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Use of a Simple Age-Structured Bioeconomic Model to Estimate Optimal Long-Run Surpluses

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Abstract *When the New Zealand government introduced individual transferable quotas for major commercial fish stocks, the initial allocation for some stocks exceeded their total allowable catches and made it necessary to buy back immediately some of the quota. Quota was offered back by tender. A simple age-structured bioeconomic model was used to estimate long-run optimal surpluses. From these, the maximum prices that should be paid by government for quota were derived. The use of an age-structured model proved convenient for this purpose as the necessary parameter estimates tend to arise naturally from literature sources and the population dynamics are transparent. If stocks were managed optimally, the long-run value of quota would be equivalent to the net present value of the surplus at the dynamic maximum economic yield. Long-run surpluses proved to be dependent on the relative changes in catch rates and costs of fishing which resulted from changes in stock biomass. Optimal surpluses of up to 45% of the greenweight revenues were obtained for heavily exploited, long-lived stocks. Only small long-run surpluses were obtained for short-lived or very lightly exploited stocks.*

Introduction

Until 1986, management of the New Zealand coastal fisheries had hardly restricted total fishing effort. Restrictions on mesh sizes and minimum fish sizes existed. Certain methods were excluded from a few areas. From 1982, few new fishing licences were granted. But since the amount of effort and the fishing power of gear employed by license holders continued to be uncontrolled, the coastal fisheries remained similar to open access fisheries, as they had been before. The inevitable overcapacity which results from such a policy is widely described in the literature, e.g., Clark (1985, 9). Mounting concern over declining catch rates and declining stocks finally led to the new management regime's being introduced. In 1986, the government introduced a system of individual transferable quotas (ITQs) within total allowable catch (TAC) limits for most major commercial fin-fish stocks. Under certain conditions, this type of management regime is optimal (Clark 1980). The owner of such quota holds the rights to catch annually for sale the specified amount of fish from a stock in perpetuity.

The introduction of the new regime involved several decisions and actions which will only be briefly described here. Most of the major commercial, coastal fin-fish species were included in the regime. These were subdivided into stocks based on existing knowledge. For each stock, a TAC was established. The primary criterion for setting the TAC was sustainability. Quota was allocated on the basis of recent landings. In most cases, vessel owners received free an ITQ equal to the mean of the best two of the previous three years' reported landings. Total allocated quota for some stocks, therefore, exceeded the TAC. As part of the package by which the new regime achieved political acceptability in the fishing industry, the government agreed to buy back excess quota. Quota holders were invited to tender quantities of quota back to the government. Where the government was unable to buy back sufficient quota at a reasonable price, it reserved the right to reduce quotas proportionally without compensation. Each quota holder was guaranteed an individual minimum holding below which he would not be involuntarily reduced.

It was necessary for the government to decide what maximum tender price was appropriate to accept for quota in each stock being bought back. The analysis which is described here was carried out to assist this decision. The analysis obtains estimates of the long-run surplus profit for each stock under optimal management. The net present value of this surplus is equivalent to the long-run value of the quota.

A total of 99 stocks was involved in the scheme, although it was necessary to buy back quota for only some of these. Hence, it was necessary to develop an analysis that was straightforward, had parameter requirements that could be met from available sources, and was applicable to a wide range of species. This was achieved, although it proved impossible in the time available to apply the analysis to more than a small number of stocks. Example results from three stocks are reported here.

The approach adopted was to define a deterministic, single species, age-structured model (Beverton and Holt 1957) with simple fisheries economics' assumptions (Anderson 19977) and to assume that all the necessary parameters, including initial values, were given. The initial stock structure and the initial present sustainable yield were used to obtain the constant recruitment. The initial stock structure and the initial open access yield were used to obtain the constant cost per unit of fishing mortality. For each stock, the model then determined long-run equilibrium stock structure, catch, and surplus profit for fixed values of fishing mortality. Optimal values of long-run equilibrium variables could then be obtained.

Due to the considerable uncertainty surrounding parameters for many stocks, a simple sensitivity analysis was carried out to determine the relative importance of the parameters. This sensitivity analysis was only first order so that interaction effects caused by variation in two or more parameters at once were not investigated.

Model

Population Dynamics

The model is age-structured with simple fishery economics' assumptions. The stock is defined by numbers of fish at age and a given weight at age curve. The dynamics involve constant knife-edge recruitment each year, given natural and non-commercial fishing mortality constant both with age and over time, and constant commercial fishing mortality with age. All fish die at a given maximum age. The initial age-structure (relative proportions at age) is defined by one or three given parameters. The stock is assumed either to have been subject to constant total mortality for the period since recruitment of the oldest age class (one parameter) or to two periods of different constant total mortality since recruitment of the oldest age class, with the change at a given year (three parameters). The initial numbers at age are determined, given the initial age-structure and the initial present sustainable yield (PSY). The constant number recruited annually is the number in the first age class. The given initial PSY is defined as the annual catch for which the initial stock biomass would remain unchanged. This definition is applied in all cases, not only in the one-parameter, equilibrium stock structure case. When it is applied to a non-equilibrium stock structure, such as the three-parameter case, the PSY would change in subsequent years. This is because, although stock biomass would remain unchanged after catching the initial PSY in the initial year, stock structure would change.

