $F_{MSY}$  and have often resorted to recommendations based on fishing mortality rates calculated from life history parameters, the most common ones being as follows:

$F_{MAX}$ : This is the rate that maximizes yield per recruit without regard to whether sufficient spawning biomass is conserved to maintain recruitment in the future. Deriso (1982) argued that in most cases,  $F_{MAX}$  is an upper bound for  $F_{MSY}$ , but as his examples showed, it is not a sharp bound. Moreover, the  $F_{MAX}$  rate of fishing mortality is typically very high, so there is little doubt that it exceeds  $F_{MSY}$  by a wide margin and fishing at this rate for any period of time will in fact deplete

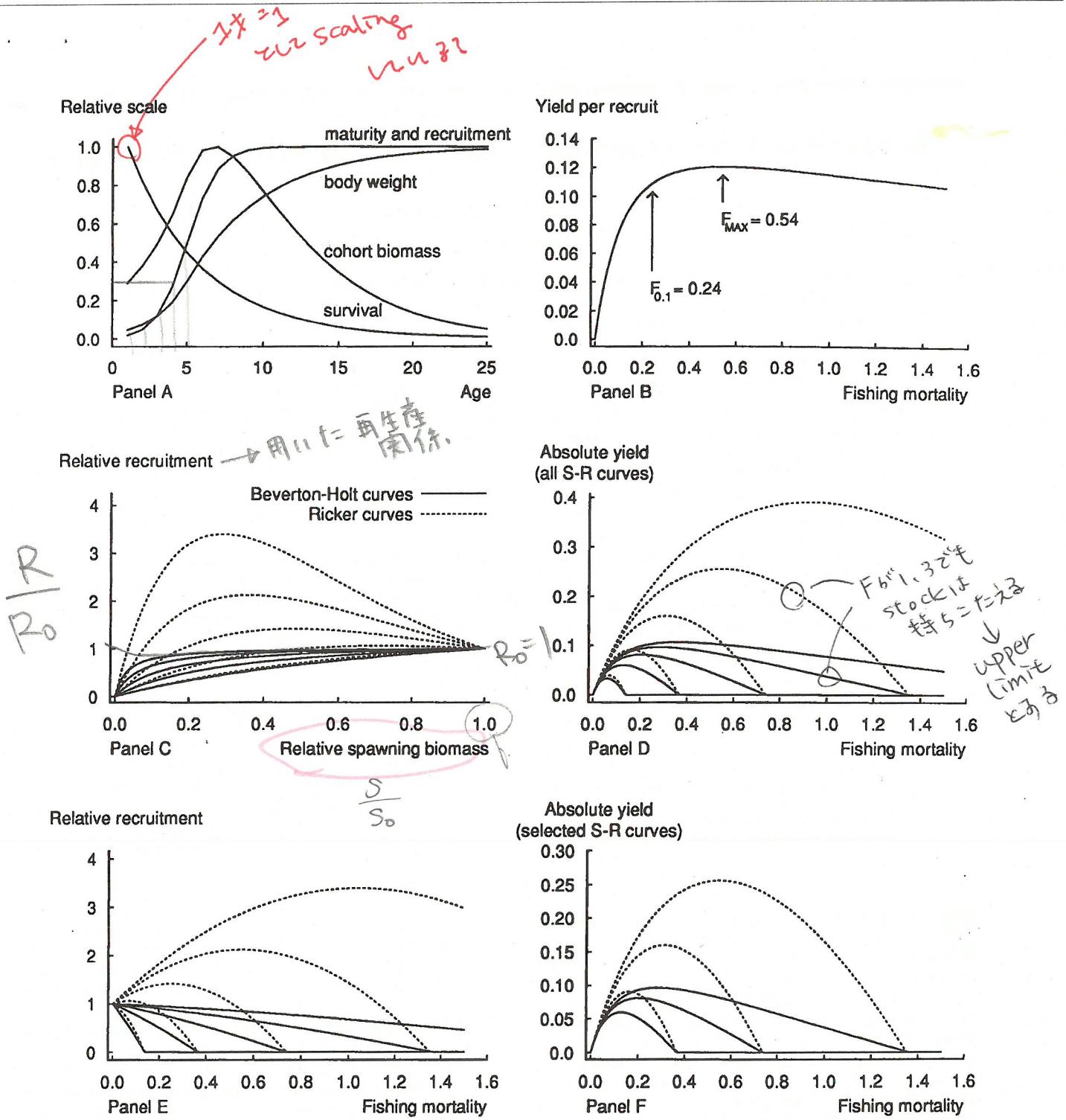


FIG. 1. Life history, recruitment, and yield of a typical demersal fish.

the spawning stock and reduce future recruitment, in some cases drastically. For these reasons,  $F_{MAX}$  has mostly passed out of favor (Deriso 1987; Sissenwine and Shepherd 1987).

$F_{0.1}$  (Gulland and Boerema 1973; Deriso 1987): This is the rate at which the slope of the yield per recruit curve (yield per recruit as a function of fishing mortality) falls to 10% of its value at the origin. Since the yield per recruit curve is typically rather flat over a wide range of higher fishing mortality

rates, the  $F_{0.1}$  rate usually provides something close to the maximum yield per recruit, and it is invariably much lower than  $F_{MAX}$ , so it is not so likely to deplete the spawning stock. Nevertheless, it is akin to  $F_{MAX}$  in that its calculation takes no account of its effect on the spawning stock or subsequent recruitment. Deriso (1987) discussed ways of checking on whether  $F_{0.1}$  (as defined there) is sustainable and conditions under which it is equal to  $F_{MSY}$ , but in any given application it cannot be known whether  $F_{0.1}$  will be greater or less than  $F_{MSY}$ .

TABLE 1. Life history parameters of New England groundfish stocks. The maturity and recruitment schedules show the ages at which 10 and 90% of a year-class are sexually mature or recruited to the fishery. Data from New England Fishery Management Council (1985, Part 5).

Stock	Natural mortality	Maturity schedule		Recruitment schedule	
		10%	90%	10%	90%
Georges Bank Atlantic cod ( <i>Gadus morhua</i> )	0.2	1	5	2	4
Georges Bank haddock ( <i>Melanogrammus aeglefinus</i> )	0.2	1	4	2	3
Pollock ( <i>Pollachius virens</i> )	0.2	1	5	2	4
Georges Bank yellowtail flounder ( <i>Limanda ferruginea</i> )	0.2	1	4	2	4
American plaice ( <i>Hippoglossoides platessoides</i> )	0.2	2	6	3	5
Georges Bank winter flounder ( <i>Pseudopleuronectes americanus</i> )	—	1	3	1	3

$F = M$  (Alverson and Pereyra 1969): This choice is based on the belief that  $F_{MSY}$  is often near the rate of natural mortality  $M$ . That may be true, but since there are few stocks for which  $F_{MSY}$  has been determined with any confidence, for the reasons stated, there is little empirical evidence to support the belief. Like  $F_{MAX}$  and  $F_{0.1}$ , this strategy takes no account of the effect of the chosen rate on spawning stock size and recruitment.

One method that has been suggested for assuring the maintenance of adequate spawning biomass is to fish at some fixed rate so long as spawning biomass remains above a threshold size, but to suspend the fishery anytime the spawning stock falls below the threshold (Hall et al. 1988; Quinn et al. 1990). This makes some sense, but without knowing the spawner-recruit relationship it is difficult to make a rational choice of either the fixed exploitation rate or the threshold. At worst this method simply imposes the requirement of choosing another parameter value in an essentially arbitrary fashion. And like other biomass-based exploitation strategies, this method is not really practical for stocks that are subject to large natural variations in equilibrium abundance, which now appear to represent the rule rather than the exception.

Another method of assuring an adequate level of spawning is to limit fishing mortality to a level that will maintain a certain value of spawning biomass per recruit, or equivalently, cohort egg production. In the form of size limits designed to guarantee one or more spawnings before capture, this is an old idea. It is also attractive, like a fixed exploitation rate, in that it will cause the spawning stock size to adjust automatically to changes in carrying capacity or to rebuild automatically from a run of poor year-classes.

Beddington and Cooke (1983) calculated the reduction in fishing mortality below  $F_{MAX}$  that would be necessary to keep spawning biomass per recruit above an arbitrary 20% of the unfished value. Botsford and Hobbs (1986) determined not only the fishing mortality rate but also the lower and upper age limits that would maximize yield subject to the constraint that cohort egg production be kept above a prescribed proportion, again chosen arbitrarily, of the unfished level. They also cited a number of other studies where cohort egg production was considered in choosing management measures.

Shepherd (1982) discussed the relationship between spawning biomass per recruit and the slope of the left-hand limb of

the spawner-recruit curve and observed that a stock would collapse if fishing mortality reduced spawning biomass per recruit below a critical level. The same reasoning was used by Sissenwine and Shepherd (1987) and Gabriel et al. (1989) in deriving a level of fishing mortality at which a cohort will just replace itself at observed levels of recruit production per unit spawning biomass. This fishing mortality rate, denoted  $F_{rep}$ , is the one that reduces spawning biomass per recruit to the median observed in a set of spawner-recruit data. If the spawner-recruit data refer to year-classes produced by very small spawning stocks,  $F_{rep}$  will be an estimate of the maximum sustainable fishing mortality rate in the sense of Shepherd (1982). If the data refer to an unfished stock,  $F_{rep}$  will be zero. Thus, while  $F_{rep}$  is always a sustainable rate, it can be much higher or much lower than  $F_{MSY}$ , like the other rates calculated from life history parameters.

