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A comparison of some biological reference points for fisheries management

J. K. T. Brodziak and W. J. Overholtz
Conservation and Utilization Division

NOAA/National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts 02543-1097

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SUMMARY

We discuss three commonly used biological reference points for fisheries management: F_{MSY}, $F_{0.1}$, and F_{MAX}. We compare these reference points to F_{MELSY}, a recently developed reference point due to Thompson (1992A) that accounts for uncertainty in stock recruitment dynamics using data for Georges Bank yellowtail flounder and Atlantic mackerel in the Northwest Atlantic. Our results based on the deterministic dynamic pool model of Thompson (1992B) suggest that an F_{MELSY} policy would lead to higher stock sizes than F_{MSY}, $F_{0.1}$, and F_{MAX} harvesting policies with little reduction in longterm yield in comparison to an F_{MSY} policy. For the depleted yellowtail stock, an F_{MELSY} policy would be unlikely to further reduce stock biomass, while for the abundant mackerel stock, an F_{MELSY} policy appears to be a useful harvest rate target for increasing yields in a conservative manner. Stock sizes under an F_{MELSY} policy appear to be relatively high in comparison to other harvest rate policies while the F values are relatively low. In cases where the stock production curve is uncertain due to limited data or natural variability, a target harvest rate of F_{MELSY} may be more appropriate for maintaining longterm productivity.

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INTRODUCTION

Fishery management plans for stocks under the jurisdiction of the United States must conform to the national standard that "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry" (U.S. PL-94-265, Section 301). Implicit in this standard is the notion that resource use should be sustainable. Therefore, fish stocks should be harvested at a level that allows natural processes to replenish what has been harvested on a continuing basis. To apply this standard, it is essential to have a good definition of what a sustainable harvest rate is. Overfishing is defined for each stock managed by a Fishery Management Plan under U.S. jurisdiction based on the best available data. Some definitions include an overfishing rate that should not be exceeded (U.S. DOC 1993), but do not incorporate a minimum level of stock biomass as a consideration. Such stocks could remain depleted (and hence overfished), even though current fishing mortality rates are below the overfishing rate.

In this paper, we discuss three more traditional rate-based reference points: F_{MSY} (Hjort *et al.* 1933), $F_{0.1}$ (Gulland and Borema 1971), and F_{MAX} (Beverton and Holt 1957). We contrast these reference points to an alternative rate-based reference point due to Thompson (1992A) known as F_{MELSY}. What is F_{MELSY} ? It stands for the **f**ishing mortality rate that produces the **m**aximum **e**xpected **l**og-**s**ustainable **y**ield. F_{MELSY} can be considered a risk-averse reference point because it formally minimizes the expected value of lost yield under a constant fishing mortality rate for a risk-averse (logarithmic) loss function. It was developed to be a robust estimate of the maximal sustainable harvest rate given uncertainty about the level of compensation in the stock recruitment relationship. We calculate F_{MELSY} for Georges Bank yellowtail flounder and Atlantic mackerel using recent assessment information. We compare expected stock sizes and yields under an F_{MELSY} policy to F_{MSY}, $F_{0.1}$, and F_{MAX} policies based on the dynamic pool model of Thompson (1992B) and discuss the potential utility of F_{MELSY} for fisheries management.

OVERVIEW OF REFERNCE POINTS

The concept of maximum sustained yield (MSY) was an important conceptual development for fisheries science (Smith 1994). Larkin (1977) characterized the development of MSY as an outgrowth of the conservation movement that emphasized efficient use of resources. Typically, MSY is depicted as the peak of the production curve that expresses sustainable yield as a function of population size. The production curve is an average relationship estimated with as the best available information. The fishing rate that would maintain the stock at the MSY level and would produce the maximum sustained yield in a deterministic sense if the production curve were perfectly known is F_{MSY}.

A primary assumption of an F_{MSY} policy is the existence of a production curve relating fishery yield and population size for the exploited fish stock. Numerous biological processes are condensed into the deterministic curve relating yield and population size, including for example, growth, natural mortality, maturation, and time lags between juvenile and adult stages. The production curve also accounts for community-level interactions such as interspecific competition and predation as well as the effects of density-independent environmental factors. Because the potential for complex interactions between population-level, community-level, and environmental factors that influence productivity is substantial for many stocks, it is not surprising that the production curve has been difficult to determine in practice. Despite this difficulty, achieving MSY is a natural a policy goal. The F_{MSY} policy is the one that optimizes harvest by extracting as much as possible from the resource now while maintaining sufficient biomass for future production. Of course, if the production curve is poorly determined, harvesting at the perceived MSY level may jeopardize future productivity.

