



SCIENTIFIC COUNCIL MEETING – SEPTEMBER 2001
(Deep-sea Fisheries Symposium – Oral)

The Boom and Bust of Deep-Sea Fisheries: Why Haven't We Done Better?

J. Anthony Koslow¹ and Geoff Tuck

CSIRO Marine Research, GPO Box 1538, Hobart, Tasmania 7001 Australia

¹Corresponding author: email: tony.koslow@marine.csiro.au

Abstract

Deepwater fisheries characteristically exhibit a boom and bust sequence, crashing within about ten years of their initial development. For some early deepwater fisheries, this could be attributed to lack of management, combined with the extreme longevity and low productivity of many of these species and their tendency to aggregate on seamounts and banks, where they are extremely vulnerable. However, these factors alone should not lead to over-exploitation, if appropriate catch limits are set in place. Considerable effort has gone into the assessment and management of orange roughy in New Zealand and Australia, but these fisheries continue to be depleted, even when quotas are reduced to levels at which assessment models indicate should lead to re-building of the stocks. One possible explanation is that recruitment variability is incorrectly parameterized in the assessment models. Long-lived deepwater fishes are characterized by highly episodic decadal-scale recruitment variability. Simulations indicate that management scenarios that are stable assuming random recruitment variability have a high probability of leading to stock collapse, if recruitment is episodic.

Introduction

Deepwater fisheries characteristically exhibit a boom and bust sequence, crashing within about ten years of their initial development. This has been observed from the 1960s and 1970s, when deepwater fisheries initially developed for species such as Pacific Ocean perch (*Sebastes alutus*) and pelagic armorhead (*Pseudopentaceros wheeleri*) to the recent development of fisheries for orange roughy around the temperate rim of the Southern Hemisphere and into the North Atlantic (Fig. 1) (Gunderson, 1977; Boehlert, 1986; Clark, 1995, 1999; Clark *et al.*, 2000; Koslow *et al.*, 2000). This pattern has been attributed to lack of management, particularly for deepwater fisheries on the high seas (some were exploited prior to the extension of fisheries jurisdictions to 200 miles offshore), combined with the extreme longevity and low productivity of many of these species and their tendency to aggregate on seamounts and banks, where they are extremely vulnerable to overfishing (Koslow, 1996; Koslow *et al.*, 2000).

Today, however, fisheries for the main stocks of orange roughy around New Zealand and Australia are actively managed. Assessments are based on estimation of the parameters regulating productivity (i.e. age, growth and natural mortality), size or age structure, fishery-dependent and fishery-independent estimates of current biomass and its trajectory since the inception of the fishery, and simulation-based management strategy evaluation (Francis, 1992, 2001; Clark, 1995; Clark *et al.*, 2000; Koslow *et al.*, 1997; Bax, 2000). In both countries, targets are set to maintain the stocks at 30% their initial biomass (B_0), and where these targets are overshot, quotas are reduced such that population models indicate the stock will rebuild within a reasonable time frame, assuming recruitment inputs based on random variation around the long-term mean.

Still, despite the adoption of best management practices, the record for Australian and New Zealand orange roughy fisheries is far from satisfactory. Clark (1999, 2001) has described the serial depletion of orange roughy from seamounts in New Zealand waters. The Challenger Plateau orange roughy fishery, first fished in 1981/82 and

one of the largest in New Zealand, was assessed to have been fished below the threshold level of 30% B_0 and the quota reduced to <2 000 tons in 1990 to allow the stock to re-build (Clark and Tracey, 1994). In 2000, however, the stock was assessed to be below 3% B_0 , and the fishery was closed altogether. The quotas to two other New Zealand orange roughy fisheries were cut drastically, based upon assessments that they were at 10-14% B_0 . These three fisheries had comprised about a third of New Zealand's orange roughy landings in 1998/99 (Anon., 2000).

Despite an active assessment and management process (Koslow *et al.*, 1997) and adoption of TACs designed to rebuild its main orange roughy stocks, Australia's main orange roughy fisheries off Tasmania's south and east coasts have similarly continued to decline. Landings off the south coast of Tasmania were less than 200 tons in 1999 (out of a quota of 1 000 tons) (Bax, 2000). The stock off the east coast of Tasmania appeared to have slipped below 20% B_0 , the threshold for closing the fishery, depending upon assumptions concerning stock structure, natural mortality and age composition (Wayte and Bax, 2001).

Where has the management gone wrong? The possibilities include mis-reporting of catch, ratcheting up of quotas in the face of uncertainty (Ludwig *et al.*, 1993) and error in the assessment process. These possibilities, although possible, are mostly uninteresting scientifically. However, a further possibility exists, which arises from a key assumption in the assessment models: that recruitment to these populations varies stochastically around some mean value.

Recruitment to fish populations is generally assumed to be a function of stock size. The shape of this functional relationship is based upon the degree of density-dependent compensation in the population. Recruitment to the unfished population is assumed to equal its natural mortality: that is, that the population is in a state of equilibrium and that natural mortality is balanced by new recruits. These assumptions are incorporated within present orange roughy assessment models (Bax, 2000; Francis, 2001). In the long term, recruitment is assumed to follow Beverton and Holt's asymptotic stock-recruit relationship with a steepness parameter of 0.75, indicating moderate density dependence, although, in fact, nothing is known about recruitment to orange roughy populations.