The present paper deals with the question of whether it is possible to calculate an exploitation rate from life history parameters that will provide a yield near MSY for any likely spawner-recruit (S-R) relationship. The approach is first to set some reasonable limits on the range of S-R relationships considered and then to construct the yield curves for those S-R relationships and a range of life history parameters typical of demersal marine fish. It will be shown that a suitable fishing mortality rate does exist for all of the cases considered, and it is always very close to the rate that reduces spawning biomass per recruit to 35% of the unfished level.

## Methods

The performance of various exploitation strategies was investigated by constructing a model population similar to marine demersal stocks and computing the equilibrium yield corresponding to a range of S-R relationships and fishing mortality rates. A key step in the process was to exclude some S-R relationships from serious consideration on the grounds that they implied either too little or too much density-dependent change in reproductive success, in comparison with the performance of real populations that have been heavily fished or overfished. It was then possible to find a fishing mortality rate that would obtain a large proportion of MSY for any of the remaining S-R relationships. Finally, yield computations were performed with the same restricted set of S-R relationships and

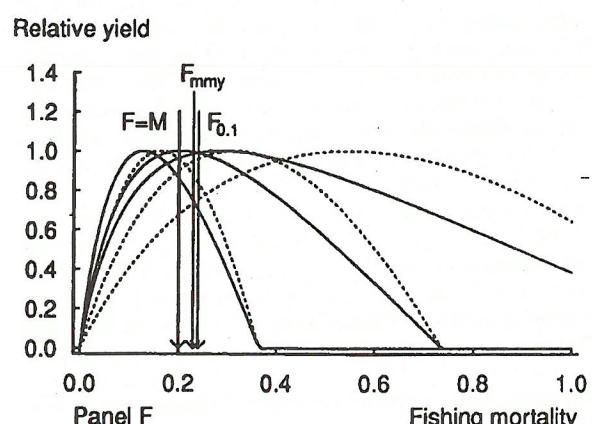
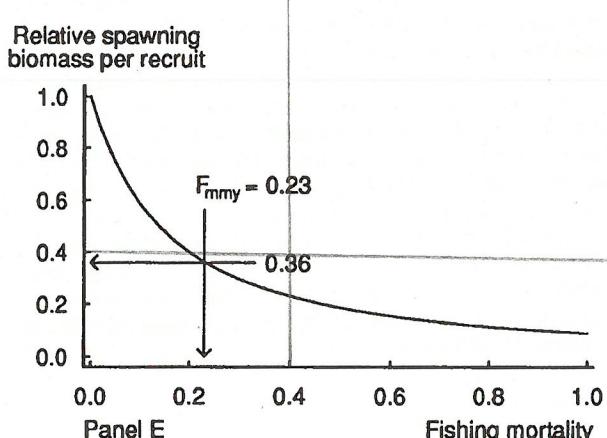
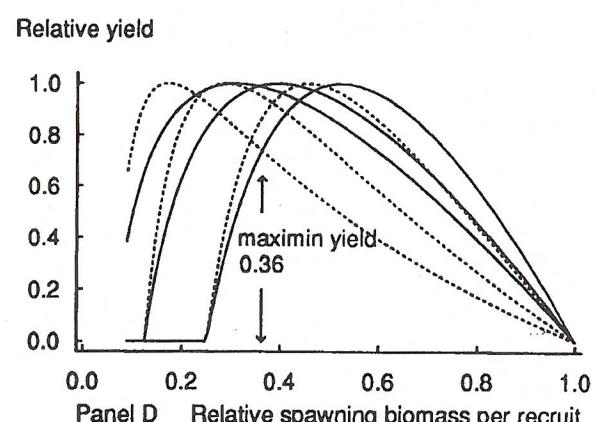
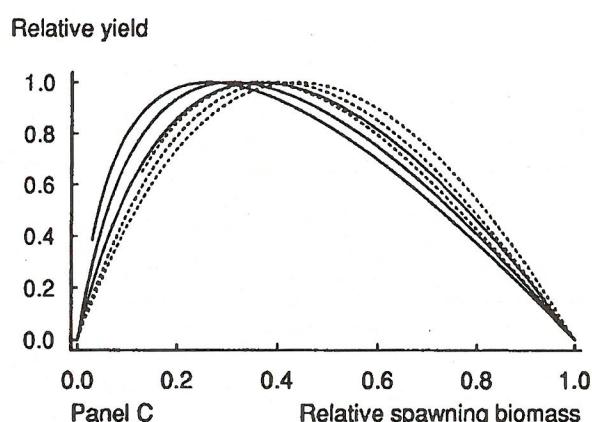
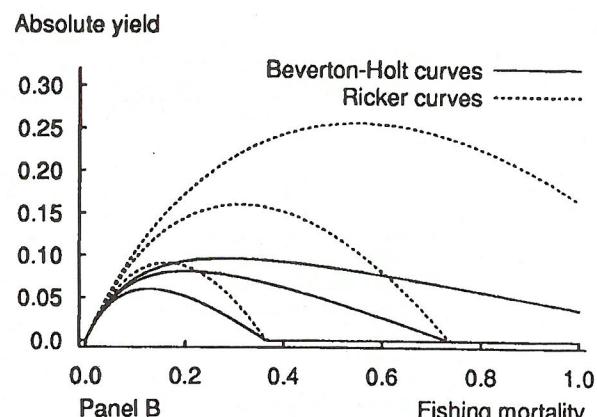
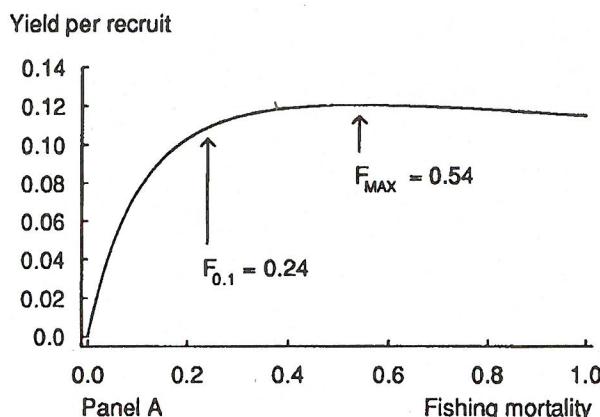


FIG. 2. Spawning biomass and yield calculations for the typical life history.

a range of life history parameter values to find a consistent method of computing the optimal fishing mortality rate from life history parameters. The steps are described below.

#### Life History Parameters

The central object of study for this paper was the typical demersal marine fish, which has an instantaneous natural mortality rate  $M = 0.2$  and a von Bertalanffy growth (in weight) coefficient  $K$  equal to  $M$ . Schedules of recruitment to the fishery

and sexual maturity were described by a logistic function that reaches 10% at age 3, 50% at age 5, and 90% at age 7. At age 5 the weight of the fish is 30% of the asymptotic weight. These standard life history features are graphed in Fig. 1A and detailed in the Appendix. As is typical, they imply a value of  $F_{0.1}$  near  $M$  and a value of  $F_{MAX}$  that is much larger (Fig. 1B).

The life history parameters given above were chosen to be typical of groundfish and will be referred to as the "typical life history" below. Many stocks in the North Atlantic and North Pacific do in fact have life histories close to the typical pattern,

