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The cost of overfishing and management strategies for new fisheries on slow-growing fish: orange roughy (*Hoplostethus atlanticus*) in New Zealand

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Abstract: The history of orange roughy (*Hoplostethus atlanticus*) stocks, primarily in New Zealand and Australia, is commonly used as an example of the inability to manage fisheries resources. We review the history and status of the New Zealand orange roughy fishery and show that the total loss of potential biological yield from overfishing is no more than 8.3% (1260 tonnes (t)·year^{-1}) of the potential yield. The losses from underfishing are estimated to be 810 t·year^{-1}. We consider the biological and economic consequences of alternative management approaches to the New Zealand orange roughy fishery. We suggest that given the uncertainty in stock abundance and productivity and market and processing capacity limits, the management of New Zealand orange roughy stocks has been close to economically optimal and has produced near maximum sustainable yield from the resource.

Résumé : On utilise souvent l'histoire des stocks de l'hoplostèthe orange (*Hoplostethus atlanticus*), particulièrement de Nouvelle-Zélande et d'Australie, comme exemple pour montrer que les ressources halieutiques sont impossibles à gérer. Nous passons en revue l'histoire et le statut de la pêche commerciale de l'hoplostèthe orange en Nouvelle-Zélande et démontrons que la perte totale de rendement biologique potentiel dû à la surpêche ne dépasse pas 8,3 % (1260 tonnes (t)·an^{-1}) du rendement potentiel. Les pertes dues à la sous-exploitation sont estimées à 810 t·an^{-1}. Nous examinons les effets biologiques et économiques des diverses approches de rechange pour la gestion de la pêche de l'hoplostèthe de Nouvelle-Zélande. Nous croyons qu'étant donné l'incertitude de l'abondance et de la productivité des stocks et des limites de capacité du marché et de l'industrie de la transformation, la gestion des stocks de l'hoplostèthe orange en Nouvelle-Zélande s'est maintenue à un niveau proche de l'optimum économique et qu'elle a produit à peu près le rendement potentiel à long terme de cette ressource.

[Traduit par la Rédaction]

Introduction

Overfishing has attracted enormous public attention in recent years, and orange roughy (*Hoplostethus atlanticus*) in New Zealand is often used as an example of one of the most egregious cases of poor fisheries management (Roberts 2002). The New Zealand (NZ) orange roughy fishery developed very rapidly in the late 1970s and early 1980s as new stocks were found and fisheries were developed. The early total allowable catches (TACs) were based on limited research biomass surveys and early productivity assumptions but have been shown to be overly optimistic. As more extensive research data and analyses indicated that orange roughy stocks were less abundant and less productive than initially assumed, the TACs were reduced over several years to sustainable levels (Clark et al. 2000).

The four largest fisheries (Northeast Chatham Rise (NECR), South Chatham Rise (SCR), Mid East Coast North Island (MEC), and Challenger Plateau (7A)) have produced more than 90% of the total NZ orange roughy catch (Table 1). In the case of the NECR, SCR, and MEC fisheries, beginning in 1989 TACs were reduced to sustainable levels in a stepped fashion over a 5- to 6-year period to ameliorate impacts on the fishing industry. In the 7A fishery, the TAC was doubled from 6000 to 12 000 tonnes (t) as part of an experimental adaptive management program. Once updated es-

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Table 1. Stock status of the major New Zealand orange roughy (*Hoplostethus atlanticus*) stocks, the estimated maximum sustainable yield (MSY), and the amount of loss due to overfishing and underfishing.