Some potential weaknesses in the biological basis of the F_{MSY} reference point were noted by Larkin (1977). Fishing at F_{MSY} does not reflect the loss of age-structure through reduced adult survival. In some cases, selective harvesting of older adults could reduce the viability of eggs produced and lead to a general decline in the per capita reproductive success. When a stock has substantial genetic heterogeneity because of local adaptation to environmental conditions, portions of the stock (substocks) inhabiting less productive areas may not be able to sustain harvest rates near the F_{MSY} estimated for the total stock. Through time, overharvest of less productive substocks could lead to an overall reduction in the genetic variability of the stock, a reduction in stock range as substocks are depleted, and an eventual loss in production (cf. Paulik *et al.* 1967). The F_{MSY} reference point also presumes ecological interactions remain stable over time. However, intensive exploitation of an ecosystem can dramatically change overall species composition; the depletion of groundfish and concurrent increase in elasmobranch biomass on Georges Bank provides one example (cf. Sissenwine and Cohen 1991). Substantial changes in the species composition of an exploited ecosystem may have unanticipated consequences for stock productivity.

The idea that MSY was an elusive quantity led to the search for practical alternatives to F_{MSY}. One alternative was the level of fishing mortality at which the slope of the yield-per-recruit curve was 10% of its (maximal) value at the origin, that is, $F_{0.1}$ (Gulland and Borema 1971). The value of 10% is arbitrary, but reflects the notion that the F where the slope of the yield-per-recruit curve is an order of magnitude below its maximum may provide a buffer for the stock and produce a stable fishery. While generally more conservative than F_{MSY}, $F_{0.1}$ requires similar biological assumptions. A principal advantage of $F_{0.1}$ is that it is readily calculated given estimates of growth, fishery selectivity, and natural mortality. Nonetheless, there is no guarantee that the $F_{0.1}$ level will, in fact, be sustainable in the long-term.

Beverton and Holt (1957) developed the biological reference point F_{MAX}, the level of fishing mortality that maximizes the yield per recruit from a cohort. This reference point uses the common assumptions that average growth is deterministic and growth parameters are known; natural mortality is a stationary process and is accurately known; the fish population can be represented as a homogeneous unit stock; fishery selectivity and fishing mortality are constant throughout a cohort's lifespan.

The F_{MAX} reference point is readily computed and appeals to the notion of maximizing the yield from a given recruitment. In theory, an F_{MAX} policy would achieve the largest possible yield in biomass from the available recruitment. For stocks that are composed of essentially one yearclass where recruitment varies substantially due to environmental factors, this approach may be useful.

On the other hand, the assumption of density-independent growth may be unrealistic for some stocks. However, a more severe limitation of F_{MAX} is that it focusses on a single-cohort dynamics and does not consider interactions between cohorts in an iteroparous, age-structured population. Further, F_{MAX} does not account for the natural biological connection between spawning stock and subsequent recruitment. For these reasons, an F_{MAX} policy gives no assurance that current production will be sustained.

Uncertainty of parameter estimates is not accounted for in the traditional reference points; their parameters are taken to be known constants. The development of reference points that incorporate uncertainty about parameter estimates has recently become a topic of interest (cf. NAFO 1991), and our goal is to examine the potential utility of one such reference point.

Thompson (1992A) used a Bayesian, decision-theoretic approach to construct a risk-averse reference point named F_{MELSY}. This reference point incorporates uncertainty about the level of compensation in the stock by using a beta distribution as the prior distribution for the shape parameter of the Cushing stock-recruitment relationship (Cushing 1971) in a deterministic, dynamic pool model of the stock (Thompson 1992B). Because F_{MELSY} has not been widely applied to date, we take an empirical approach to see how it compares to F_{MSY}, $F_{0.1}$, and F_{MAX} policies for two stocks in the northwest Atlantic, Atlantic mackerel (*Scomber scombrus*) and Georges Bank yellowtail flounder (*Pleuronectes ferrugineus*).

STOCK DESCRIPTIONS

The yellowtail flounder is a valuable, fast-growing flatfish found in shelf waters of the northwest Atlantic from Labrador to Chesapeake Bay (Bigelow and Schroeder 1953). Within the U.S. EEZ, yellowtail flounder are present in commercially significant quantities on Georges Bank, off Cape Cod, and in Southern New England waters (NEFSC 1992). The Georges Bank stock of yellowtail flounder has been commercially exploited since the 1940's (Royce *et al.* 1959). During 1963-1976, total landings of Georges Bank yellowtail averaged 16,300 mt, but declined to an average of 1,900 mt during 1988-1990. Overall, downward trends in landings and research survey indices indicate that this stock is severely depressed. One recent stock assessment concluded that the Georges Bank yellowtail flounder was being overfished and was presently at a low level of abundance (NEFSC 1991). If current fishing mortality rates were maintained, it was projected that the spawning stock biomass of this stock would continue to decrease from its record low level in 1990. Substantial yields could be realized if the Georges Bank yellowtail flounder stock was rebuilt to former productivity, but "rebuilding of the stock will require a major reduction in fishing mortality and several years of improved recruitment" (NEFSC 1992).