↑  
typical  
parameters

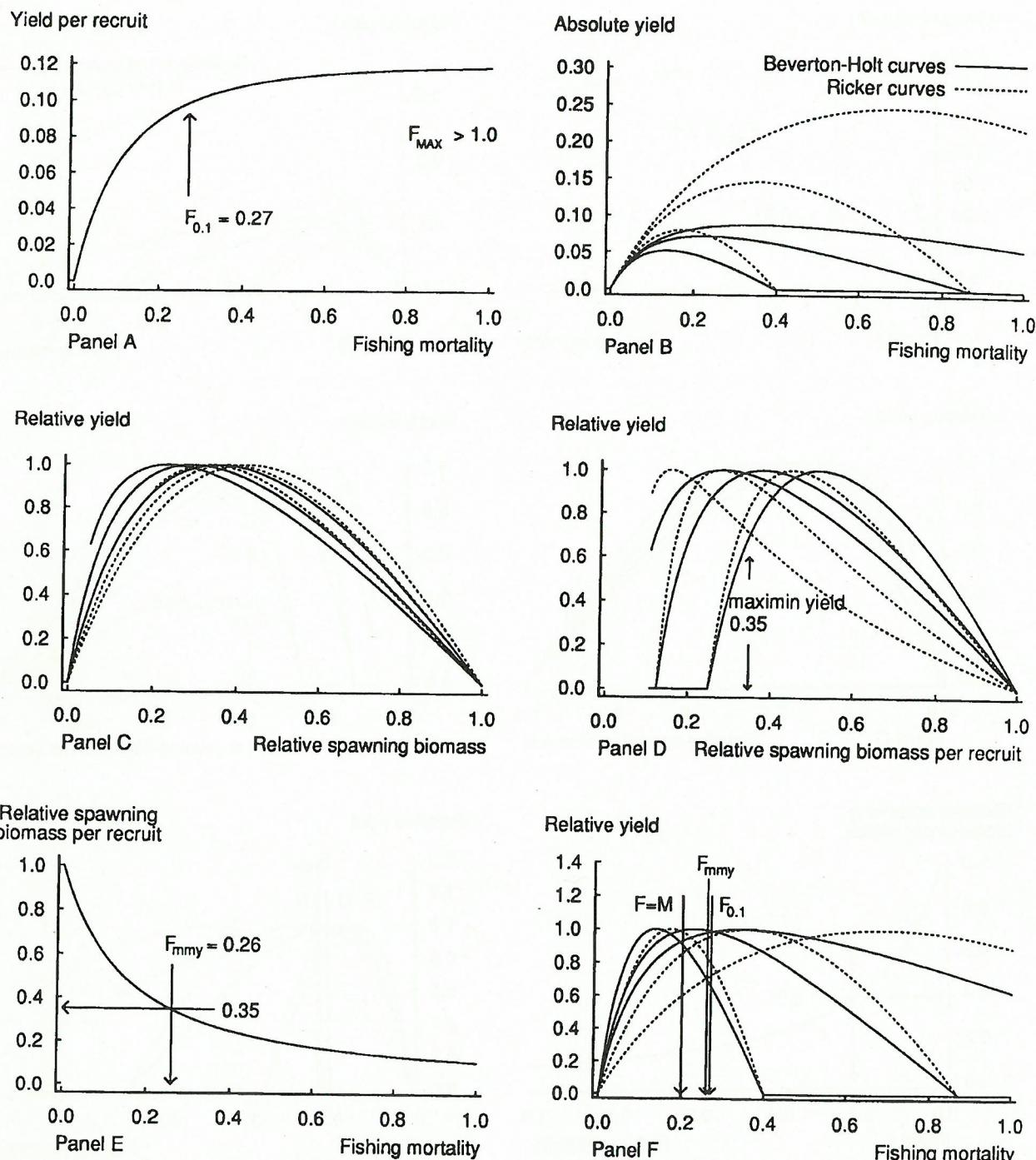


FIG. 3. Spawning biomass and yield calculations for the case of slow growth ( $K = M/2$ ).

as exemplified by the listing of New England stocks in Table 1, but a range of natural mortality ( $M$ ) and growth rates ( $K$ ) occurs. Empirical data (Pauly 1980) and evolutionary theory (Roff 1984) both indicate a correlation of  $K$  and  $M$ , and they are often of similar size, but the ratio  $M/K$  is substantially less or greater than unity for many stocks. Therefore, while  $M$  and  $K$  are both set at 0.2 in the typical life history, other values (0.1 and 0.4) are used later in the paper to investigate the effect of different absolute and relative values. Similarly, while recruit-

ment and maturity schedules often coincide, they are quite different for many stocks. These two schedules are therefore taken to be coincident for the typical life history, but a shift of one relative to the other is considered later in the paper. The duration of the recruitment and maturity schedules, e.g. the 4 yr from 10% maturity to 90% maturity in the typical life history, does vary among stocks, but different values are not considered in this paper because the effect of schedule duration on yield comparisons is minor.

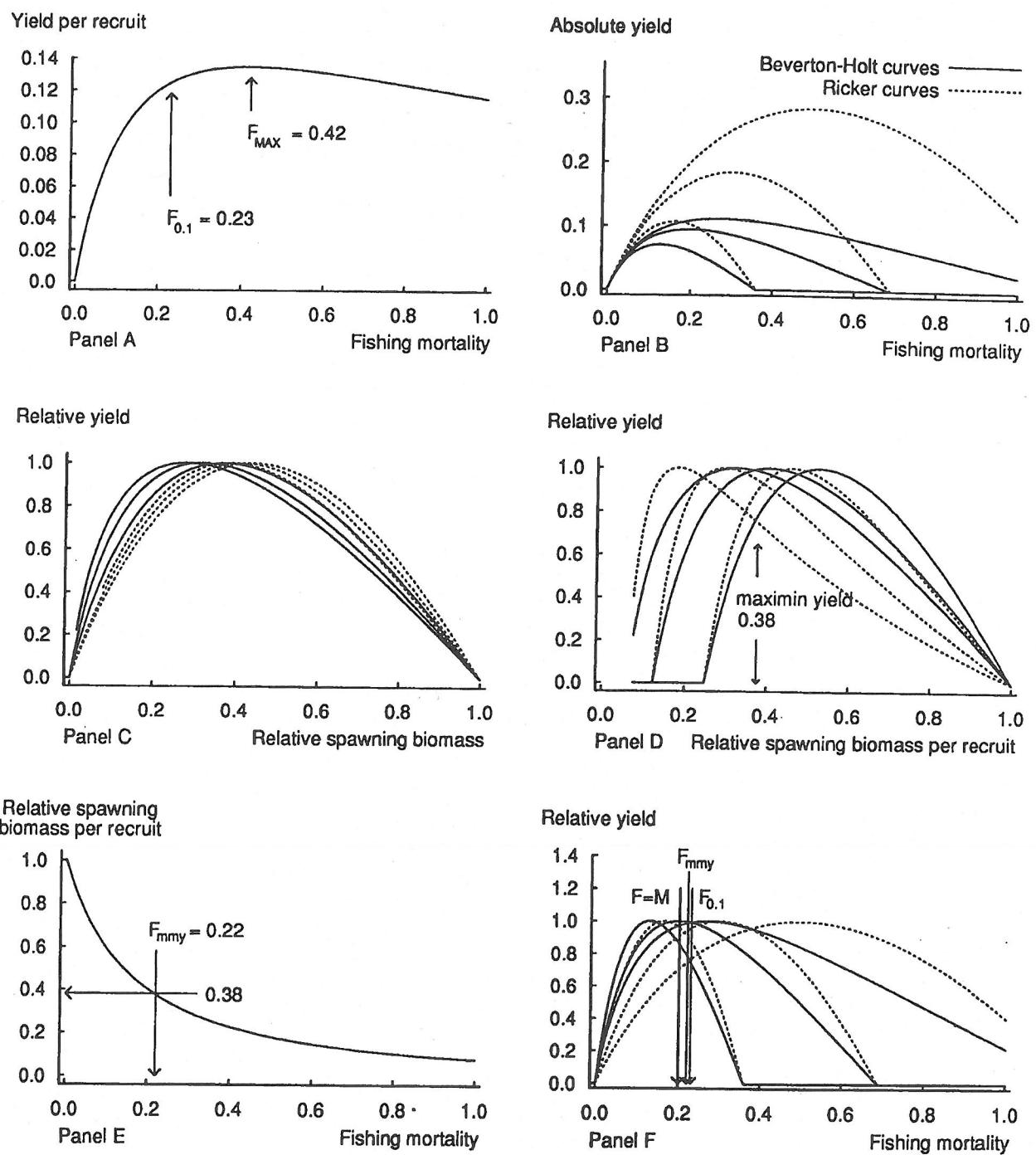


FIG. 4. Spawning biomass and yield calculations for the case of rapid growth ( $K = 2M$ ).

#### Initial Specification of Spawner-Recruit Relationships

The S-R relationships considered initially were sets of the Beverton-Holt and Ricker forms, representing asymptotic and domed curves (Fig. 1C). A large number of other forms might be considered, but these two can approximate the other forms adequately.

The formulation of the relationships is that of Kimura (1988); each curve describes *relative* recruitment as a function of *relative* spawning biomass (both measured relative to their unfished levels) and is determined by a single shape parameter.

The value of the shape parameter determines the potential for density-dependent increase in the specific reproductive rate, meaning number of recruits per unit spawning biomass. The five initial curves of each form represent potential increases in specific reproductive rate by factors of 2, 4, 8, 16, and 32, meaning that at very low spawning stock size, spawners are 2–32 times as successful as they are at the unfished spawning stock size, according to the shape parameter of the S-R curve. It will be argued below that this range of parameter values exceeds what can realistically be expected in nature, at both

