

Gauging the impact of fishing mortality on non-target species

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The most obvious effect of fishing on non-target species is direct mortality. To quantify this effect on the vulnerability of species requires measurement of the current fishing mortality rate and of the tolerance of the species to fishing mortality. These are difficult to estimate for the little-studied non-target species. We describe two potential methods for estimating current fishing mortality rate when data are limited. Their application is illustrated for dab (*Limanda limanda*) and grey gurnard (*Eutrigula gurnardus*), two common non-target species in the North Sea. We also develop approaches to define tolerance levels for fishing mortality for little-studied and rare species, based on the ϕ potential jeopardy level: the fishing mortality that causes a ϕ reduction in spawning stock biomass per recruit relative to the unexploited situation. We propose that for non-target species, models founded on basic knowledge of life history parameters, and on generally established relationships between these parameters, may offer the only practical approach.

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Introduction

Despite many advances in understanding the ecosystem effects of fishing (ICES, 1994, 1995, 1996; Jennings and Kaiser, 1998; Lindeboom and de Groot, 1998; Hall, 1999; Kaiser and de Groot, 2000), the direct and indirect impacts of fishing on many non-target species remain poorly known. Because these species have little or no economic value, they have been given low priority in research. However, it is important to develop methods for assessing the vulnerability of such species because they would help to predict the impact of fishing on species of conservation concern and to predict how the structure of a community may change in response to exploitation.

Most studies of non-target species have been based on abundance trends on local rather than population-wide scales (Jennings and Kaiser, 1998). However, an assessment of vulnerability at the population level requires

estimates of (i) the current overall fishing mortality rate (F) and (ii) the capacity of the population to withstand that mortality. We consider how fishing mortality rates and vulnerability can be estimated for non-target species. Because the methods we propose are based on minimal data and a basic knowledge of life histories, they can be applied to many populations that will never be assessed using conventional data-intensive approaches.

To estimate mortality rate, we consider an extension to Jones's (1981) length cohort analysis. This requires catch-at-length data, such as might be available from discard sampling programmes. A second approach, based on estimates of swept areas from fishing fleets, requires even less information.

To assess the impacts of mortality on populations, we estimated the fishing mortality that would reduce spawning-stock biomass per recruit to some arbitrary but supposedly safe percentage (ϕ) of its unfished level.

We describe this as the ϕ potential jeopardy level of fishing mortality, $F'(\phi)$. This approach was preferred to Holden's (1974) method for assessing vulnerability of elasmobranchs based on the age at 50% maturity and the average number of young that a mature female produced, because many non-target species are highly fecund and little is known about their spawner–recruit relationships. Biological reference points that scale impacts to maximum yield were also deemed inappropriate because non-target species are economically unimportant.

To illustrate the calculation of fishing mortality rate and $F'(\phi)$, the techniques developed will be applied to two common non-target North Sea fish species, dab (*Limanda limanda*) and grey gurnard (*Eutrigula gurnardus*).

Methods

Extended length cohort analysis

Jones's (1981) length cohort analysis is a convenient way of converting the total catch-at-length distribution (or its proxy) from a steady-state fishery into estimates of population size and fishing mortality at size. Properly, its use requires an estimate of the steady-state catch-at-length distribution of the total catch together with model parameters describing natural mortality and growth. In most applications, a quasi-steady-state length distribution is constructed from the average of the catch-at-length distributions over a number of years. Subject to the assumptions that recruitment and the erosion of cohorts by fishing and by natural mortality have remained stable, the analysis provides estimates of fishing mortality rate-at-length and absolute population size-at-length. The method has been examined in detail and its limitations noted (ICES, 1988a). A virtue of the length cohort analysis is that a simple inversion of the method can be used to predict the steady-state catch and spawning-stock biomass (SSB) expected under any new rate and patterns of exploitation (Jones, 1981).

The method may also be applied to the relative catch-at-length distribution of a species to provide estimates of fishing mortality rates and relative population size-at-length; thus the relative catch-at-length of a single fleet might be used instead of that of the total catch. However, clearly this will lead to bias unless the single-fleet catches are truly representative of the aggregate catch. The use of relative catch-at-length distributions still allows the proportional change in SSB to be calculated by inversion. Proportional changes suffice for the estimation of $F'(\phi)$.

Application of the approach to non-target species would be little different from other usage. However, a common problem is that the two sexes have different growth rates and that only unsexed length distributions

are available. In this case, the technique applied to aggregated data will lead to bias. The best approach would then be to sample and to analyse length data by sex, but this would preclude the use of large amounts of data already extant.