Atlantic mackerel are distributed from Labrador to North Carolina in the northwest Atlantic. This fast-swimming, schooling species is highly migratory. Interannual variability in the spatial distribution of the stock is substantial because the stock is strongly influenced by water temperatures (Murray *et al.* 1983; Overholtz *et al.* 1991A). From 1960-1966, landings of Atlantic mackerel averaged 15,700 mt (NEFSC 1991). Landings increased substantially in the late 1960's and averaged 273,500 mt during 1967-1977 due to intensive exploitation by foreign fleets. During 1978-1990, landings have averaged 51,500 mt. At present, the stock is at a high level of abundance due, primarily due to above-average recruitment and low levels of landings (NEFSC 1992). However, due to the imprecision of current assessments and the influence of intra- and inter-specific interactions, the stock size and potential yield for the mackerel stock are a major source of uncertainty (Overholtz 1991; Overholtz *et al.* 1991B)

The condition of these stocks are very different: the northwest Atlantic mackerel stock is abundant and the Georges Bank yellowtail stock is depleted. Overall, this provides an interesting contrast between the goals of rebuilding a depleted resource and safely harvesting an abundant one.

METHODS

The dynamic pool model of Thompson (1992B) was estimated for the Georges Bank yellowtail and Atlantic mackerel stocks using weight-at-age and stock recruitment data from the most recent assessment of these stocks (NEFSC 1991; NEFSC 1995). This led to an estimate of F_{MSY} (Thompson 1992A, Eqn. 2):

$$F_{MSY} = M \cdot \left[\frac{-(q+1)K+1+\sqrt{(q+1)^2K^2+(6q-2)K+1}}{2q} - 1 \right]$$

where q is the exponent of the Cushing stock recruitment model. The parameter K is defined as $K=1/[M(a_r-a_0)]$ where M is the instantaneous natural mortality rate, a_r is the age of knife-edged recruitment to fishing mortality, and a_0 is the age intercept for a linear weight-at-age growth model (Thompson 1992B, Eqn. 20). An estimate of F_{MELSY} was computed (Thompson 1992A, Eqn. 20) as

$$F_{MELSY} = M \cdot \left[\frac{[(m+2)K-2]u - (m+1)K + 1 + \sqrt{k_2u^2-k_1u+k_0}}{2m(1-u)} - 1 \right]$$

where m is the mean of the beta distribution for the Cushing exponent q, $u=v/[m(1-m)]$ is the scaled variance of the beta distribution with variance v, and the constants k_0, k_1, and k_3 are $k_0 = (m+1)^2K^2 + (6m-2)K + 1$,

$k_1 = (2m^2 + 6m + 4)K^2 + (18m-8)K + 4$, and

$k_2 = (m+2)^2K^2 + (12m-8)K + 4$.

For Georges Bank yellowtail, the instantaneous natural mortality rate (M) was fixed at 0.2 and the age of knife-edged recruitment (a_r) was 3 years. The intercept of the linear growth model (a_0) was estimated to be -0.418. This led to an estimated K of 1.463. Parameters of the Cushing stock recruitment model were estimated using stock recruitment data (NEFSC 1991) for Georges Bank yellowtail (N=16); the estimates were p_{est}=1.98 and q_{est}=0.186 with σ_q^2=.077.

For Atlantic mackerel, M was fixed at 0.2, a_r was set to 4 years, and a_0 was estimated to be 0.146. This led to an estimated K of 1:297. Parameters of the Cushing model were estimated using stock recruitment data (NEFSC 1995) for Atlantic mackerel (N=29); the estimates were p_{est}=18.023 and q_{est}=0.348 with σ_q^2=0.087. These parameters were then used to numerically integrate expressions for the mean and variance (m and v) of the beta distribution for the Cushing exponent (Thompson 1992A, Eqns. 34 and 35). Estimates of F_{MSY} and F_{MELSY} and associated yields and biomass levels for the dynamic pool model were then calculated (Table 1) for comparison to estimates of $F_{0.1}$ and F_{MAX} taken from recent assessments (NEFSC 1991).