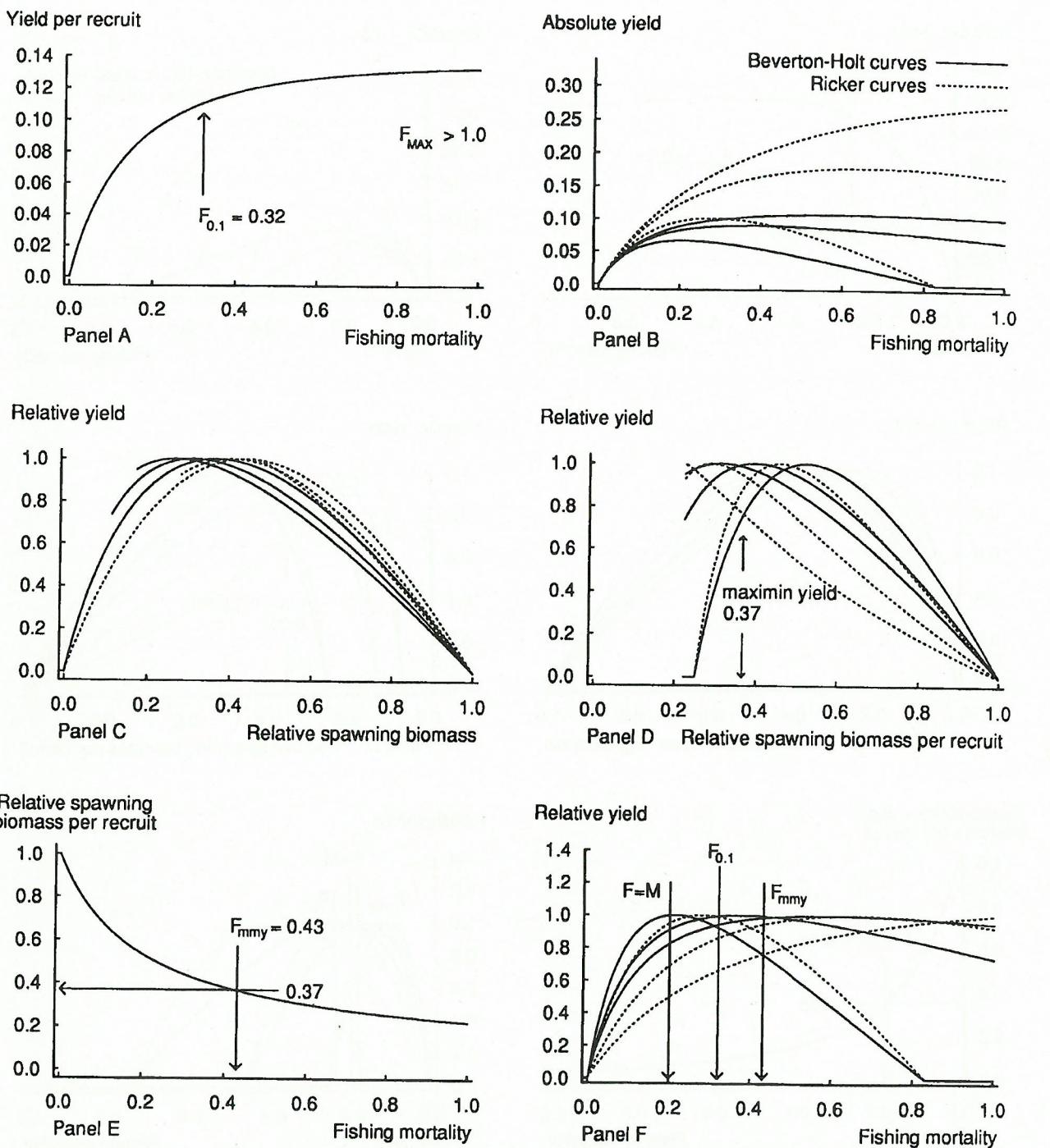


FIG. 5. Spawning biomass and yield calculations for the case of delayed recruitment (2 yr).

the upper and lower ends, so that a subset of the initial S-R relationships will serve as a reasonable approximation of the true range in nature.

#### Exclusion of Some Spawner-Recruit Relationships

The yield curves corresponding to the initial S-R curves are extremely diverse, with  $F_{MSY}$  values ranging from less than 0.1 to almost 1.0 (Fig. 1D). If all of the S-R curves had to be considered, there would clearly be no possibility of choosing a

compromise fishing mortality rate that would serve reasonably well for all of the yield curves.

But some of the S-R relationships can be ruled out on the basis of experience and common sense. The least density-dependent pair of S-R curves implies that the stock would be driven to extinction by a fishing mortality rate less than  $M$  (Fig. 1E), and the next pair implies extinction at a fishing mortality rate less than  $2M$ . This could be true for some stocks, but the author is not aware of any cases. Meanwhile there are numerous examples of demersal stocks that have sustained fishing mor-

全部のS-R CURVEは  
実際のところ  
ほとんどがFを超過する

least density-dependent  
pair と呼ぶ

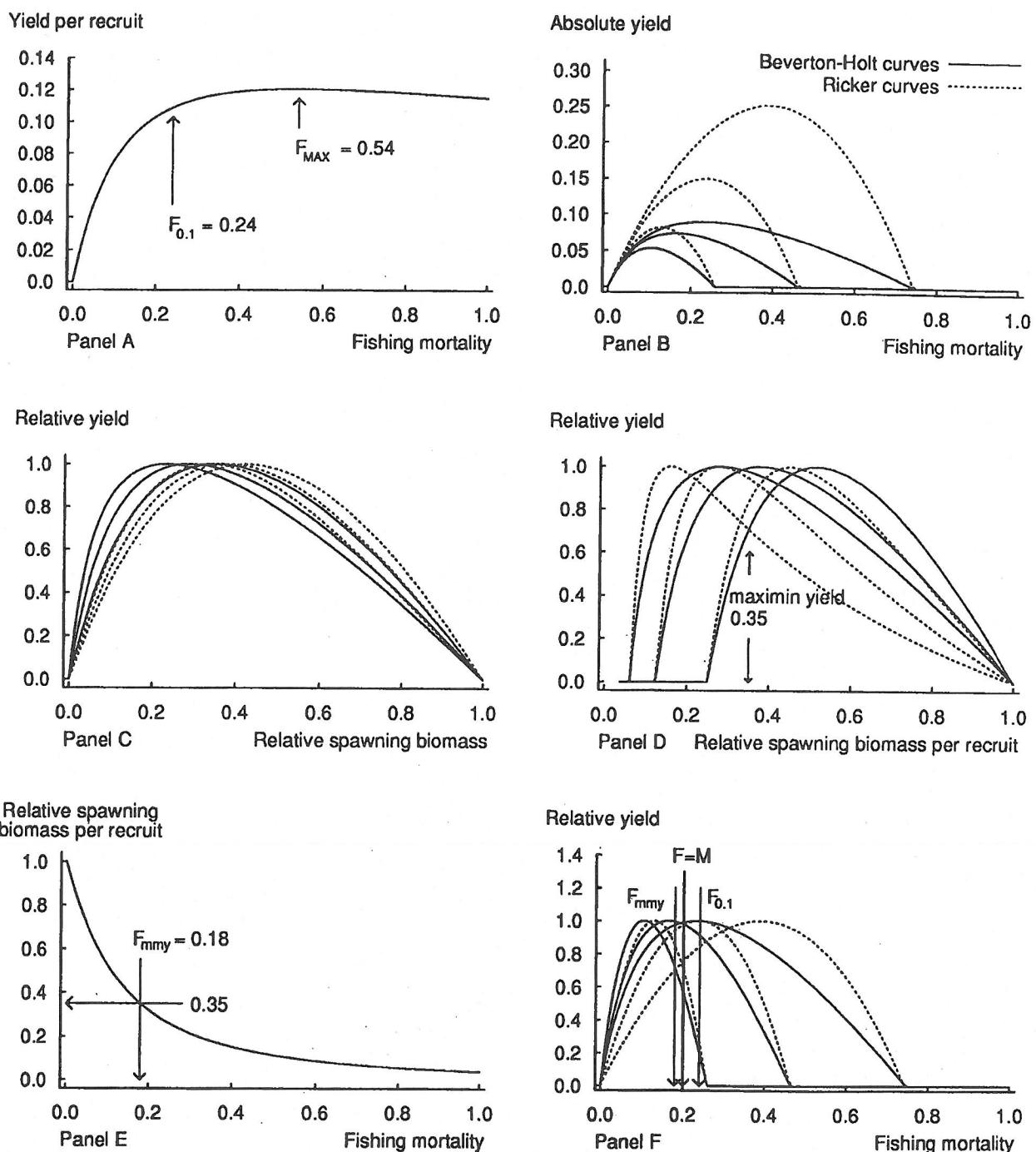


FIG. 6. Spawning biomass and yield calculations for the case of delayed maturity (2 yr).

tality rates well above  $2M$  for long periods. Lacking clear evidence for a particular stock, therefore, it seems reasonable to exclude the lowest pair of S-R curves from the range to be considered and to treat the next pair as a lower bound for the S-R relationship.

At the other extreme, the most density-dependent pair of curves indicates hardly any ill effect of fishing at  $F = 1.0$ . Again, this may be true for some stocks, particularly where gear regulations postpone recruitment until after one or two spawnings, but in most cases, fishing at such a high rate can

be expected to reduce recruitment and yield dramatically. Even the next lower pair of curves seems quite optimistic, as they imply that the stock could sustain  $F = 1.3$  or so. It therefore seems reasonable to rule out the uppermost pair of S-R curves and to treat the next pair as an upper bound on the S-R relationship.

With the extreme portions of the initial range of S-R relationships excluded, it is possible to choose a fishing mortality rate in the range of 0.20–0.25 that will provide a large fraction of MSY regardless of which of the remaining S-R curves is

most density-dependent pair?