The problems of differential growth and mortality rates between sexes (s) may be circumvented by extending the length cohort analysis. As with the standard approach, natural mortality rate at length [M_l] and growth parameters by sex (K^s , L_∞^s) are required. The extended approach also requires the assumption that fishing mortality rate at length per unit time (F_l) is not a function of sex, and the assumption that the sex ratio of the youngest age is known (typically unity).

Assuming an initial population size (the same for each sex) and arbitrary levels of F_l for each length group, the value of Δt (the time to grow through a length group) is calculated for each length group by sex. Next, for each sex, $F_l^s \Delta t_l^s$ and $M_l^s \Delta t_l^s$ (fishing mortality rate and natural mortality rate for the time interval, respectively) are calculated. The population by sex surviving at each length and the catch by length group and sex may be calculated using standard formulae. After summing estimated catches-at-length of males (C_l^{m*}) and females (C_l^{f*}), an objective function (Obj) may be constructed as

$$\text{Obj} = \sum_l (C_l^{\text{obs}} - C_l^{m*} - C_l^{f*})^2 \quad (1)$$

where C_l^{obs} represents the observed unsexed catch per length class. Obj can then be minimized (e.g. by using the solver function in Microsoft Excel), with the initial population size and the estimates of F_l on all but the largest length group as variables. The terminal F on the largest length group remains as an input assumption. Minimizing Obj to zero thus finds a set of fishing mortalities and an initial population size which satisfy the data and the assumptions.

The model may be inverted using the Jones (1981) technique to provide estimates of steady-state yield and SSB per recruit for any value of F . Typically, female SSB would be the measure chosen, which may be calculated for zero F . Solver (or an equivalent minimizing program) may then be used to estimate the F that reduces SSB to $\phi\%$, equating to $F'(\phi)$.

Weighted swept-area method

Fishing mortality estimates based on swept-area approaches are undemanding of data and would be increasingly applicable in many intensively fished shelf areas where the activities of larger fishing vessels are now tracked by satellite to verify reported effort data.

In the weighted swept-area approach, local F is considered proportional to the fraction of the area swept by fishing gear (Daan, 1991). By assuming that the gear catches all fish in its track (i.e. catchability coefficient = 1)

and that tows are random with respect to the local population, the annual local fishing mortality rate F_r can be obtained from the local area fished by the gear divided by the total local area. The total fishing mortality rate (F_{tot}) for the overall stock can then be obtained by weighting F_r with the total local area (A_r) and the catch rate of the species per unit area (C_r) available from surveys, as:

$$F_{\text{tot}} = \sum_r (A_r \cdot C_r \cdot F_r) / \sum_r (A_r \cdot C_r). \quad (2)$$

The thus-estimated F may be regarded as an overestimate because actual catchability is typically less than the assumed value of 1. If data on distribution of fishing effort and of the species are available at smaller scales (Rijnsdorp *et al.*, 1998), the estimates can be improved (Lindeboom and De Groot, 1998). However, assuming a random distribution of both at any scale probably also gives an overestimate, because it seems unlikely that the distribution in fishing effort would conform to the patchiness of non-target species.

In such a case of limited data, an approach to estimating the potential jeopardy level $F'(\varphi)$ is to use a Beverton and Holt (1957) formulation of the problem. This assumes knife-edged selection at age t_c to the fishery, constant F and M at age and a von Bertalanffy growth pattern. The value of the SSB-per-recruit may be defined by the length at subsequent spawnings in terms of the length at first spawning (L_a). If the fish become exploited before they reach L_a , then length at the $j+1$ th spawning may be written as:

$$L_{a+j} = L_{\infty} \{1 - \exp(-jK) \cdot (1-h)\}, \quad (3)$$

where K and L_{∞} are the parameters of the von Bertalanffy growth function and where the dimensionless ratio $h = L_a/L_{\infty}$.

Designating the weight at the $j+1$ th spawning as W_{a+j} and assuming isometric growth with $a = W/L^3$, and defining coefficients $U_i = 1, -3, 3, -1$ for $i=0 \dots 3$, respectively, then:

$$W\Sigma_{a+j} = aL_{\infty}^3 \sum_{i=0}^3 U_i \cdot (1-h)^i \cdot \exp(-jK)^i. \quad (4)$$

The number P_j at the $j+1$ th spawning are given by:

$$P_j = R \cdot \exp\{-M(t_c - t_r) - Z(t_a - t_c) - jZ\}, \quad (5)$$

where R is the initial population at age t_r , t_a is the age of first maturity, and total mortality rate $Z = F + M$.