Stock	Unfished biomass (1000 t)	Current biomass (1000 t)	Current level as fraction of unfished	Percent loss in potential yield	MSY (1000 t)	Annual loss from overfishing (1000 t)	Annual loss from underfishing (1000 t)
NWCR	67	23	0.347	–0.02	1.3	0.00	0.03
NECR	373	166	0.445	–0.10	7.2	0.00	0.72
SCR	104	37	0.356	–0.03	2.0	0.00	0.06
Puysegur	17	1.1	0.065	0.37	0.3	0.12	0.00
East Cape	21	5.1	0.243	0.00	0.4	0.00	0.00
MEC	101	26	0.253	0.00	2.0	0.00	0.00
7A	91	2.5	0.027	0.65	1.8	1.14	0.00
7B	14.5	5	0.345	–0.03	0.3	0.00	0.01
Total	789	266	0.337		15.2	1.3	0.81

Note: Negative loss in potential yield indicates stock is underfished. NWCR, Northwest Chatham Rise; NECR, Northeast Chatham Rise; SCR, Southern Chatham Rise; MEC, Mid East Coast North Island; 7A, Challenger Plateau (west of North Island); 7B, Cook Canyon (west of South Island). All values are from 2005 stock assessments found in Sullivan et al. (2005). t, tonnes.

timates of biomass and productivity became available, the sustainable yield was re-estimated and the TAC was reduced to 2500 t in one year and then closed completely several years later when the catch rate continued to decline.

During the development of the fishery, orange roughy yields were much higher than the sustainable level as the virgin biomass was fished down to the level where long-term yield is maximized (Fig. 1*a*). The concept of a period of nonsustainable yields during a fishing-down phase is well understood among fisheries scientists (Hilborn and Walters 1992), but the general public, and particularly environmental groups, repeatedly interpreted the TAC declines in the early 1990s as an indication that the management strategy had failed and that overfishing had led to a TAC reduction. Since the early 1990s, total removals have been at about the same level as the overall maximum sustained yield (MSY) using current biological assumptions.

The objectives of fisheries management are diverse and include the production of food, economic wealth, employment, and preservation of ecosystems. Most national legislations specify that the primary objective is MSY and often contain only marginal wording relating to social, economic, and environmental impacts (Hilborn 2006). For this reason we will concentrate on analyzing the loss of biological yield relative to MSY resulting from overfishing in the NZ orange roughy fishery.

Secondly, we will explore the history of the NZ orange roughy fishery and compare a range of alternative development strategies to determine what the economically optimal strategy would have been, given perfect hindsight about the size and productivity of the orange roughy stock.

Materials and methods

The status of NZ orange roughy stocks is summarized in an annual report of the stock assessment plenary meeting (Sullivan et al. 2005). Where the plenary report contained multiple scenarios, we used the value of current stock size and unfished stock size for each orange roughy stock averaged across the various scenarios presented.

To calculate the loss of yield resulting from overfishing, we used the standard fisheries age-structured model that forms the core of all NZ stock assessments (Bull et al. 2005) and calculated the yield that would be obtained at the current stock size and divide this by the maximum possible yield. In all cases we used the biological parameters assumed for Chatham Rise orange roughy. Although there are some slight variations in these parameters from stock to stock, they constitute a trivial difference.

We calculated the MSY for each stock from the production relationship and compared that with the yield at the current stock size using the method of Lawson and Hilborn (1985). These represented both ideal and equilibrium conditions. The resulting MSY was generally greater than the MSY assumed by NZ working groups, which are based on maximizing yield under a risk tolerance (Sullivan et al. 2005) rather than under equilibrium assumptions. We calculated potential yield by assuming that the stock could be maintained at the biomass supporting MSY, with no natural variability or management error. Assuming our estimates of the current stock size and unfished stock size were correct, we overestimated the loss in yield because the denominator was a theoretical MSY, not one that would result under an MSY policy.

A simple economic model was used to evaluate alternative management histories. Revenues from fishing were calculated as

$$(1) \qquad R_t = C_t P$$

where R_t is fishing revenue at year t, C_t is catch at year t, and P is fish price.