Biological variables are defined as follows:

• recruitment age (yr.)	r (given),
• maximum age (yr.)	m (given),
• number of age *a* at start of year *i*	$N_{i,a}$,
• number of recruits per year (age *r*)	R,
• weight at age *a* at start of year (kg)	w_a (given),
• instantaneous natural mortality (yr^{-1})	M (given),
• instantaneous amateur fishing mortality (yr^{-1})	A (given),
• instantaneous fishing mortality during year *i* (yr^{-1})	F_i,
• instantaneous total mortality during year *i* (yr^{-1})	$Z_i = M + A + F_i$,
• number at age *a* caught during year *i*	$C_{i,a}$,
• yield during year *i* (kg. yr^{-1})	Y_i,
• initial PSY (kg. yr^{-1})	Y_S (given).

Conventional age-structure dynamics and catch equations are used. The equation by which each number at age at the start of a year is obtained from the previous year's stock is:

$$N_{i+1,a+1} = e^{-Z_i} N_{i,a}, \qquad i > 0, r <= a < m \tag{1}$$

$$N_{i,r} = R, \qquad i > 0, \tag{2}$$

The catch equation for each age class is:

$$C_{i,a} = (F_i/Z_i)(1 - e^{-Z_i})N_{i,a}, \qquad i > 0, r <= a < m \tag{3}$$

The yield during year *i*, taking account of the mean weight of fish during the year,

$$Y_i = \sum_{a=r}^{m-1} C_{i,a}(w_a + w_{a+1})/2$$

The total stock biomass at the start of year *i* is obtained by summing,

$$\sum_{a=r}^{m} N_{i,a} w_a$$

For the one parameter case, we assume that initially the stock is in equilibrium after $m - r$ years of constant fishing mortality, F_0. M and A are also given so that the stock structure can be defined by a single parameter, the recent total mortality,

$$Z_0 = F_0 + M + A.$$

The initial number of age a is then,

$$N_{1,a} = e^{-(a-r)Z_0}R, \qquad r <= a <= m \tag{4}$$

The fishing mortality corresponding to the initial PSY, F_S, is that which will maintain the stock at its initial biomass. Hence,

$$F_S = F_0$$

The initial PSY is given by,

$$Y_S = (F_0/Z_0)\,(1 - e^{-Z_0}) \sum_{a=r}^{m-1} e^{-(a-r)Z_0}R(w_a + w_{a+1})/2 \tag{5}$$

Since Y_S is given, this equation can be simply solved for R. The initial number in each age class is then determined. In this case, the stock size and structure remain unchanged from their initial states, if this level of fishing mortality is maintained.

In the three-parameter case, we assume that initially the stock structure results from two periods of different constant fishing mortality. It can, therefore, be defined by three parameters: recent fishing mortality, F_0; previous fishing mortality, F_{-1}; and the age below which age classes have only been subject to the recent fishing mortality, b. Z_0 and Z_{-1} are defined accordingly so that the number in age class a is

$$N_{1,a} = e^{-(a-r)Z_0}R, \qquad r <= a <= b,$$

and

$$N_{1,a} = e^{-(b-r)Z_0}e^{-(a-b)Z_{-1}}R, \qquad b < a <= m$$

In this second case, the total mortality, Z_S, which corresponds to the initial PSY, is obtained by equating the initial stock biomass with the after one year's fishing

$$\sum_{a=r}^{b} e^{-(a-r)Z_0}w_aR + \sum_{a=b+1}^{m} e^{-(b-r)Z_0}e^{-(a-b)Z_{-1}}w_aR = w_rR$$
$$+ e^{-Z_S}\left(\sum_{a=r}^{b} e^{-(a-r)Z_0}w_{a+1}R + \sum_{a=b+1}^{m-1} e^{-(b-r)Z_0}e^{-(a-b)Z_{-1}}w_{a+1}R\right) \tag{6}$$

This equation is solved for Z_S which lies between Z_0 and Z_{-1}. Hence, F_S is obtained by subtracting M and A from Z_S. F_S is independent of R, which cancels from both sides of the equation. Using an equation similar to equation 5, *R* is obtained.

Fishery Economics

Further variables need to be defined to establish the economic structure of the model.

Economic variables are defined as follows:

- initial open access yield (kg. yr^{-1}) — Y_A (given),
- instantaneous fishing mortality at initial open access (yr^{-1}) — F_A,
- cost per unit fishing mortality ($. yr), — x,
- greenweight (unprocessed) price of fish paid to fisherman ($. kg^{-1}) — p (given),
- average surplus profit in year *i* ($. yr^{-1}) — S_i,
- annual discount rate (%. yr^{-1}) — d (given).

The total revenue from the catch is determined by a given constant price per kilogram. There are no fixed costs of fishing, and each increment of effort which corresponds to an equal increment in fishing mortality is of equal cost. This cost assumption is commonly used in the simplest bioeconomic models, e.g., Clark (1985).