Hence (summing the j th power terms as infinite geometric series) the sum of the products of Equations (4) and (5) for all j from 0 to ∞ gives the resulting SSB for a given fishing mortality as:

$$\begin{aligned} \text{SSB} = R \cdot \exp\{-M(t_c - t_r) - Z(t_a - t_c)\} \cdot aL_{\infty}^3 \sum_{i=0}^3 U_i \\ \cdot \{(1-h)^i / [1 - \exp(-Z-iK)]\}. \end{aligned} \quad (6)$$

Writing $\Omega\{g\}$ for the expression under the summation term (where g is the expression in terms of Z or M), the condition for F to equal $F'(\varphi)$ is therefore that

$$\varphi = 100 \cdot \{ -F'(\varphi) \cdot (t_a - t_c) \} \cdot \Omega\{Z'(\varphi)\} / \Omega\{M\} \quad (7)$$

Equivalent (but less tidy) equations might be written for $t_c > t_a$. It is also possible to extend the theory to include the more realistic case where natural mortality varies by length (MacDonald *et al.*, 1994).

Test data

Length cohort analysis

Table 1 gives the average length distribution of discards of dabs and grey gurnards for the period 1977 to 1983 for the Dutch beam-trawl fleet. These were determined from samples of discards and landings taken during commercial beam-trawl trips (van Beek, 1990). No discards were sampled between 1984 and 1988 inclusive. In the absence of estimates of M for these species, the general relationship between M and weight (W) for North Sea species (ICES, 1988b) was adopted:

$$M = 4 \cdot \exp[0.268 - 0.386 \cdot \ln(W)]. \quad (8)$$

Growth and female maturity parameters used in the extended length cohort analyses are given in Table 2.

Swept-area method

We used data from the ICES atlas of distribution of North Sea fishes (Knijn *et al.*, 1993), which provides catch rates by species and rectangle in the ICES co-ordinated groundfish surveys. We estimated catch rates in unsampled rectangles as the average of the catch rates of sampled adjacent rectangles.

Commercial effort data for the Dutch beam-trawl fleet in 1989 were extracted from the Scientific, Technical, and Economic Committee for Fisheries (STECF) database. This year was chosen (MacDonald *et al.*, 1994) because it represented the most recent year for which data from several sources were available.

The original effort data were recorded as days at sea in fishermen's log-books. These were converted to hours fishing by ICES statistical rectangle and to area swept by the fleet in each rectangle. Conversions were based on information on vessel operations collected during the discard sampling programme. The numbers of hours fished in each rectangle were estimated by multiplying days at sea by 13.6 h. This value was calculated from the

Table 1. Average per mille distributions of dab and grey gurnard in discards from the Dutch beam trawl fleet (1977–1983).

Length (cm)	Dab	Grey gurnards
5	0.03	0.00
6	0.06	0.00
7	0.16	0.00
8	0.52	3.94
9	1.36	6.05
10	4.49	7.10
11	8.41	14.88
12	19.43	39.12
13	32.38	35.08
14	56.57	32.38
15	88.06	31.67
16	116.09	36.06
17	136.49	77.89
18	117.94	95.32
19	109.43	155.67
20	88.63	161.99
21	66.70	117.90
22	49.30	90.21
23	39.50	80.04
24	24.85	69.92
25	19.54	46.54
26	9.17	44.78
27	5.59	32.32
28	2.60	17.06
29	1.86	12.83
30	0.69	17.75
31	0.13	3.88
32	0.02	0.34
33	0.00	0.28
34	0.00	1.03
35	0.00	0.28

Table 2. Von Bertalanffy growth parameters (K , L_{∞}) by sex and size at first maturity (L_a) of females for dab (Lee, 1972) and grey gurnard (T. Boon, MAFF; pers. comm.).

Species	Sex	Parameter		
		K	L_{∞} (cm)	L_a (cm)
Dab	M	0.46	22	12
	F	0.20	37	
Grey gurnard	M	0.16	40	19
	F	0.14	45	

average number of hours spent fishing per trip (67.3) by vessels in the discard sampling programme divided by the normal number of days spent at sea on a fishing trip (5 d). The effort data were used to calculate swept areas for the fleet of vessels <300 hp and of vessels >300 hp separately. The calculations were based on the larger vessels towing two beams of 12 m per beam at a speed of 13 km h⁻¹ and the smaller vessels towing two 4 m beams at a speed of 5.93 km h⁻¹.