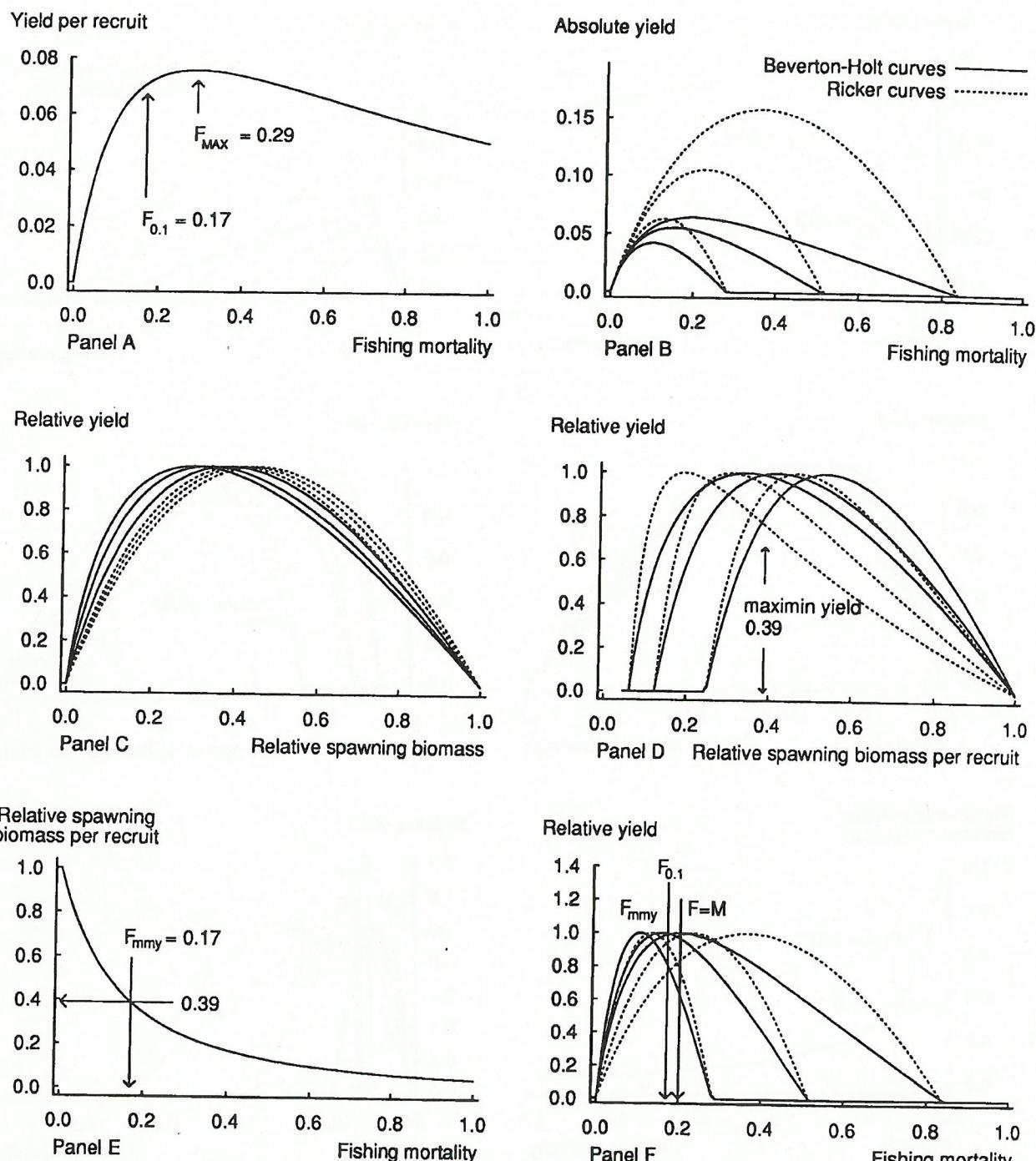


FIG. 7. Spawning biomass and yield calculations for the case of small size at entry (weight at entry equal to 10% of asymptotic weight).

correct (Fig. 1F). Specifically,  $F = 0.23$  will provide about 75% of MSY if either the most density-dependent Ricker curve (corresponding to the uppermost yield curve) or the least density-dependent Bevinton-Holt curve (corresponding to the lowermost yield curve) is the correct one. For any of the intermediate S-R and yield curves,  $F = 0.23$  will provide a larger fraction of MSY.

This is essentially the procedure devised by Lenarz (1984) to choose a fishing mortality rate for widow rockfish (*Sebastodes entomelas*): decide which S-R curves to entertain, plot the cor-

responding yield curves, and choose a fishing mortality rate that performs well across the entire range of possible yield curves.

#### Investigation of Exploitation Strategies

The Lenarz procedure is adequate by itself for choosing a fishing mortality rate in any particular case, but it was of interest to pursue the study of the case at hand further to see what features were invariant with respect to the S-R relationship,

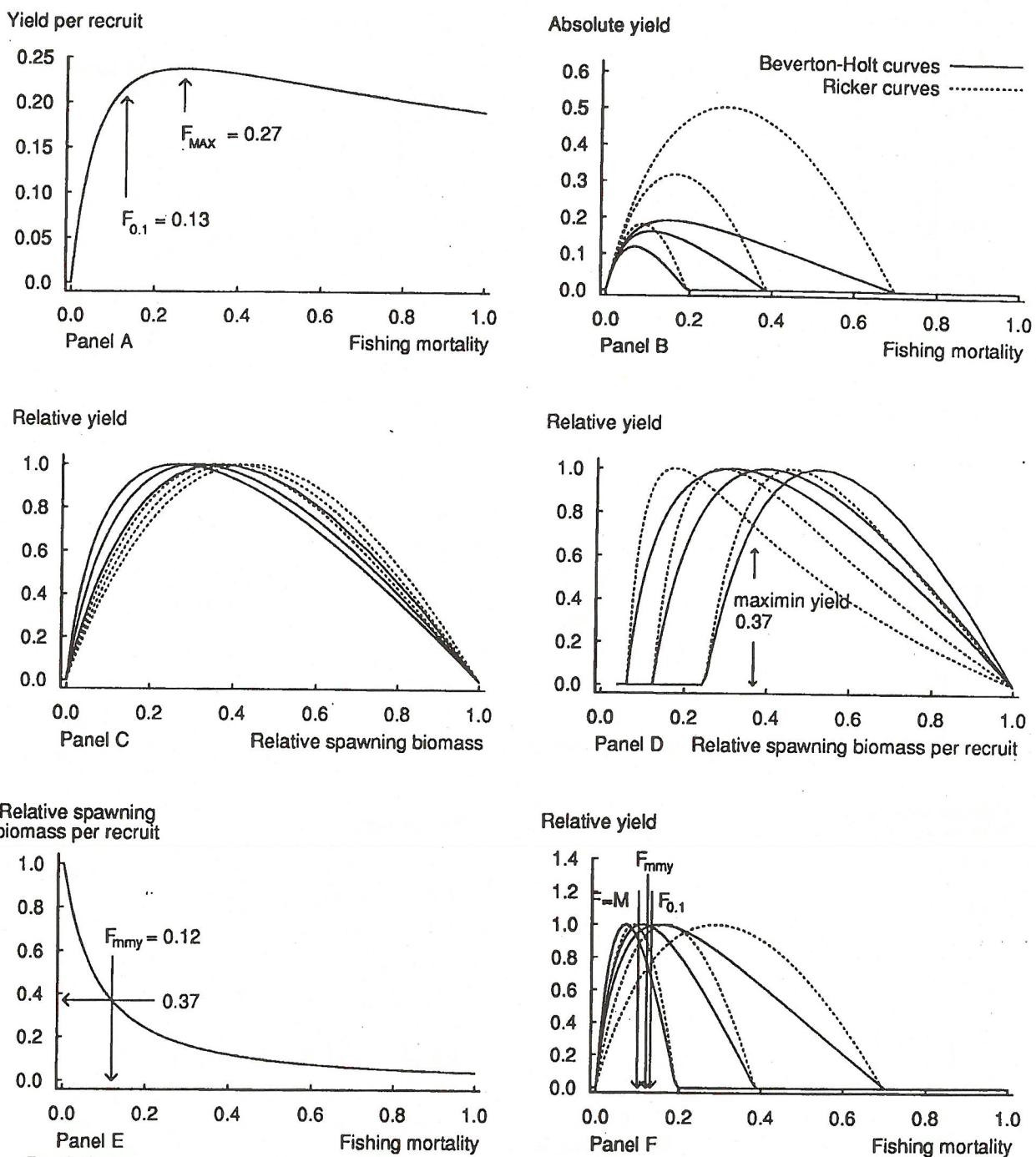


FIG. 8. Spawning biomass and yield calculations for the case of low natural mortality ( $M = 0.1$  but  $K = 0.2$  as elsewhere).

and in particular whether a suitable fishing mortality rate could be calculated from the life history parameters alone. The results presented below were obtained by investigating the behavior of the model population.

## Results

### Relationship between Spawning Biomass and Yield

Even with the extreme S-R relationships excluded, the plot of yield against fishing mortality depends quite strongly on the

form of the S-R curve (Fig. 2B, same as 1F). But when relative yield (i.e. yield as a fraction of MSY for each yield curve) is plotted against relative spawning biomass, all of the curves nearly coincide (Fig. 2C). This result holds even when the extreme S-R curves are included, and it holds for a wide variety of life history parameters, including all combinations of all the parameter values listed in the Appendix. Moreover, the graph has a fairly broad summit, indicating that a yield of at least 75% of MSY would be obtained by any strategy that kept the