We assumed that the catch in tonnes per tow was proportional to stock abundance, so

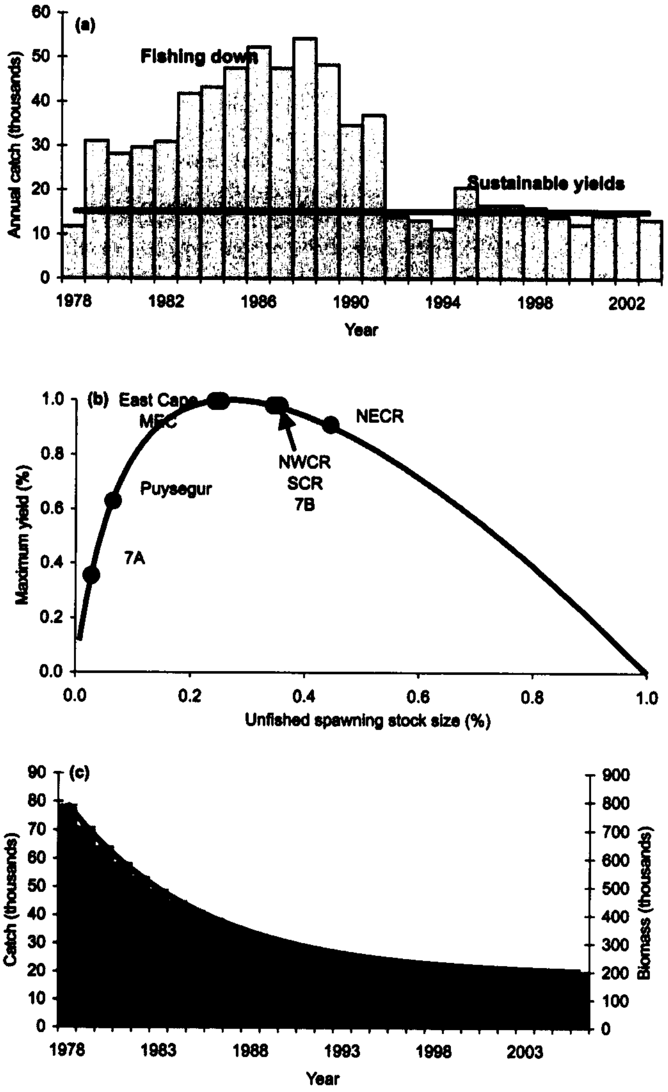
$$(2) \qquad \mathrm{CPUE}_t = qB_t$$

where B_t is stock abundance at year t.

Assuming vessels could make five tows per day, the effort (in vessel days) required to achieve any annual catch was calculated as

$$(3) \qquad E_t = \frac{C_t}{5\,\mathrm{CPUE}_t}$$

Fig. 1. (*a*) The annual catch of orange roughy (*Hoplostethus atlanticus*) in New Zealand (vertical bars) and the estimated maximum sustainable yield summed over all stocks (solid line). (*b*) The relationship between stock size and potential yield for New Zealand orange roughy, with each stock plotted on the curve at its current size. NWCR, Northwest Chatham Rise; NECR, Northeast Chatham Rise; SCR, Southern Chatham Rise; MEC, Mid East Coast North Island; 7A, Challenger Plateau (west of North Island); 7B, Cook Canyon (west of South Island). (*c*) Trends in stock biomass and stock size using a fixed escapement policy with exploitation rate capped at 10% of the stock biomass.



where E_t is the boat days required to achieve the target catch in year t.

Harvesting costs were calculated as

$$(4)\qquad H_t = E_t V \text{ and } \pi_t = R_t - H_t$$

where H_t is harvesting costs at year t, V is the price of operating a vessel for one day, and π_t is profits at year t.

The net present value (NPV) of the profit stream, simulated from 1978 to 2078, is

$$(5)\qquad \mathrm{NPV} = \sum_{t=1}^{t=100} \frac{\pi_t}{(1+r)^t}$$

where r is the discount rate and $t = 1$ in 1978.