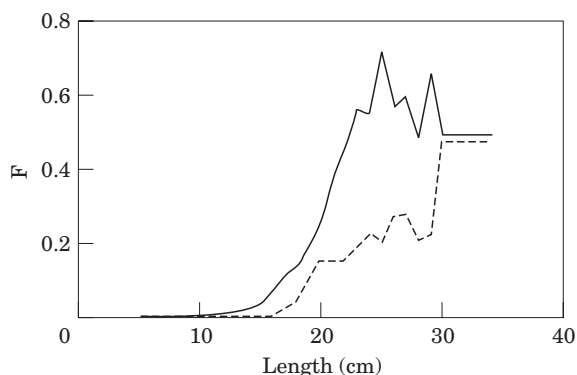


Figure 1. Fishing mortality rate by length for North Sea dab (solid line) and grey gurnard (dashed line) estimated using the extended Jones length cohort analysis.

Ideally, the error of the swept-area estimates would be calculated as well as the point estimates so that variability could be ascribed to the results. However, this was not possible with the example data.

The area of each ICES rectangle was calculated and divided into the swept area for each fleet in each rectangle to give an estimate of F_r . The mortality estimate per rectangle was then raised (Equation [2]) by the corresponding catch rate per rectangle given in Knijn *et al.* (1993).

Part of the Dutch beam-trawl effort could not be allocated to rectangles: unallocated effort comprised 11% of the total days at sea recorded by beam trawlers >300 hp and 27% by those <300 hp. This unallocated effort was not used to estimate F , and thus the estimates given in the results section may be biased downward.

Results

Figure 1 shows the fishing mortality rate by length group for North Sea stocks of dab and grey gurnard calculated by using the differential growth version of the length cohort analysis. There is no fishing mortality on individuals of either species that are less than 12 cm in length, and F rises rapidly between 15 and 25 cm. F at length for gurnard is lower than for dabs. Estimates of effort multipliers for North Sea fisheries that would generate $F'(20\%)$ were 279 for dab and 10 for grey gurnard. For $F'(10)$ they were 786 and 19, respectively.

Table 3 shows the swept-area estimates of fishing mortality for dabs and grey gurnards generated by the total Dutch beam-trawl fleet in each quarter of 1989. The analyses indicate similar levels of fishing mortality on the two species, with little seasonal variation.

While Equation (7) clearly shows that the value of $t_a - t_c$ is a critical determinant of $F'(\phi)$, the impact of the other variables is less clear. To envision the solution of

Table 3. Swept-area estimates of F for dab and grey gurnard generated by the total Dutch beam-trawl fleet in 1989 by quarter.

Quarter	Dab	Grey gurnard
1	0.09	0.09
2	0.12	0.14
3	0.12	0.10
4	0.11	0.11
Annual total	0.43	0.44

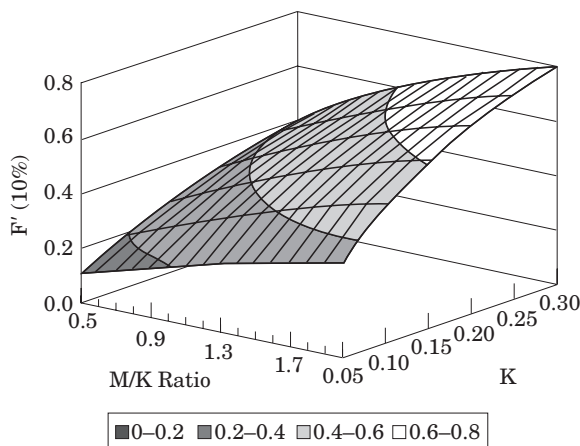


Figure 2. The 10% potential jeopardy surface as a function of K and M/K for $h=0.7$ and of $t_a - t_c=4$.

Equation (7), $F'(\varphi)$ was calculated for a range of life-history parameters. Some results are shown in Figures 2 and 3. These give the 10% potential jeopardy surface as a function of K and the M/K ratio under different assumptions about h ($=L_\infty/L_0$) and the time elapsing between when the fish become available to fishing and when they become mature.