An open access fishery is one in which there is no management constraint on the amount of fishing effort employed by anyone who wishes to fish. The theoretical consequences of this are well known, e.g., Clark (1985). In such a fishery, only a "normal" rate of profit on input costs exists, one equal to that available elsewhere in the economy. Surplus is defined as profit in excess of normal profit. If any positive surplus existed, then, in an open access fishery, it is assumed that more effort would be introduced until it was absorbed and conversely. Hence, it is assumed here that effort has adjusted to the open-access level appropriate to the initial stock state. This open-access yield produces a zero surplus at this stock state but is not necessarily sustainable. Recent changes in costs and prices may result in the initial open-access yield differing from the initial PSY even if the initial stock structure is in equilibrium. The cost (including normal profit) of fishing effort at the initial stock state is equal to the total revenue from the given initial open access catch. This effort corresponds to fishing mortality F_A, and, hence, cost per unit fishing mortality is obtained. We have

$$Y_A = (F_A/(F_A + A + M))\,(1 - e^{-F_A-A-M}) \sum_{a=r}^{m-1} e^{-(a-r)Z_0} R(w_a + w_{a+1})/2 \quad (7)$$

for the single parameter initial stock structure and similarly for the three-parameter case. This equation is an implicit equation for F_A with all the other variables now known. The solution was obtained numerically using a Newton-Raphson iteration. Hence, the cost per unit fishing mortality

$$x = pY_A/F_A \quad (8)$$

If the surplus corresponding to a non-open-access yield at the initial stock state is given instead, then equation (8) can be simply modified accordingly to give x. The subsequent surplus for an annual yield of Y_i, which corresponds to a fishing mortality of F_i, is obtained by

$$S_i = pY_i - xF_i, \qquad i > 0$$

Expressed as a percentage of the greenweight price per kilogram of fish, the surplus is

$$100\left(1 - \frac{xF_i}{pY_i}\right)$$

For a particular constant fishing mortality, it is now possible to calculate the long-run (equilibrium) stock state, yield, and surplus. Hence, it is possible to find the maximum sustainable yield (MSY), the maximum economic yield (MEY), and the dynamic maximum economic yield (DMEY). The MSY is the maximum equilibrium catch biomass that can be achieved. The MEY is the equilibrium catch for which the surplus is the maximum. This is sometimes referred to as the static maximum economic yield (Anderson 1977). The DMEY depends on net present value (NPV) considerations regarding the series of annual surpluses. The NPV of a series of surpluses is the sum of the surpluses with each surplus discounted according to the number of years into the future at which it occurs

$$S_1 + S_2/(1 + d/100) + S_3/(1 + d/100)^2 + \ldots$$

From any initial stock state, the series of annual yields with the maximum NPV (not necessarily at constant fishing mortality) will converge to an equilibrium yield. This is called the DMEY and is unique. These properties will not be proved here.

The DMEY can be obtained without establishing an optimal NPV yield series. For any fishing mortality, F, the corresponding equilibrium stock structure is obtained. At this equilibrium, the fishing mortality is perturbed slightly for a single year and then returned to its original value. The NPV of the surpluses associated with the series of fishing mortalities $F, F, F, \ldots$ and $F + \delta F, F, F, \ldots$ are then compared. If the NPVs of the two series differ, then F is not the fishing mortality corresponding to the DMEY. A decrease in the NPV caused by a perturbation in one direction implies an increase by a perturbation in the other. Any series of fishing mortalities converging to F is, therefore, not optimal, because a temporary perturbation in the fishing mortality can increase the NPV. At the DMEY, a small perturbation in the fishing mortality for one year does not change the NPV of the series of yields. Searching for the fishing mortality corresponding to the DMEY presents no difficulty.

Calculating the series of yields which is economically optimal, i.e., maximizes the NPV of surpluses from a stock in an arbitrary initial state, is an optimal control problem. For multi-cohort stocks, these are difficult to solve, and no solution is attempted here. Recent work by Kennedy (1987) and Horwood and Whittle (1986) gives methods of obtaining numerical solutions in cases where both fixed and variable costs are modeled. Here all costs are assumed variable, which is unrealistic in the short run but satisfactory in the long run. We obtain the surplus for each stock at its (long-run) DMEY equilibrium. The value of quota is related to this surplus.

The value of quota, i.e., the value of the rights to catch for sale annually a unit quantity of fish from a stock in perpetuity, can be calculated by capitalizing the future infinite series of surpluses per unit of quota. The NPV of this series of surpluses, using an appropriate discount rate, is the value of quota. It was a value calculated on this basis that was used to establish maximum acceptable tender prices when quota was bought back by government. It was intended that prices be reasonably generous. An approximation used was to set each annual surplus per unit of quota equal to the estimated surplus at the DMEY, i.e., constant. This approximation will usually produce a value higher than that obtainable under optimal management. In the real world, the extent of this will depend on the state of the stock and the existing non-malleable capital in the industry. Reduction of profit to the quota holder through proposed resource rentals was not allowed for.

Results

Results are given for stocks of three species, a long-lived species, one of moderate life span, and a short-lived species. Results for the other stocks modeled will be available in an internal report from Fisheries Research Centre, MAFFISH, P.O. Box 297, Wellington, New Zealand.

Snapper (**Chrysophrys auratus**), *north-east North Island (Cape Runaway to North Cape)*

Parameters and results are given in Tables 1 and 2. All the main fishing methods in this area target for snapper except purse seining. Much research has been carried out on this stock. The important parameters of PSY and recent fishing mortality are based on results from major tagging experiments (Sullivan 1987). The results indicate that movement between Bay of Plenty, Hauraki Gulf, and the north-east coast is probably sufficient to justify treating the whole area as containing a single stock. Results from the model are consistent with the species' being long lived, highly vulnerable to fishing, and of high value. There is a long history of fishing, and the stock size is now about 20% of its virgin size. The equilibrium surplus at the DMEY is high (35%) and is achieved at about half the initial open access effort after the stock biomass has increased by 50% of its initial size.