We used the following economic parameters to qualitatively address the potential biases caused by the assumptions that harvest volume had no impact on price and that there were no fixed investment costs: a price per tonne of NZ$ 4500, which represented an average of port price and export price, a discount rate of 8%, a vessel cost per day of NZ$ 30 000, and vessel efficiency set at 50 t/day in the unfished state. These costs and revenues are in 2006 dollars and are based on nonpublished industry sources.

We explored a range of alternative harvest strategies including: (*i*) a fixed escapement policy, (*ii*) a fixed escapement policy constrained by a 10% maximum harvest rate, and (*iii*) a two-staged harvest rate in which there is one harvest rate during the fishing-down period and another harvest rate during the period of sustainable management. We maximized the NPV in 1978 for each policy simulated over a 100-year period by searching over the parameters that controlled the harvest strategy.

Results

The production relationship for orange roughy, based on the assumptions used in NZ stock assessments, showed that the sustainable yield was maximized at about 30% of unfished spawning stock biomass, but the yield was very close to the MSY value over the range of 20%–40% of virgin biomass (Fig. 1*b*). This is a typical result for most fisheries population models, and nothing in the life history of orange roughy makes this species unusual in this respect. The key assumption is the steepness value used in NZ assessments of 0.75. Lower values of steepness would result in more lost yield and higher values would result in less lost yield; 0.75 has been chosen for NZ orange roughy as an average of a range of fish stocks as none of the data sets for orange roughy provides information on this parameter.

The key inputs and outputs for each NZ orange roughy stock are shown (Table 1). The majority of the orange roughy stock are near the stock sizes that produce MSY. The 7A stock is the most depleted and shows the most loss relative to the MSY, losing 65% of the potential yield at the current low stock size, estimated to be 1140 t·year^{-1}, from a total loss across all stocks of 1260 t·year^{-1}. There is also a loss from underfishing (primarily for the NECR stock) of 810 t·year^{-1}. The 1260 t·year^{-1} loss from overfishing from a total 15 190 t of potential yield constitutes a loss of 8.3% per year.

We explored three alternative harvest strategies. As expected from economic theory, a fixed escapement policy maximized the net present value of the resource at NZ$ 2.6 billion. This policy involved fishing the stock down to 23% of its virgin biomass in the first year and then setting a subsequent annual catch at about 14 000 t. The fixed escapement policy with the exploitation rate capped at 10% was similar to the highest exploitation rate ever observed. This resulted in a more gradual development of the fishery and reduced the NPV to NZ$ 1.8 billion. In this scenario, the stock was held at 24% of its virgin biomass. We show the trend in catch and biomass (Fig. 1*c*), where there is a gradual decline in catch as the stock declines under the 10% harvest rate, then the catch and biomass approach equilibrium values.

Another strategy would have been to fish at a high harvest rate during a fishing-down phase and then apply a lower, long-term harvest rate. The optimal policy under this strategy would be to fish-down rapidly, with an annual harvest rate of 27%, and then cut the harvest rate back to 7% during the period of sustainable management. This policy produced a NPV of NZ$ 2.1 billion. In comparison, the actual catch history for the stock resulted in a NPV of NZ$1.2 billion, the lower value primarily due to the slower increase in yields in the early years of the fishery.

We explored the sensitivity of the results to the choice of discount rate. Although the absolute value of the NPV is much higher with lower discount rates, the basic results are the same, with rapid development and fishing-down to low but sustainable levels always the optimal path. The primary impact of discount rates is that the long-term population size is higher at lower discount rates; for instance, at a 2% discount rate, the long-term population size is about 25% higher than at an 8% discount rate.

Discussion

Given that the popular conception around the world is that orange roughy stocks in NZ have collapsed, our estimated 8.3% loss in yield will come as a surprise to most readers. Only two of the stocks, Puysegur and 7A, have been reduced to such low levels that yield is appreciably reduced, and both of those fisheries have been closed.