The surface in Figure 2 shows the predicted response, with the potential jeopardy level of fishing mortality increasing with K and the M/K ratio. Thus species with “faster” life histories are less vulnerable to fishing mortality. $F'(\varphi)$ also increases with h for given values of $t_a - t_c$ (graph not shown). However, a species with a higher h is also likely to have a larger value of $t_a - t_c$, which would counteract the increase in $F'(\varphi)$ with h . Moreover, for a given K , the possible values that $t_a - t_c$ can take depend upon the value of h . The effects of these interrelationships are shown more clearly in Figure 3. Here, length-at-first-capture has been set at 10% of L_∞ and hence, for given K and h , the value of $t_a - t_c$ is fixed. With this constraint, the value of $F'(\varphi)$ still increases with K and with the M/K ratio, but decreases with increases in h (graph not shown).

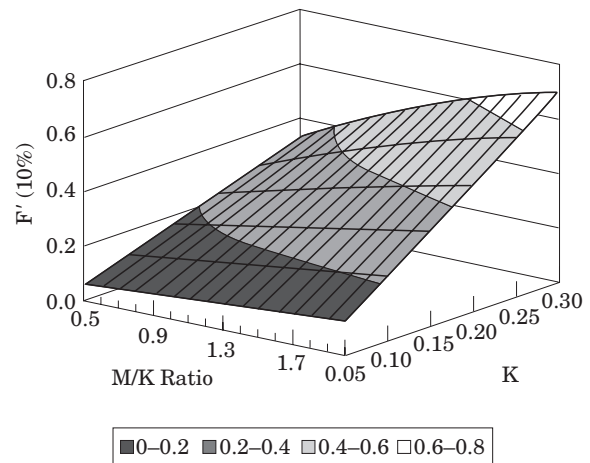


Figure 3. The 10% potential jeopardy surface as a function of K and M/K for $h=0.5$ and assuming that the length of first capture (t_c) is always 10% of L_∞ .

Discussion

Age-based methods are typically too expensive for use with non-target species. The length cohort analysis approach of Jones (1981) offers a practical approach for common non-target species. Given a modest amount of discard sampling data and biological information, the method can be used to estimate current fishing mortality rate, and its inversion can estimate the potential jeopardy level. In practice, many non-target species have differential growth rates by sex. The extension described here offers one approach to circumvent this problem.

The fishing mortality rates estimated by the extended length cohort analysis (Fig. 1) seem plausible. However, like all proposed models, the technique should be tested stringently before coming into general use, and the impacts of input errors and assumptions on the outputs need to be assessed. This could possibly be achieved by application to target species for which the age-structured population dynamics are already well known. In the case of dab, the estimated F on larger fish are similar to those for the target species of the Dutch beam-trawl fleet (plaice 0.40; sole 0.45) over a comparable time period (ICES, 1997). We note that fishing mortality rates decline sharply on length groups less than 20 cm. Because the beam trawl is the most retentive flatfish gear used in the North Sea, this is probably a real decline in F with size rather than a sampling-gear effect. Because dab are largely restricted to the southern and eastern parts of the North Sea (Knijn *et al.*, 1993) where the beam-trawl fleet operates, the by-catch of the Dutch fleet is likely to represent the major part of the total catch. So the estimates of F should be approximately correct.

For grey gurnard, the extended length cohort analysis results are similar to those based on swept area. Gurnards are caught also in other gears, because the distribution extends more northward (Knijn *et al.*, 1993). Because this applies particularly to the larger sizes, the size distribution of the Dutch beam-trawl fleet may be truncated compared with that of the total catch. Such a bias would result in a mortality estimate that is too high. As with dab, the observed reduction in F below about 20 cm probably gives a realistic estimate of the minimum size of capture.

The inverted length cohort analysis is particularly simple to apply and provides an easy way to predict how SSB per recruit would change with F . The results suggest that these two species are not vulnerable to current fishing mortality levels. The sizes of first maturity of females (dabs 12 cm; grey gurnards 19 cm) are lower than the size at which these species are fully recruited to the fishery (20–25 cm). Consequently, females have an opportunity to spawn before they are much fished and hence their spawning potential is eroded rather little by existing levels of fishing mortality. Because it would take many-fold (279 for dab; 10 for grey gurnard) and unrealistic increases in F to reduce these species to even the $F'(20\%)$ level, these fish are little affected by current by-catch rates. This conclusion is unsurprising, as they are amongst the most abundant species of fish in the North Sea, and recent groundfish surveys suggest that their abundance is increasing (Heessen and Daan, 1998).