Red gurnard (**Chelidonichthys kumu**), *Hauraki Gulf*

Parameters and results are given in Tables 3 and 4. Red gurnard is a minor species in the trawl fishery aimed at snapper and, to a lesser extent, also in the other snapper fishery methods. Catch has been relatively constant from 1950 onwards (although somewhat higher recently), so constant recent total mortality is assumed. This is taken as the value obtained by Elder (1976) for this stock. Male and female growth rates are different, and a mean of the two has been used. Amateur fishing mortality rate is guessed. The main defect with the modeling of

Table 1
Parameters for Snapper, North-East North Island
(Cape Runaway to North Cape)

Parameter		Estimate	Source
1. Weight at age on 1 Jan (starting age 1 yr.)	(kg)	0.08 0.19 0.32 0.47 0.60 0.73 0.85 0.99 1.12 1.27 1.37 1.47 1.56 1.65 1.73 1.80 1.87 1.94 2.00 2.06 2.12 2.17 2.22 2.27 2.32 2.36 2.40 2.44 2.48 2.52 2.55 2.58 2.61 2.64 2.66 2.69 2.71 2.74 2.76 2.79 2.81 2.84 2.86 2.89 2.91 2.94 2.96 2.98 3.00 3.02	based on data from FRV Kaharoa cruises K03/82, K13/84, K21/84 and Paul (1976)
2. Natural mortality	(inst., /yr.)	0.06	Gilbert (1986 result for Bay of Plenty stock)
3. Amateur mortality	(inst., /yr.)	0.03	based on Sullivan (unpub.)
4. Recruitment Age	(yr.)	3	age at 25 cm (legal size)
5. Maximum age	(yr.)	50	based on 1974–5 shed samples from lightly exploited west North Island stock
6. Commercial fishing mortality over recent period	(inst., /yr.)	0.11	based on Sullivan 1987 (unpub.)
7. Initial PSY	(t/yr.)	5,200	Sullivan (1985), Hore et al (1986)
8. Initial open-access catch	(t/yr.)	6,500	fishery statistics

Table 2
Results for Snapper, North-East North Island (Cape Runaway to North Cape)

Result Variable		Estimate
1. Initial stock biomass	(t)	49,000
2. Equilibrium yield at effort equal to initial PSY effort	(t/yr.)	5,200
3. Maximum sustainable yield (MSY)	(t/yr.)	5,400
4. Maximum economic yield (MEY)	(t/yr.)	3,700
5. Dynamic maximum economic yield (DMEY)	(t/yr.)	4,500
6. Equilibrium surplus at DMEY	(%)	35
7. Ratio of DMEY effort to open-access effort		0.5
8. Ratio of initial stock biomass to virgin stock biomass		0.2
9. Ratio of DMEY stock biomass to initial stock biomass		1.5

Table 3
Parameters for Gurnard, Hauraki Gulf

Parameter		Estimate	Source
1. Weight at age on 1 Jan (starting age 1 yr.)	(kg)	0.06 0.14 0.23 0.30 0.34 0.37 0.38 0.38 0.38 0.38 0.38 0.38	based on Elder (1976) mean length of males and females and weight at length from FRV Kaharoa cruise K03/83
2. Natural mortality	(inst., /yr.)	0.3	Elder (1976): 34–36, 61–63
3. Amateur mortality	(inst., /yr.)	0.05	guess (cf. Hauraki Gulf snapper tagging expts, Sullivan 1987)
4. Recruitment Age	(yr.)	4	length of age curve (Elder 1976)
5. Maximum age	(yr.)	10	Elder (1976)
6. Total mortality over recent period	(inst., /yr.)	0.63	Elder (1976)
7. Initial PSY	(t/yr.)	400	McGregor & Voller (1985)
8. Initial open-access catch	(t/yr.)	400	fishery statistics

this stock is the assumption that the fishing costs for red gurnard from the multi-species fishery can be separated and are proportional to the fishing mortality on red gurnard. The DMEY is obtained at an effort of half the initial open access effort after the stock has increased by 20%. The equilibrium surplus at the DMEY is then about 20%.

Yellow-belly flounder (Rhombosolea leporina), *Firth of Thames*

Parameters and results are given in Tables 5 and 6. This is a short-lived species for which landings have fluctuated substantially around an apparently stable mean. Recruitment is known to vary substantially. The model parameters represent mean

Table 4
Results for Gurnard, Hauraki Gulf

Result Variable		Estimate
1. Initial stock biomass	(t)	1,900
2. Equilibrium yield at effort equal to initial PSY effort	(t/yr.)	400
3. Maximum sustainable yield (MSY)	(t/yr.)	800
4. Maximum economic yield (MEY)	(t/yr.)	240
5. Dynamic maximum economic yield (DMEY)	(t/yr.)	240
6. Equilibrium surplus at DMEY	(%)	20
7. Ratio of DMEY effort to open-access effort		0.5
8. Ratio of initial stock biomass to virgin stock biomass		0.6
9. Ratio of DMEY stock biomass to initial stock biomass		1.2

Table 5
Parameters for Yellow Belly Flounder, Firth of Thames

Parameter		Estimate	Source
1. Weight at age on 1 Jan (starting age 1 yr.)	(kg)	0.02 0.32 0.57 0.68	based on Colman (unpub.) mean length of males and females and unpublished weight at length curve
2. Natural mortality	(inst., /yr.)	1.25	guess
3. Amateur mortality	(inst., /yr.)	0.15	guess
4. Recruitment Age	(yr.)	2	Colman (1974)
5. Maximum age	(yr.)	4	ibid
6. Commercial fishing mortality over recent period	(inst. /yr.)	0.50	Colman (unpub.) (annual rate = 40%/yr.)
7. Initial PSY	(t/yr.)	150	long-term mean from fishery statistics
8. Initial open-access catch	(t/yr.)	150	fishery statistics

conditions for the stock. The growth curve used is a mean weight at age of males and females. The equilibrium surplus at the DMEY is low (15%) but is achieved by reducing effort to half that at initial open access. The corresponding stock biomass increases only about 10%.