RESULTS AND DISCUSSION

The estimated fishing mortality rate at F_{MELSY} was between 36% to 92% lower than the other rate-based reference points for both stocks (Table 1). However, the yields corresponding to F_{MELSY} were only 6% and 11% lower than the F_{MSY} yield for Georges Bank yellowtail flounder and Atlantic mackerel, respectively. As expected, the risk averse reference point would give lower yields than the use of a F_{MSY} or a $F_{0.1}$ policy, but maintain much higher levels of stock biomass. As a result, the reduced level of yield under an F_{MELSY} policy would be more likely to be economically efficient than an F_{MSY} or an $F_{0.1}$ policy because catch rates would be maintained at higher levels given more stock biomass. In contrast, an F_{MAX} policy would entail a much higher harvest rate than F_{MELSY} and lead to a lower stock biomass for both stocks. Moreover, yields and catch rates under an F_{MAX} policy would also be lower.

Table 1. Biological reference points: F_{MELSY}, F_{MSY}, $F_{0.1}$, and F_{MAX} and associated yields (mt) and population biomass levels (mt) for Georges Bank yellowtail flounder and Northwest Atlantic mackerel.

Georges Bank yellowtail flounder

Reference Point	Fishing Mortality	Yield (mt)	Stock Biomass (mt)
F_{MELSY}	.16	2,683	18,146
F_{MSY}	.29	2,865	11,381
$F_{0.1}$	.25	2,855	12,907
F_{MAX}	.63	2,656	5,682

Northwest Atlantic mackerel

Reference Point	Fishing Mortality	Yield (mt)	Stock Biomass (mt)
F_{MELSY}	.08	131,265	1,823,125
F_{MSY}	.17	148,217	1,029,285
$F_{0.1}$	.27	141,726	659,191
F_{MAX}	.96	87,642	154,259

For Georges Bank yellowtail, the low yields associated with all the reference points suggest a conservative approach to the harvest of this resource. Portions of the stock were severely impacted by foreign fishing in the early 1970's and continued overfishing by domestic vessels into the late 1980's. At present, the surplus production and biomass of this stock are very low in comparison to historic levels. The adoption of anything other than a risk averse harvest rate policy would be likely to reduce stock biomass and further jeopardize the economic viability of the fishery. Thus, the use of F_{MELSY} as a potential management target seems reasonable for the depleted yellowtail stock.

For the northwest Atlantic mackerel stock, the yield associated with F_{MELSY} suggest that the resource has been underexploited in recent years, even when uncertainty in the stock recruitment relation is considered. Density-dependent growth of Atlantic mackerel (Overholtz 1989) can be expected to affect the level of compensation in the stock, especially at the high stock sizes of recent years. The F_{MELSY} reference point appears to be a potentially useful management target for increasing the harvest rate on Atlantic mackerel in a conservative manner while maintaining stock biomass.

Our results suggest that the F_{MELSY} reference point is lower and hence more conservative than the other reference points. In general, fishery management based on harvest rate alone can jeopardize a stock because there is no guarantee that spawning biomass and stock productivity will be maintained . While this is true for F_{MELSY}, the expected stock size under an F_{MELSY} policy is greater than under the other harvest rate policies while the fishing mortality rate is lower. In cases where the stock production curve is poorly known due to limited data or natural variability, a target harvest rate of F_{MELSY} may be more likely to maintain productivity. For many stocks, an adequate time series of fisheries data is available for a few decades. Such time series are often too short to accurately estimate resource productivity given the natural variability in marine ecosystems. One way to ensure that longterm data sets are available is to use a harvest rate policy that fosters a stable fishery.

Recently, much debate has occurred over whether sustainable use of renewable resource systems is possible when uncertainty is substantial (Ludwig *et al.* 1993; Rosenberg *et al.* 1993). We contend that fishery yields will be sustained only if realistic bounds on harvest levels can be determined and firmly maintained. In particular, achieving sustainable fisheries will require quantitative management goals that account for the inherent uncertainty in resource productivity. When longterm viability of resources is a policy goal, low to moderate fishing rates and moderate to large stock sizes may be needed to sustain production and economic viability. In this context, the F_{MELSY} reference point may be a useful harvest rate target when the level of compensation in the stock recruitment relationship is not well determined. Although fisheries science has advanced considerably in recent decades, there is still much to be discovered about the dynamics of exploited fish populations in marine ecosystems. Given the present state of knowledge, harvest rate policies such as F_{MELSY} that recognize uncertainty may preserve future options and ensure stable longterm yields from marine fish stocks.

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