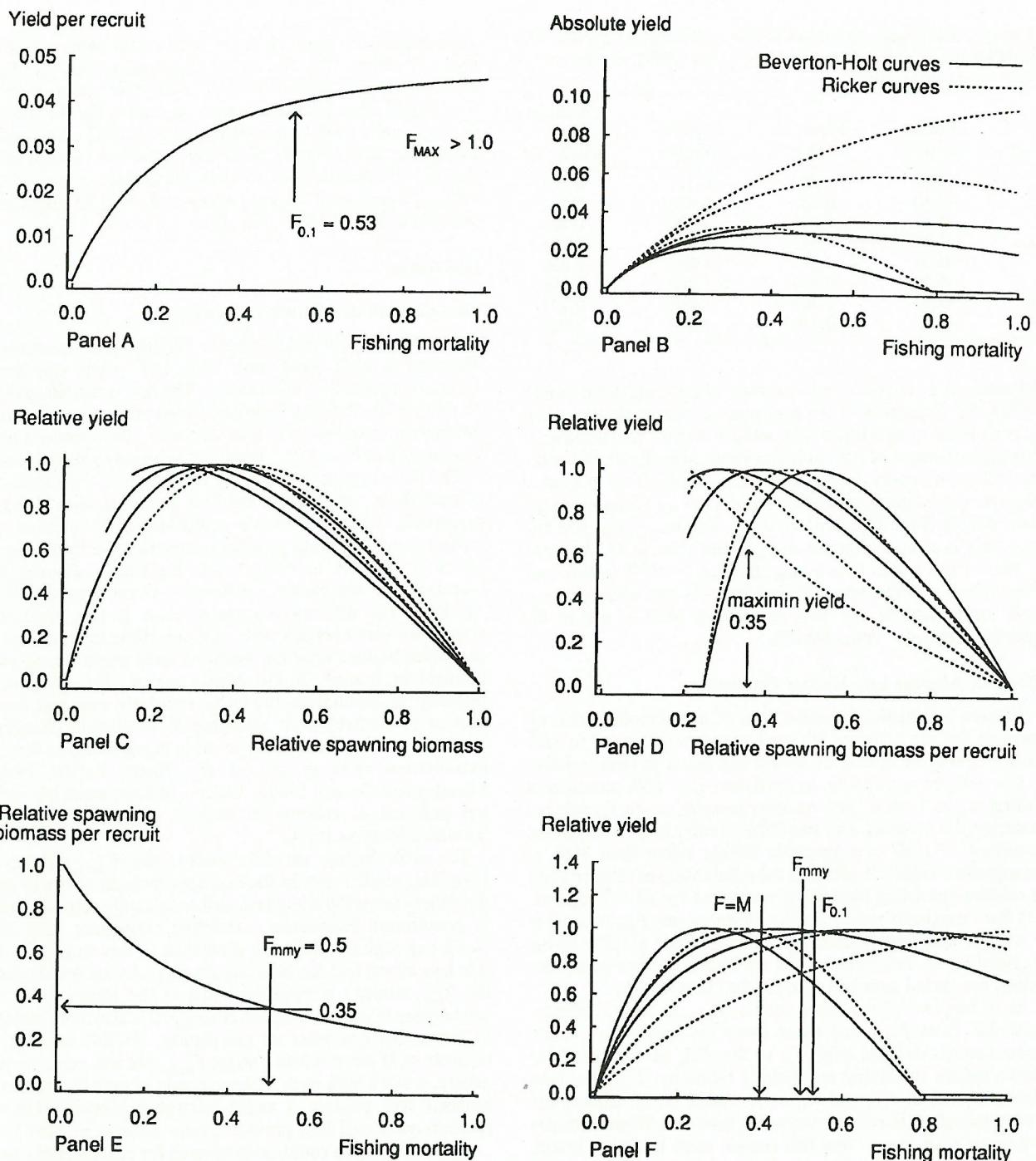


FIG. 9. Spawning biomass and yield calculations for the case of high natural mortality ( $M = 0.4$  but  $K = 0.2$  as elsewhere).

relative spawning biomass anywhere in the range of roughly 20–60% of the unfished level.

By itself, the very consistent relationship between relative spawning biomass and relative yield, nearly identical for all S-R curves, argues for a biomass-based strategy rather than an exploitation rate strategy. It is clear that even if unfished spawning biomass were known only very roughly, say with a precision of the half-to-double variety, one could still be reasonably sure of getting something close to MSY simply by holding the spawning biomass in the vicinity of 35–40% of the

estimated unfished level.

#### Relationship between Spawning Biomass per Recruit and Yield

An alternative strategy that does a fairly good job of exploiting the same relationship is to lower the relative spawning biomass *per recruit* to a point somewhere near the middle of the 20–60% range (Fig. 2D). In this case the curves do not coincide as well, but there is a level of spawning biomass *per recruit* that provides a large fraction of MSY even under the least

TABLE 2. Life history parameters of Bering Sea walleye pollock. The recruitment schedule is from Quinn and Collie (1990); all other values from Wespestad (1989).

Age	Natural mortality	Proportion mature	Proportion recruited	Average body weight (kg)
2	0.45	0.008	0.127	0.105
3	0.30	0.289	0.438	0.251
4	0.30	0.641	1.000	0.409
5	0.30	0.842	1.000	0.465
6	0.30	0.901	1.000	0.650
7	0.30	0.947	1.000	0.798
8	0.30	0.963	1.000	0.892
9+	0.30	0.970	1.000	0.970

favorable S-R curves. This is shown as the "maximin yield" in Fig. 2D because it is the maximum of the minimum yields at each level of spawning biomass per recruit. (Alternatively, it is the maximum of the minimum yields at each rate of fishing mortality.) It occurs at 36% of the unfished value of spawning biomass per recruit, which corresponds to a fishing mortality rate of 0.23 (Fig. 2E), denoted  $F_{mmy}$ . For the typical life history, this is almost identical to  $F_{0.1}$ , and close to  $M$ . Any one of those rates would take a large fraction of MSY in this case (Fig. 2F).  $F_{mmy}$  takes about 75% of MSY if either of the extreme S-R curves applies and 90% or more of MSY if one of the intermediate S-R curves applies.

#### Effect of Altering Life History Parameters

Figures 3–7 depict the same sorts of calculations and comparisons for life histories with one parameter changed in each case to show the effects of slower and faster growth (relative to  $M$ ), delayed recruitment to the fishery (i.e. 50% recruitment shifted to age 7 while 50% maturity remains at age 5), delayed maturity (the reverse), and small size at entry (50% recruitment occurring at 10% of asymptotic weight rather than 30% of asymptotic weight). In all cases the relationship of relative yield to relative spawning biomass is very close for all S-R curves, and the "maximin yield" fishing mortality rate  $F_{mmy}$  occurs at a level of spawning biomass per recruit close to 35% of the unfished level. The same results are obtained when parameter values are varied simultaneously rather than singly.

In all but two of the cases shown,  $F_{mmy}$  is nearly indistinguishable from  $F_{0.1}$ , and those cases are instructive. When recruitment is delayed (Fig. 5), so that fish have a chance to spawn before sustaining any fishing mortality,  $F_{mmy}$  is much higher than both  $F_{0.1}$  and  $M$ , as it should be to achieve the proper reduction in relative spawning biomass. When maturity is delayed (Fig. 6), so that fish sustain some mortality before spawning,  $F_{mmy}$  is considerably lower, in this case to prevent an excessive reduction in spawning biomass. These examples show that  $F_{0.1}$  is probably a reasonable exploitation rate so long as the recruitment and maturity schedules of a stock coincide, but that  $F_{mmy}$  is generally preferable because it can be relied on to maintain an appropriate level of spawning biomass per recruit for any set of recruitment and maturity schedules.

#### Effect of Error in the Estimate of Natural Mortality

In most cases,  $F_{mmy}$  is also close to the natural mortality rate  $M$ , and its value is of course quite sensitive to the value of  $M$ , which is notoriously difficult to estimate. In many groundfish

assessments, the estimate  $M = 0.2$  is used more out of habit than conviction. For the typical life history (Fig. 2),  $F_{mmy}$  is 0.23 when  $M$  is taken to be 0.2. If the true value of  $M$  were 0.1, but all other parameters were the same, the desired value of  $F_{mmy}$  would be 0.12 and fishing at  $F = 0.23$  could severely deplete the stock (Fig. 8). Similarly, if the true value of  $M$  were 0.4 and all other parameters were the same, the desired value of  $F_{mmy}$  would be 0.50 and fishing at  $F = 0.23$  might obtain only about half of MSY (Fig. 9).

#### Discussion

##### Consideration of Alternative Strategies

The results presented above suggest two methods for obtaining a high yield with little risk when one has no knowledge of the S-R relationship. The first is to hold spawning biomass at 20–60% of the unfished level and harvest the surplus production, whatever that turns out to be. The second is to fish consistently at  $F = F_{mmy}$ , whatever happens to stock biomass.

The first strategy, presumably implemented with some kind of smoothing procedure to stabilize annual catches, is clearly preferable when a stock's equilibrium abundance (i.e. environmental carrying capacity) appears to be fairly constant and it is possible to estimate the unfished spawning stock biomass with reasonable confidence. Great precision is not required. The difficulty in many cases is that equilibrium abundance varies considerably in the medium term, so that one can never be sure what the unfished level might be, or where it might be headed. In the Alaska region, for example, the majority of groundfish stocks (particularly cod and several species of flatfish) have exhibited 5- to 10-fold changes in abundance during the last 20 yr while being fished at very low exploitation rates or not at all (North Pacific Fishery Management Council 1989a, 1989b). In these cases it is clearly not practical or rational to attempt to maintain a certain spawning biomass level.

For such highly variable stocks, the  $F_{mmy}$  strategy or something similar may be the best approach, since it will allow the fishery to track the yield curve through large natural changes in equilibrium abundance, extracting something near MSY under any regime. The main drawback to this strategy is that it is less robust than the biomass strategy. As the results show, the  $F_{mmy}$  strategy is more sensitive to the form of the S-R relationship than is the biomass strategy. It is also more sensitive to errors that can enter its calculation. A 50% error in the estimate of  $M$  can produce a target  $F_{mmy}$  that will perform quite poorly, while a 50% error in the estimate of unfished spawning biomass will produce a target spawning biomass that will perform quite well (i.e. provide a large fraction of MSY).

Hybrid strategies could be developed for cases where a catch limit recommendation could be made either way but with less than complete confidence. A hybrid strategy could take on some of the adaptive behavior of an exploitation rate strategy while preserving some of the robustness of a biomass strategy.