Sensitivity Analysis

The main focus of the sensitivity analysis is on those output variables relevant to management. Each of 10 parameters was independently varied by 10% from its best estimate, and the consequential percentage changes in the output variables were obtained. Tables 7–9 give the results. These are rounded to the nearest

Table 6
Results for Yellow Belly Flounder, Firth of Thames

Result Variable		Estimate
1. Initial stock biomass	(t)	520
2. Equilibrium yield at effort equal to initial PSY effort	(t/yr.)	150
3. Maximum sustainable yield (MSY)	(t/yr.)	540
4. Maximum economic yield (MEY)	(t/yr.)	80
5. Dynamic maximum economic yield (DMEY)	(t/yr.)	80
6. Equilibrium surplus at DMEY	(%)	15
7. Ratio of DMEY effort to open-access effort		0.5
8. Ratio of initial stock biomass to virgin stock biomass		0.8
9. Ratio of DMEY stock biomass to initial stock biomass		1.1

Table 7
Sensitivity of Output Variables to Parameters[a] in an Age-Structured Bioeconomic Model for Snapper, North-East North Island

	DMEY	Equilibrium Surplus at DMEY	F[b] @ DMEY / F @ Open Access	Initial Biomass	Initial B[c] / Virgin B	DMEY B / Initial B
Growth curve[d]	0	1	0	0	−2	0
Natural mortality	−1	−2	−1	0	7	−1
Amateur mortality	−1	−1	−1	0	−2	−1
Recruitment age	−1	−1	0	0	3	−1
Maximum age	0	0	+1	0	−4	0
Initial PSY	10	0	9	10	0	0
Initial open-access yield	0	0	−10	0	0	0
Recent F	2	6	−3	−9	−7	3
Initial surplus[e]	4	8	10	0	0	−6
Discount rate	1	−3	1	0	0	−1

[a] Percentage change caused by 10% increase in parameter from best estimate.
[b] F = commercial fishing mortality.
[c] B = stock biomass.
[d] For growth curve maximum weight is increased 10%, weight at age 0 by 0%, and curve adjusted linearly in between.
[e] Initial surplus is increased from 0% to 10%.

Table 8
Sensitivity of Output Variables to Parameters[a] in an Age-Structured Bioeconomic Model for Gurnard, Hauraki Gulf

	DMEY	Equilibrium Surplus at DMEY	F^b @ DMEY / F @ Open Access	Initial Biomass	Initial B^c / Virgin B	DMEY B / Initial B
Growth curve[d]	0	1	0	0	−1	0
Natural mortality	−1	−3	0	1	3	−1
Amateur mortality	0	0	0	0	−1	0
Recruitment age	−1	−3	0	1	3	−1
Maximum age	2	6	0	−1	−4	1
Initial PSY	8	−3	9	10	−1	0
Initial open-access yield	2	3	−8	0	0	−1
Recent F	1	7	−1	−8	−3	1
Initial surplus[e]	16	18	23	0	0	−4
Discount rate	0	0	0	0	0	0

[a] Percentage change caused by 10% increase in parameter from best estimate.
[b] F = commercial fishing mortality.
[c] B = stock biomass.
[d] For growth curve maximum weight is increased 10%, weight at age 0 by 0%, and curve adjusted linearly in between.
[e] Initial surplus is increased from 0% to 10%.

Table 9
Sensitivity of Output Variables to Parameters[a] in an Age-Structured Bioeconomic Model for Yellow-Belly Flounder, Firth of Thames

	DMEY	Equilibrium Surplus at DMEY	F[b] @ DMEY / F @ Open Access	Initial Biomass	Initial B[c] / Virgin B	DMEY B / Initial B
Growth curve[d]	0	0	0	−1	−1	0
Natural mortality	0	−5	0	3	3	−1
Amateur mortality	0	0	0	0	0	0
Recruitment age	−1	−7	0	8	3	−1
Maximum age	2	13	0	−7	−3	1
Initial PSY	12	−15	15	10	0	0
Initial open-access yield	6	8	−5	0	0	−1
Recent F	0	9	−1	−8	−1	0
Initial surplus[e]	25	35	29	0	0	−2
Discount rate	0	0	0	0	0	0

[a] Percentage change caused by 10% increase in parameter from best estimate.
[b] F = commercial fishing mortality.
[c] B = stock biomass.
[d] For growth curve maximum weight is increased 10%, weight at age 0 by 0%, and curve adjusted linearly in between.
[e] Initial surplus is increased from 0% to 10%.

whole percent. These specific cases can be used as a guide to the general sensitivity of the model to each parameter.

Growth Curve

This is really a vector of parameters. It was varied by increasing the weight at the maximum age by 10% and that at age 0 by 0% and making a linear adjustment in between. Sensitivity to this parameter is extremely small for all the important output variables. Because the initial stock biomass is essentially determined by the initial PSY and the recent fishing mortality, variation in the growth curve only redistributes biomass within the stock structure. In principle, this alters the proportions of production due to growth and due to recruitment, but, in practice, this variation is extremely small.