The bioeconomic analysis showed that without accounting for marketing, processing, and capacity constraints, the NPV of the resource would have been maximized by a rapid fishing-down period followed by long-term sustainable management at a similar level as presently exists. Such a policy would have been unrealistic because of market, harvest, and processing constraints. Price would also likely be affected by the high level of catches in a single year.

The third management scenario, high initial harvest rates followed by lower sustained fishing, was similar to what happened in NZ, although the actual fishing-down of the orange roughy stocks was much slower. The harvest rate required during the fishing-down period in this scenario would also have been constrained by markets and harvesting capacity. Obvious limitations to the model used are the assumptions that there is no impact of harvest volume on price and that there are no fixed or investment costs. In addition, our calculations of lost yield were dependent on the assumptions of the stock assessment. If there is less compensation in the spawner recruit curve and the B_{MSY} (biomass that produces maximum sustainable yield) occurs at a higher level than assumed, we have underestimated lost yield, whereas if there is more compensation than assumed, we will have overestimated lost yield.

Many fisheries agencies now use B_{MSY} as a lower limit and strive to keep the stocks above this level. This is in part due to the historical performance of many fisheries that have kept the stocks, on average, below this level and in part because some of the objectives of fisheries management are enhanced by larger stock sizes.

Some members of the public have the desire to maintain pristine marine ecosystems. However, it is an unfortunate fact of harvesting natural populations that one cannot produce harvest from pristine ecosystems, and the more one attempts to maximize yield, the lower the stock size will be. It is not widely understood outside the fisheries science community that depleting a stock to 20%–40% of its original state is required to achieve the management objective of MSY, not an indication of management failure. Development trajectories such as found in NZ orange roughy have led to orange roughy stocks in NZ and Australia being proposed under World Conservation Union (IUCN) criteria as threatened or endangered.

There are now widespread controversies over the status of fish stocks that revolve around those who see low abundance as a symptom of fisheries failure and those who see low abundance as a consequence of maximization of yield. Jackson et al. (2001) refer to Gulf of Maine cod (*Gadus morhua*) as "ecologically extinct" yet the average surplus production for that stock in the 1980s and 1990s was as high or higher than any period in the 20th century (authors' calculations based on NOAA catch data and stock assessments http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0118/). Although Myers and Worm (2003) argued that large pelagic fish stocks throughout the world were depleted to less than 10% of their original abundance by 1980, the catches of this group of species have continued to rise for the last 25 years (authors' calculations from the Food and Agricultural Organization of the United Nations catch statistics (http://www.fao.org/fi/default.asp)) and are much higher than they were during the period when they were supposedly being depleted. Authors who focus on stock size rarely examine the productivity of the stocks and tend to describe stocks at low abundance as "depleted" or "crashed", even if they are producing near optimal yields. Indeed, if Myers and Worm's estimates of abundance trends are correct, then the large pelagics, as a group, exhibited negative surplus production until they reached low abundance.

There is a widely perceived risk of "stock collapse" when stocks are harvested down to low abundance. Analyses by Myers et al. (1995) and Liermann and Hilborn (1997) suggested that fish stocks rarely show depensatory dynamics that would lead to heavily overfished stocks not recovering or showing dramatic declines in rates of increase at low densities. Hutchings (2000) has argued that many stocks do not recover from overfishing when fishing pressure is reduced, but in most cases that he examined, the fishing pressure was reduced but still remained considerable. At present, there is no accepted measure of the "risk" associated with overfishing. In NZ, both orange roughy fisheries that are thought to be well below the level that produced MSY are completely closed to fishing.

Orange roughy do pose considerable challenges to management, particularly because abundance is difficult to index using either acoustic or trawl survey methodologies. However, the widespread use of NZ orange roughy as an example of failed fisheries management seems misguided, and although mistakes have been made and lessons learned, the overall outcome has produced sustainable biological and economic benefits that appear to be nearly as high as could be expected.

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