##### Examples: Bering Sea Pollock and Cod

The walleye pollock (*Theragra chalcogramma*) stock of the eastern Bering Sea is unusual among Alaska groundfish stocks in that its abundance has varied by a factor of only three or so over the last two decades. Fishing mortality rates have been moderate (mostly much less than  $M = 0.3$ ). There is no indication that carrying capacity has changed greatly, and

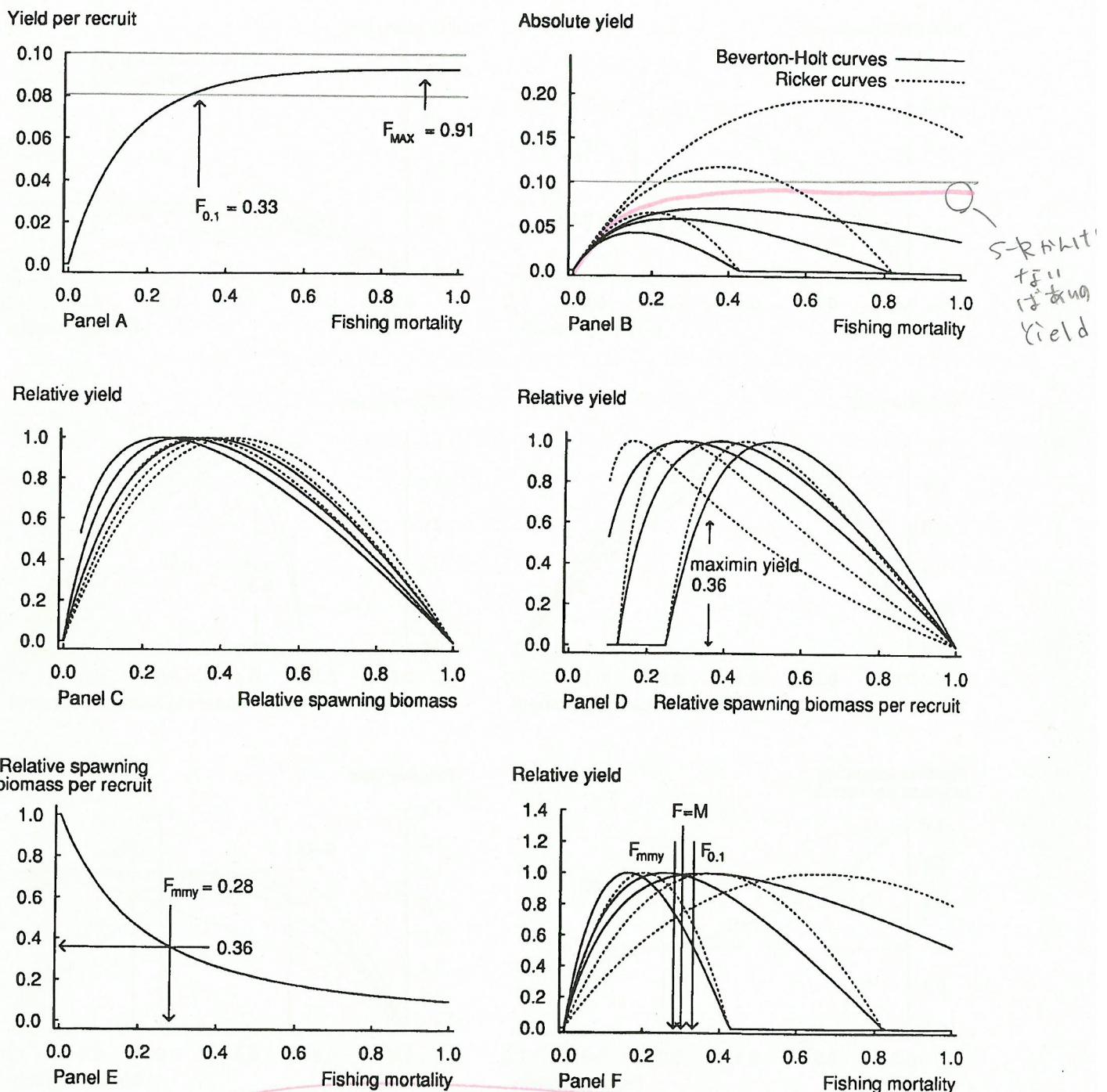


FIG. 10. Spawning biomass and yield calculations for Bering Sea walleye pollock.

Table 21

recruitment (age 2) has averaged about 10 billion fish, with considerable year-to-year variation but no trend. S-R data suggest a domed S-R relationship, but the points are so scattered that the form of the relationship is uncertain. Stock histories and assessments are given in Wespestad (1989) and Quinn and Collie (1990).

This stock is clearly a candidate for a biomass-based strategy. The unfished spawning stock size can be estimated from the recent recruitment level and the unfished spawning biomass per recruit, calculated from life history parameters (Table 2).

It is about 10 million metric tons. (If the S-R relationship is in fact dome-shaped, this estimate will be too high, since the recent recruitment level will be somewhat greater than the unfished level, but for present purposes the possible error is not important.) A target spawning biomass of 4 million metric tons, at the center of an acceptable range of 2–6 million metric tons, will provide the bulk of MSY regardless of the actual form of the S-R relationship. Production modelling by Quinn and Collie (1990) indicated that the MSY level of *exploitable* biomass is about 6 million metric tons, which corresponds to a spawning

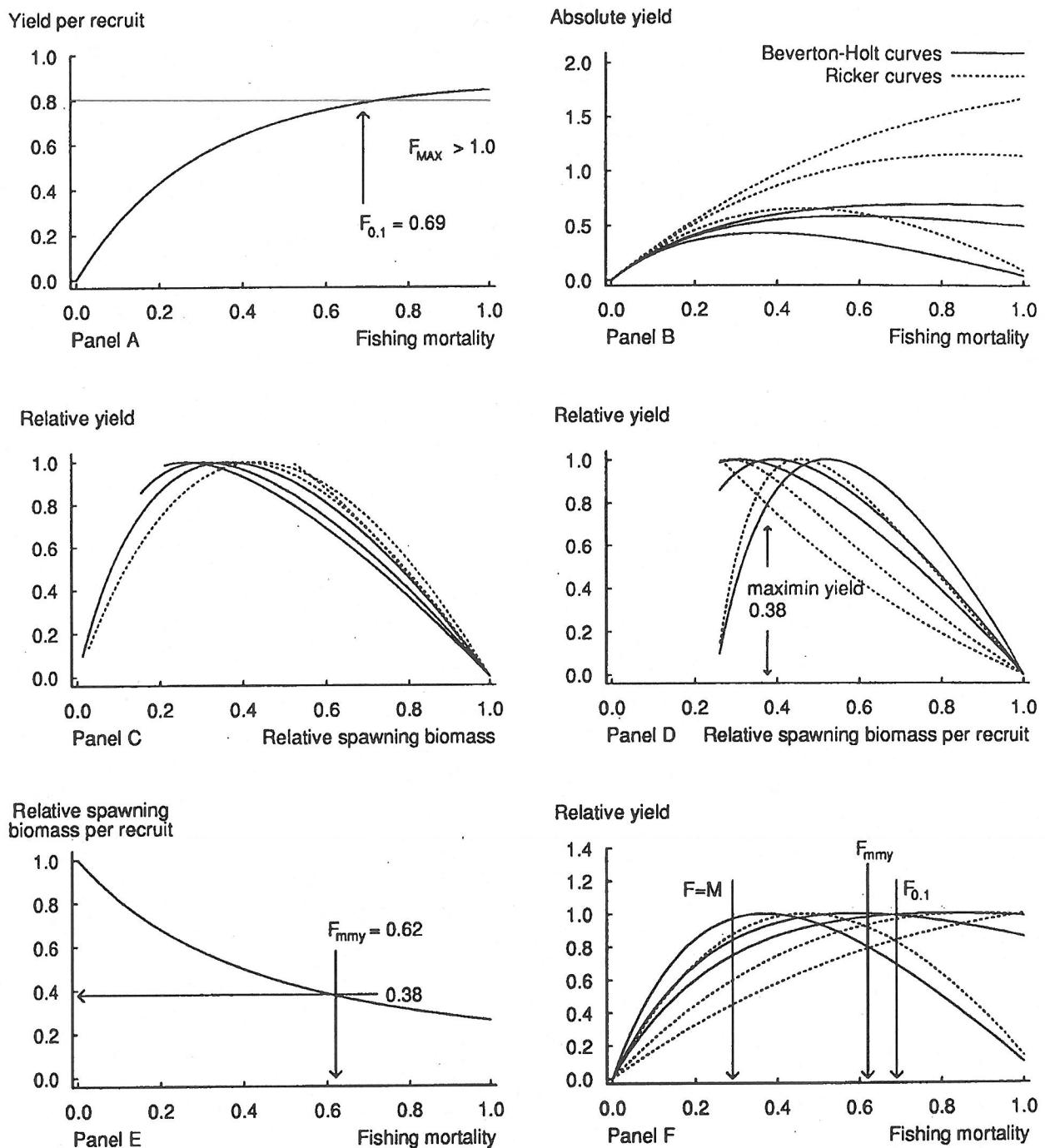


FIG. 11. Spawning biomass and yield calculations for Bering Sea Pacific cod.

stock biomass of 4.5–5.0 million metric tons.

Alternatively, the stock could be fished at a steady  $F_{mmy} = 0.28$  (Fig. 10), which happens to be very close to Quinn and Collie's (1990) estimate of  $F_{MSY} = 0.32$ .

Either way, the exploitation strategies developed in this paper, which require only life history parameters, agree very well with the strategies based on a long series of empirical data on the productivity of the pollock stock. This provides some

reassurance for adopting one or the other strategy in cases where empirical productivity data are unavailable or unreliable, such as Bering Sea Pacific cod (*Gadus macrocephalus*).