Natural Mortality

This parameter was increased by 10%. The most important effect of this was on the surplus at the DMEY for the short-lived species. This was reduced by 5%; and, for the gurnard and snapper, it was reduced by 3% and 2%, respectively. The reason is that, at the stock level corresponding to the DMEY, increased natural mortality results in less production being available to fishing. This causes a slight reduction in the DMEY, which reduces the surplus margin. When expressed as a percentage of the relatively low DMEY surplus of the short-lived species, the reduction is moderate. When the value of the natural mortality parameter is subject to some doubt, as is often the case, this causes a moderate degree of doubt to attach to the surplus estimated at the DMEY for stocks where this surplus is low.

For the long-lived species, there was also a moderate decrease in the virgin biomass.

Amateur Mortality

This parameter was increased by 10%. Although this parameter acts in the same way as natural mortality (except in the virgin stock), it was small relative to the other mortality parameters, and the effects of its variation were minimal.

Recruitment Age

This parameter was increased by one year, and the changes in the output variables were scaled so that they corresponded to a 10% increase. The effects of variation in this parameter are not very important because its value is normally well known as it corresponds to a minimum commercial fish size. The main effect is a reduction in the surplus at the DMEY, which is moderate for the short-lived species. The reason is that the initial stock biomass, which is essentially determined by the PSY, and the recent fishing mortality are contained in fewer age classes, and so there is a slightly larger loss of fish biomass from the maximum age class in which all fish die. As before, a small decrease in the DMEY corresponds to a larger percentage decrease in the surplus, especially when this is small.

Maximum Age

This parameter was decreased by 10% rounded to a whole number of years, and the changes in the output variables were scaled and changed in sign so that they corresponded to a 10% increase. The effects of variation in this parameter are important for short-lived species. Its value is often not well known. For the short-lived species, the important effect was a more than 10% increase in the surplus at the DMEY. For the species of moderate life span, the effect was less. The effect is the reverse of that for increasing recruitment age, except that the change in maximum age is a percentage of a larger value and so is larger.

Initial PSY

This parameter was increased by 10%. Most of the biomass variables are directly proportional to the initial PSY. For each stock, there was a corresponding 10% increase in initial biomass, recruitment, virgin biomass, DMEY (approximately), and the ratio of fishing mortality at the DMEY to initial open access fishing mortality (approximately). The surplus at the DMEY, however, was reduced, by 0%, 3%, and 15% for the snapper, gurnard, and flounder stocks, respectively. When the initial PSY is increased, the initial open-access yield is taken from an increased initial stock biomass and taken at a lower fishing mortality. The reason for the reduction in the surplus at the DMEY relates to the non-linearity between yield and fishing mortality. Increases in fishing mortality result in less than proportionate increases in yield with other variables held constant. The degree of non-linearity decreases with decreasing fishing mortality. Hence, when fishing mortality is lower, the potential gains from reducing fishing mortality are less, and lower surpluses at the DMEY result. The sensitivity effect is greatest for the flounder stock where fishing mortality is highest.

Initial PSY is an important parameter. The DMEY and the ratio of fishing mortality at the DMEY to that at initial open access are moderately sensitive to it for all stocks, and the surplus at the DMEY is sensitive to it for stocks where fishing mortality is high.

Initial Open-Access Yield

This parameter was increased by 10%. For the short-lived species, this caused a moderate increase in the DMEY and in the equilibrium surplus at the DMEY. For each stock, the ratio of fishing mortality at the DMEY to fishing mortality at initial open access was moderately reduced. The reason is that increase in this parameter reduces the cost of a unit of fishing mortality. The value of this parameter was always set to the recent annual yield which was always known. The sensitivity to this parameter was, therefore, related to whether the open access assumption was true. Hence, it was more useful to examine the sensitivity to the surplus parameter at initial "open access."

Recent Fishing Mortality

This parameter was increased by 10%. In all three stocks, this decreased the initial biomass by just under 10%, because the initial PSY divided by the recent fishing mortality essentially determines the initial stock biomass. More importantly, it increased the surplus at the DMEY by 9%, 7%, and 6% for the flounder, gurnard, and snapper stocks, respectively. The reason for the increase in the surplus at the DMEY relates to the non-linearity between yield and fishing mortality. The degree of non-linearity increases with increasing fishing mortality so that reductions from a greater initial fishing mortality produce relatively greater surpluses.

This is a moderately important parameter whose value may not be well known. Substantial error in this parameter would produce substantial error in the equilibrium surplus at the DMEY but not a great deal in the DMEY and in the fishing mortality at the DMEY relative to that at the initial open access.

Surplus at Initial Open Access

This parameter was increased from zero to 10%. Strictly speaking the definition of open access always requires this parameter to be zero. However, we have weakened the definition to allow for fisheries where adjustments to recent discoveries, changes in market prices or changes in catching costs are not instantaneous. In these cases, there will be an "open-access" yield with a non-zero surplus. In all three, stocks' variation in this parameter had a greater effect on the surplus at the DMEY than variation in any other parameter. For the two shorter-lived species, it also had a large effect on the DMEY and the fishing mortality at the DMEY. All these effects were positive and were caused by the reduction in the cost of a unit of fishing mortality. For stocks where the surplus at the DMEY is low, even a small variation in the value of the surplus at initial open access parameter will have a significant effect on the surplus at the DMEY.

This is the most important parameter from the point of view of the sensitivity analysis. Since fisheries often experience changing conditions, the value of the surplus at initial open access will often differ from zero. Unfortunately, this is not at all easy to estimate. Error in this parameter will affect all the output variables relevant to management.