Unlike the length cohort analysis method, the swept-area method does not require sampling of commercial by-catches and the required data on the distribution and abundance of non-target species are often available from surveys (Künitzer *et al.*, 1992; Knijn *et al.*, 1993). The key assumptions are that fishing is at random with respect to the species of interest and that all individuals in the path of the gear are killed. Because we are only considering non-target species, the fishing effort is not directed at them and the assumption of random encounter is safer than for target species. However, fishing effort is patchy within ICES rectangles and repeated trawling along the same “tows” would reduce fishing mortality on sedentary species (Rijnsdorp *et al.*, 1998). With the introduction of international satellite monitoring of large North Sea trawlers in 2000, it will become possible to account for small-scale spatial and temporal patterns in fishing effort. However, to improve swept-area mortality estimates may require distributional data for the species to be collected at a similar scale. The validity of the assumption that all animals in the track are killed may be addressed by specific studies. Since the beam trawl is a specialized ground-hugging gear, the geometry of which is closely constrained, this assumption is probably more realistic for dab and grey gurnard (which are both adapted to life on the sea-bed)

than for species more loosely associated with benthic habitats.

Although the method appears to provide plausible mortality estimates for fully selected size classes when compared with estimates obtained from the extended length cohort analysis and those for target species of the beam-trawl fishery, it provides no information on which sizes are fully selected. These might be estimated by invoking the selection characteristics of similarly shaped commercial species, but invertebrates are likely to require specific studies that account for selection and for their survival when discarded after capture (Lindeboom and de Groot, 1998).

The assumption that all individuals of a species in the trawl track are caught will rarely be appropriate, but obtaining a better estimate may prove difficult. However, intensive local studies might yield estimates for some common species that could be extended by analogy to rarer species of similar structure, habit, and behaviour. In the meantime, the swept-area estimates provided for dab and grey gurnard are upper estimates of the mortality generated by the allocated effort of the Dutch fleet alone. Because they do not differ substantially from the length cohort analysis estimates on the larger sizes, it seems probable that beam-trawl fisheries represent the major cause of fishing mortality on these species.

If data are insufficient to apply the swept-area method, then some rough estimates of F might still be obtained by invoking Pope's Postulate. This states that fishing fleets generate a fishing mortality on non-target species which is less than or equal to that generated on the target species. Clearly, by whatever method fishing mortality rates are estimated for non-target species, it is appropriate that estimates should, if anything, be biased upwards to reflect the application of the precautionary approach (FAO, 1995).

Estimates of F for non-target species have little utility unless they can be linked to a limit reference point. We advocate the use of the ϕ potential jeopardy fishing mortality rate for this purpose. For species for which little information exists, Equation (7) allows $F'(\phi)$ to be expressed in terms of simple life-history parameters, which are often the first and maybe the only facts known about a species (Beverton and Holt, 1959; Reynolds *et al.*, 2000).

There are interrelationships between life-history parameters in fishes. For instance, ratios between parameters such as M and K , L_α and L_∞ or K and L_∞ are consistent within taxonomic groups (Beverton and Holt, 1959; Beverton, 1963; Charnov, 1993). These dimensionless ratios have particular application because they allow life-history parameters that are notoriously difficult to measure, such as M , to be estimated from easily determined growth parameters (Beverton and Holt, 1959). Moreover, in the present context, the relatively constant

values of these invariants within taxonomic groups may mean that their values can be inferred and used to provide an initial estimate of $F'(\varphi)$.

As explained in the results section, the form of the equations provides insights into how their life-history parameters determine the vulnerability of a species to fishing mortality rate. Moreover, for species that are too uncommon to be sampled easily, knowledge of relationships between life-history parameters might be used to estimate their vulnerability to the current fishing mortality rate.

Conclusions

Ecosystem effects of fishing are difficult to predict. One definition of a sustainably exploited ecosystem, advanced by Dr J. Rice in discussions at the Symposium and elsewhere, is a system where no species has been pushed by exploitation towards extinction. A practical interpretation of this view would be an ecosystem where all stocks were fished within sensible limit reference points. We provide an attempt to calculate these for non-target species, by estimating current fishing mortality rate and the ϕ potential jeopardy level. Further development of methods will have to contend with the probability that results for non-target species will be biased, owing to the general paucity of data available. Consequently, new techniques will need to be interpreted using a precautionary approach that gives the benefit of any doubt to the biota.

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