The Pacific cod stock of the Bering Sea has increased by roughly an order of magnitude since the mid-1970's. Fishing mortality rates have been low or nil during most of this period. Carrying capacity may have changed dramatically, or the upsurge in stock abundance may be the chance result of a few

TABLE 3. Life history parameters of Bering Sea Pacific cod (Dr. G. G. Thompson, National Marine Fisheries Service, Seattle, WA, pers. comm.).

Age	Natural mortality	Proportion mature	Proportion recruited	Average body weight (kg)
3	0.29	0.004	0.036	0.651
4	0.29	0.114	0.086	1.726
5	0.29	0.666	0.208	3.149
6	0.29	0.946	0.498	4.721
7	0.29	0.990	0.982	6.289
8+	0.29	0.997	0.397	7.752

strong year-classes. Fish of this stock are difficult to age, so catch at age has been estimated from catch at length, with the result that data on year-class strength are imprecise. In this situation, fitting a production model or S-R relationship is a difficult proposition. Thompson (1989a) reviewed the stock history and discussed alternative management strategies.

This stock is clearly a candidate for a fixed exploitation rate strategy, which will perform reasonably well through large fluctuations in equilibrium abundance. The life history parameters (Table 3) imply a full-recruitment  $F_{\text{mmy}} = 0.62$ , which is the rate required to reduce spawning biomass per recruit to the maximin yield level of 38% (Fig. 11).  $F_{\text{mmy}}$  is high in this case because growth is rapid, recruitment lags maturity, and only one age-class (age 7) is more than 50% vulnerable to the fishery. This example illustrates the importance and utility of determining the effect of a given fishing pattern on spawning biomass per recruit, not only to avoid overfishing but also to avoid underfishing.

#### Hazards and Limitations

The approach to choosing an exploitation rate developed here is based on the Lenarz procedure of computing a separate yield curve for each of several S-R relationships. An alternative procedure would be to set a probability distribution on the collection, or on the shape parameter, and compute a single expected yield curve. There are several pitfalls here. By not inspecting the yield curve corresponding to each S-R curve, one may include some clearly unrealistic S-R relationships in the calculations. Also, one may choose an optimum  $F$  that carries the risk of severely depleting the stock under one or more of the plausible S-R curves, when the aim is to maximize expected yield subject to the constraint that there be no serious risk of overfishing, as is often the case.

Perhaps the worst hazard is that a single expected yield curve, once computed, would be treated as an estimate of the actual yield curve of the stock, which it most certainly would not be. It should be stressed that the methods presented above supply only one result, namely a relative spawning biomass level or a fishing mortality rate that will obtain a large fraction of MSY. None of the calculations supplies any information about the actual magnitude of MSY, or the value of  $F_{\text{MSY}}$ , or the consequences of fishing at rates above  $F_{\text{mmy}}$ .

#### Physical Yield and Economic Yield

Finally, it should be kept in mind that the exploitation strategies derived here only serve to obtain a physical yield near the

maximum. As shown by Thompson (1989b), this sort of strategy can be, and usually is, far from any rational economic strategy. It may be useful in cases where the management objective happens to be a high physical yield, but in other cases its main function will be simply to provide a biological reference point or upper limit for quota deliberations. On the other hand, there is no reason why the methods used above could not be applied to the problem of locating an exploitation strategy that would reliably obtain something close to the maximum of some chosen economic value, much as Die et al. (1988) employed standard per-recruit calculations to investigate the utility rather than the physical yield that would be obtained from different management measures.

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## Appendix. Mathematical Details

Yield computations were performed with a range of life history parameters (natural mortality, growth, recruitment, and maturity schedules) centered on the values typical of groundfish stocks, and a range of spawner-recruit (S-R) relationships. Life history parameters were treated as fixed and independent of stock size. The parameter values and computations are detailed below.

### Natural Mortality

For the typical life history, the instantaneous rate of natural mortality was  $M = 0.2/\text{yr}$ . Other values used in some of the computations were 0.1 and 0.4/yr.

### Standard Age at Entry

The standard age at 50% maturity and 50% recruitment was  $k = 5 \text{ yr}$ . This value was chosen because groundfish tend to mature and recruit at an age around  $1/M$  and the standard  $M$  was 0.2, but the actual value of  $k$  employed in the calculations is unimportant. Exactly the same results would have been obtained with any other value of  $k$ .

### Growth

Growth in weight was represented by a Brody curve, usually with coefficient  $\rho = \exp(-M)$ . This is the same thing as a von Bertalanffy curve with  $K = M$ . Let

- $w_a$  = weight (mean weight in catch) at age  $a$
- $w_k$  = weight at the standard age at entry  $k$
- $w_\infty$  = asymptotic weight
- $c = w_k/w_\infty$
- $\rho$  = Brody growth coefficient.

For ages  $\geq k$ , the growth equation was

$$\begin{aligned} w_{k+i} &= w_\infty(1 - \rho^i) + \rho^i w_k \\ &= w_\infty[1 - \rho^i(1 - c)]. \end{aligned}$$

This is equivalent to equation 1.16 of Schnute (1985). For ages  $< k$ , a tail was appended to the standard Brody curve that has the same slope at age  $k$  and growth increments that decrease toward age zero in the same way (but not at the same rate) that

growth increments decrease beyond age  $k$  (see Fig. 1A). The equation for ages  $\leq k$  was

$$w_{k-i} = w_k \eta^i \text{ where } \eta = \rho^{(1-c)/c}.$$

The tail was added to avoid the negative weights that can occur at ages  $< k$  when the standard Brody curve is used. The weights so determined are sensible enough, but they have little effect on the calculations because the weights must be small in any case and the age groups in question are only fractionally mature and recruited.

For the typical life history,  $\rho = \exp(-M) = \exp(-0.2) = 0.82$  and  $c = 0.3$ , the latter value chosen to make the yield-per-recruit curve typically flat-topped. Other values used in some of the computations were  $\rho = \exp(-0.1)$  and  $\exp(-0.4)$  and  $c = 0.1$ . Asymptotic weight  $w_\infty$  was simply set to unity.

### Maturity and Recruitment Schedules

Let  $k_m$  = age at 50% maturity (= standard age at entry  $k$  in almost all cases). The proportion  $m_a$  mature at age  $a$  was given by the logistic

$$m_a = 1/[1 + \exp\{-\gamma(a - k_m)\}]$$

with slope parameter  $\gamma = 1$ . At this value of  $\gamma$ , there is a period of 4 yr between the ages at which fish reach 10% maturity and 90% maturity, which is typical. Partial recruitment to the fishery was represented by the same logistic, but with an age at 50% recruitment  $k_r$  that could be different from  $k_m$ . To investigate the effect of delayed maturity,  $k_m$  was raised to  $k + 2$  with  $k_r = k$  as usual. To investigate the effect of delayed recruitment,  $k_r$  (and only  $k_r$ ) was raised to  $k + 2$ . The parameter  $k$ , used in the growth equation, was always kept at 5.

### Calculation of Yield per Recruit and Spawning Biomass per Recruit

Given the growth, maturity, and recruitment schedules above, and any fishing mortality rate  $F$ , it was straightforward to compute yield per recruit and spawning biomass per recruit in the usual way.

### Spawner-Recruit Curves

The customary formulation of the Ricker S-R curve is

$$R = \alpha S \exp(-\beta S).$$

Let  $S_0$  denote the equilibrium spawning biomass in the absence of fishing and  $R_0$  the corresponding unfished level of recruitment. With  $A = \beta S_0$ , the Ricker equation can be rewritten

$$(R/R_0) = (S/S_0) \exp[A(1 - S/S_0)]$$

so that relative recruitment  $(R/R_0)$  is given as a function of relative spawning biomass  $(S/S_0)$  and the single shape parameter  $A$  (Kimura 1988).

Another way of writing the equation is

$$(R/S) = (R_0/S_0) \exp[A(1 - S/S_0)]$$

which provides the means of solving for the equilibrium spawning biomass at any fishing mortality rate  $F$ . The ratio  $(R_0/S_0)$  is just the reciprocal of spawning biomass per recruit in the absence of any fishing, and the ratio  $(R/S)$  is the reciprocal of spawning biomass per recruit when  $F$  is applied. Once these ratios have been computed, the S-R equation can be solved for  $(S/S_0)$ .

The one-parameter form of the Beverton-Holt S-R curve is  
$$(R/R_o) = (S/S_o)/[1 - A(1 - S/S_o)].$$

For all of the computations in this paper,  $R_o$  was set to unity, and  $S_o$  was then determined by the values of the life history parameters. The initial values of  $A$  used for the Ricker curves were 0.693, 1.386, 2.079, 2.773, and 3.466. For the Beverton-Holt curves the values were 0.500, 0.750, 0.875, 0.938, and 0.969. For both forms of the S-R relationship, these shape parameters imply potential density-dependent increases in reproductive success (recruits per unit spawning biomass) by factors of 2, 4, 8, 16, and 32, respectively.

#### Calculation of Absolute and Relative Yields

Yield per recruit and spawning biomass per recruit were calculated for each value of  $F$ , as explained above. For each S-R curve and each value of  $F$ , equilibrium spawning biomass and recruitment were determined by solving the S-R equation, and absolute yield was obtained as  $Y = R(Y/R)$ . It was then straightforward to locate MSY for each S-R curve and finally to obtain relative yield ( $Y/MSY$ ) for each  $F$ .

TD  $\Delta$