Discount Rate

This parameter was increased from 10% to 11%. This had no effect whatever on the two shorter-lived species and a small effect on the long-lived species. The main effect in that case was a small reduction in the surplus at the DMEY. This is because an increased discount rate reduces the present value of surpluses in the future. Along an optimal path to the DMEY, this results in taking larger surpluses (in dollar terms) early, at the cost of reduced surpluses when the DMEY is reached.

Discussion

Modeling

The use of an age-structured model for the purposes of the present analysis might seem somewhat unexpected as such a model requires more parameters and initial values than most non-age-structured models. Furthermore, the potential of age-structure to model age-differential effects, such as catchability varying with age, was not exploited. An advantage of using an age-structured model like this is that parameter estimates tend to be more directly available from literature sources than those for most non-age-structured models. The contribution of each factor to the stock dynamics is quite transparent in this type of model. For the many stocks to be modeled, it was necessary to find or educe parameter estimates from the available published and unpublished literature. Many parameters had wide error bounds.

The estimates of surpluses at the DMEY were determined by the relative changes in catch rates and costs of fishing effort resulting from changes in stock biomass. The important output variables in the model were not unduly sensitive to the parameters which specifically involved age-structure. The model was not sensitive to the weight at age curve. It was moderately sensitive to the size of the recent fishing mortality parameter which defines the initial stock structure and which together with the initial PSY determines the initial stock biomass. The model was quite insensitive to changes in the shape of the initial age-structure curve when the three-parameter case was used. Age-structure was, therefore, a useful framework, but the main results depended on the aggegate effects of changes in stock biomass. This means that the results are likely to be robust with respect to the model structure, provided the stocks modeled do not have strongly age-differential dynamics.

The model includes recruitment and the growth curve in the equations for the stock dynamics simply as constants. It is sometimes hypothesized that, as stock sizes decrease, fish growth rates tend to increase, age of maturity tends to lower, fecundity tends to increase and recruitment tends to increase, e.g., Cushing (1981); and the reverse is assumed when stock sizes increase. These effects are implicit in some non-age-structured models such as the Schaeffer model. They are extremely plausible but, in reality, have not been established for any New Zealand species and have rarely been established or measured with accuracy elsewhere. If recruitment or growth rate did decrease with stock increase in any of the modeled stocks, the effect would be to reduce the DMEY and the surplus at the DMEY, as the DMEY always occurred at increased stock size. (A DMEY at a reduced stock size could occur if the initial stock were virgin or had experienced very light exploitation). Stock size increases from the initial stock size to that at the DMEY were, in most cases, no more than 50%. It would seem surprising if the compensatory mechanisms of many stocks were very great with changes of this magnitude. Substantial compensatory mechanisms are most likely to occur at the extremes of the possible stock size range. For a few of the long-lived and heavily exploited stocks, the initial stock size was about 20% of the virgin biomass. In such cases, we cannot rule out the possibility that compensatory mechanisms do occur. This would mean that recruitment and growth would be initially higher than they would be after the stock biomass had been allowed to increase towards its optimum size. The conclusion is that there is a possible positive bias in our estimates of the DMEY and surplus at the DMEY due to lack of compensatory mechanisms in the model structure. This would be greatest for stocks whose initial size was a small fraction of their virgin size.

In the case of two elasmobranchs which were modeled (results not given here), the stock dynamics would be more complex again, as the females give birth to a relatively few live young. Hence, at least over some range of stock size, recruitment must bear a depensatory relationship with stock size: the greater the biomass of mature females the greater the recruitment. In that case, the DMEYs and the surpluses at the DMEYs would be greater than those predicted by this model.

A defect in the model caused by the failure to allow for depensatory mechanisms at very low stock size is the overestimation of the MSY. This is more serious theoretically than practically. In most of the stocks modeled, the MSY occurred at very high fishing mortalities. Corresponding stock levels were extremely low, and the yield was maintained almost entirely from the (constant) annual recruitment. That constant recruitment should be maintained no matter how low stock biomass becomes is unrealistic. However, if constant recruitment is a valid assumption over even a moderate range of stock sizes, then the conclusion that the MSYs were nearly always taken at severely uneconomic levels of fishing effort may not be so unrealistic. However, in the present framework, this variable is of little interest.

One of the assumptions of the model is that the costs of fishing each stock are independent, so that, when effort is altered in fishing one stock, this has no effect on the costs of fishing any other stock. In fact, many of the fisheries are multi-species, and two or more species are caught together during fishing operations. It is not clear that the treatment of stocks independently will produce the same results as an analysis which properly models the true multi-species relationships. Even if the population dynamic interactions are insignificant, an optimum effort level will depend on the value of the catch of two or more species caught together in relative quantities which can only partly be controlled by the fishermen. It is likely that the results from a model of a multi-species fishery would be dominated by the species which has the greatest value in the catch. The optimal values of output variables for minor or low value by-catch species would depend on the cost of modifying fishing practices to alter catch mixes. In general, however, they would tend to be forced by those for the dominating species away from the values produced by the independent analyses of the minor species. For example in the northern New Zealand trawl fisheries, snapper is the target; and red gurnard, trevally, and John dory are by-catches. A multi-species model would probably estimate a substantial reduction in effort for optimality, due to the snapper stock. Such a reduction would be greater than each of those indicated by the independent analyses of the other species.

Consideration of stochastic or environmentally induced fluctuations in parameters, especially recruitment and catchability, is beyond the scope of the present analysis; but, in reality, these may be important, especially for short-lived species. An economically optimal stock management policy would involve fluctuating yields and fluctuating surpluses, even in the long run. This would depend on the probability structure of the fluctuations and on the economic costs of short-run adjustment of effort. Under stochastic fluctuations, a long-run management regime that involved government entering the market for quota to control the annual percentage surplus at a mean optimal constant value would probably be fairly close to optimal. One which controlled effort at a constant level would be less so, and one which set a constant TAC would be quite sub-optimal.

Management

The surpluses at the DMEYs were used to give the relative value of quota for the stocks. Prices actually paid by government in the tender round to buy back excess quota for each species are given in the internal report. The factor that capitalized the annual surplus at the DMEY varied somewhat from species according to the tenders received. The relative ranking of prices paid generally corresponded to expectations. Long-lived species which had recent high fishing mortalities relative to their natural and amateur mortalities gave the highest surpluses. Short-lived species which had recent low fishing mortalities relative to their natural and amateur mortalities gave the lowest surpluses.

The high levels of the highest surpluses (45%) at the DMEYs were somewhat unexpected. These are achieved without any technological improvements in fishing methods simply by reducing wasteful resource input in the fishing operations. The high levels of these surpluses are a measure of the economic inefficiency caused by managing this common property resource with a largely open-access policy. The long-run economic gains are not the result of increases in the productivities of the stocks. The gains are the result of increases in the productivity of the fishing operations. At lower effort levels, the long-run higher stock sizes allow higher catch rates per unit of effort, i.e., per unit of cost. In general, the results showed that substantial reductions in effort, often over 50%, result in slight or moderate reductions in long-run annual yields from larger stocks and, hence, often substantial surpluses.

For stocks about which the amount of information available is very limited, it is obviously not possible to obtain reliable estimates of optimal yields or surpluses. In the present context, the most difficult stocks are those for which the present level of exploitation is only very recent. In a virgin stock, the PSY is zero, as any fishing will reduce the stock biomass. A stock close to its virgin size will have a PSY near zero. This parameter will be very difficult to estimate because there is no history of yield and stock size. It is also the case that, if the initial open-access level of fishing effort differs substantially from that of the recent past, then the open access surplus may not be zero. This is because the industry can be assumed to be still in the process of adjusting to a positive or negative surplus. This surplus will also not be easy to estimate. Because the model is sensitive to the initial PSY and to the surplus at initial open access, either circumstance will lead to results of low reliability.

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References

Anderson, L. G. 1977. *The Economics of fisheries management.* Baltimore: J. Hopkins Univ. Press.

Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. *Fish. Invest., Minist. Agric. Fish. Food, G.B. Ser. 2* (19).

Clark, C. W. 1980. Towards a predictive model for the economic regulation of commercial fisheries. *Can. J. Fish. Aquat. Sci.* 37:1111–1129.

Clark, C. W. 1985. *Bioeconomic modelling and fisheries management.* New York: J. Wiley & Sons.

Colman, J. A. 1974. Growth of two species of flounders in Hauraki Gulf, N.Z. *N.Z. Journ. Mar. Freshw. Res.* 8(2):351–370.

Colman, J. A. Unpublished results. MAFFISH, Minist. Agric. Fish., P.O. Box 297, Wellington, N.Z.

Cushing, D. H. 1981. *Fisheries biology: A study in population dynamics.* Wisconsin: Univ. of Wisconsin Press.

Elder, R. D. 1976. Studies on age and growth, reproduction, and population dynamics of red gurnard in Hauraki Gulf, N.Z. *Fish. Res. Bull., Minist. Agric. Fish., N.Z.* 12:81 pp.

Gilbert, D. J. 1986. A stock reduction analysis of Bay of Plenty snapper. *N.Z. Journ. Mar. Freshw. Res.* 20:641–653.

Hore, A. J., K. J. Sullivan, and V. H. Wilkinson. 1986. Snapper. In Background papers for the Total Allowable Catch recommendations for the 1986-87 N. Z. fishing year. Unpublished report, composed and edited by G. G. Baird and J. L. McKoy, 148–153. Fisheries Research Centre, MAFFISH, P.O. Box 297, Wellington, N.Z.

Horwood, J. W., and P. Whittle. 1986. The optimal harvest from a multi-cohort stock. *IMA Journ. Math. Appl. Med. Biol.* 3:143–155.

Kennedy, J. O. S. 1987. Optimal harvesting and vessel capacity in a multicohort fishery. Paper presented at Op. Res. Ann. Conf., Univ. Edinburgh, Sept. 1987.

McGregor, G. A., and R. W. Voller. 1985. Gurnard. In Background papers for the 1985 Total Allowable Catch recommendations. Unpublished report, composed and edited by J. A. Coleman, J. L. McKay, and G. G. Baird, 101–109. Fisheries Research Centre, MAFFISH, P.O. Box 297, Wellington, N.Z.

Paul, L. J. 1976. A study on age, growth and population structure of the snapper, Chrysophrys auratus in Hauraki Gulf, N.Z. *Fish. Res. Bull., Minist. Agric. Fish., N.Z.* 13:63 pp.

Sullivan, K. J. 1985. Snapper. In Background papers for the 1985 Total Allowable Catch recommendations. Unpublished report, composed and edited by J. A. Colman, J. L. McKoy, and G. G. Baird, 187–214. Fisheries Research Centre, MAFFISH, P.O. Box 297, Wellington, N.Z.

Sullivan, K. J. 1987. Unpublished results. Fisheries Research Centre, MAFFISH, P.O. Box 297, Wellington, N.Z.