However, several lines of evidence indicate that recruitment to long-lived deepwater fish species may be highly episodic. Leaman (1991) showed that recruitment to the long-lived (50-100 year old) Pacific Ocean perch (*Sebastes alutus*) occurred in bursts at ca. 10-20 year intervals.

Orange roughy appear to experience similar extended periods of poor recruitment. The initial age distribution of orange roughy from the Tasmanian east coast fishery had a modal age of about 50 years, although the fish recruit to the fishery at about 25-30 years, indicating an extended period of about 20 years of poor recruitment. An age sample three years later showed the massive depletion of older fish in the stock and a preponderance of young fish newly-recruited to the population (Smith *et al.*, 1998). The orange roughy fishery in the so-called Spawning Box of the Chatham Rise, New Zealand's largest and longest-standing orange roughy fishery, showed no consistent decline in size composition or mean otolith weight (a more sensitive measure of age) over the period 1984-95, despite an estimate 80% decline in biomass (Clark, 2001). Simulation models indicate that a decline in mean size of 1-2 cm would be expected, if recruitment were at expected levels over this period (Francis and Smith, 1995).

We examine here the implications to long-term management strategy of highly episodic recruitment in long-lived fishes. We adopt a simulation model, originally developed to evaluate management strategies for Patagonian toothfish (Tuck *et al.*, 2000). Incorporating orange roughy life-history parameters, we examine stock dynamics with and without fishing, under conditions of randomly varying and episodic recruitment. Harvest strategy is based on TACs presently considered sustainable in Australia and New Zealand (Bax, 2000; Francis, 2001).

Methods

To examine the implications of episodic recruitment, three recruitment models are considered:

- (i) deterministic annual recruitment
- (ii) stochastic annual recruitment, and
- (iii) stochastic episodic recruitment.

The first model shows no random fluctuations in recruitment and the annual number of new recruits to the population are based on a deterministic application of the Beverton and Holt stock-recruitment function. The second recruitment model shows random fluctuations about the stock-recruitment relationship with recruitment occurring on an annual basis. For the stochastic episodic recruitment model, the recruitment in each annual cycle is either zero or $\rho = 10$ times the mean long-term recruitment, based on the stock recruitment relationship. Such good recruitments occur randomly with a frequency of $\rho^{-1} = 0.10$. The recruitment models are described in more detail within the Appendix. The biological model of the orange roughy population is an age- and sex-structured dynamical population model based on standard catch and population dynamic equations (see Mace and Doonan, 1988; Smith *et al.*, 1996). The parameters of the model are given in Table 1 (see Appendix). Values are from Francis (1992), except the age of maturity (Smith *et al.*, 1995).

The deterministic pre-exploitation equilibrium available biomass is set to $B_0 = 10\,000$ tons. The initial numbers at age are determined by iterating the population dynamics equations for 200 years prior to the establishment of the fishery. Fish reach sexual maturity at approximately 30 years of age, at which time they also become fully available to the fishery (at 35 cm). Fishing and natural mortality occur throughout the year and spawning occurs in mid-season.

Fishing was simulated by the following management regime. During the initial years of the fishery (the fish down) if the available stock biomass, which for orange roughy is equivalent to the adult spawning stock, was greater than 50% B_0 , the fishing quota was set at $TAC_1 = 10\% B_0$. Once stock biomass slipped below the threshold of 50% B_0 , the TAC was set at a level equivalent to the so-called 'conservative' long-term sustainable yield: $TAC_2 = 0.3 MB_0$ (Francis, 1992). This level is approximately two-thirds maximum sustainable yield (MSY). If the available biomass fell below 10% B_0 then the fishery was closed, $TAC_3 = 0$, until such time as the biomass increased above this level. The TAC was then set at TAC_2 . If the available biomass recovered to levels above B_0 , then the TAC was reset to TAC_1 , until the biomass dropped below 50% of B_0 .

Under present management regimes in Australia and New Zealand, the target biomass threshold is set at 30%, rather than 50% of B_0 . The applied management strategy in the model is thus more conservative than present orange roughy management strategies, although there is no provision in the model to further reduce the quotas until B_0 slips below 10% of B_0 .

The dynamics of the population and fishery are simulated 100 times and for each simulation the biomass of available fish is recorded. The frequency of the biomass falling below specific levels of B_0 can then be reported. This process is repeated for each recruitment model (although the deterministic model clearly only requires a single simulation).

Results

In Fig. 1, we show the median population trajectories for an orange roughy population under conditions of stochastic and episodic recruitment without fishing. Population trajectories are more variable under the episodic recruitment regime (there is a three-fold increase in the range of the envelope of population trajectories encompassing the 95% confidence limits), but the mean population trajectories (not shown) under all three recruitment regimes are virtually identical, as they must be if mean recruitment and biomass under the regimes are equivalent. There is a high probability (84%) that a population with episodic recruitment will decrease below 50% of its equilibrium available biomass over a 100-year simulation, but a low probability (7%) that it will decline below 10% of B_0 (Fig. 2). In contrast, natural variation for the population exhibiting stochastic annual recruitment shows that biomass trajectories rarely fall below 50% B_0 and never decrease to less than 10% B_0 .

When the model population is subject to exploitation, the median available stock biomass under stochastic and deterministic annual recruitment is maintained at approximately 50% B_0 , whereas the population with episodic recruitment is maintained at slightly below 20% B_0 (Fig. 3). However, there is an even more striking difference in the risk of stock collapse between the recruitment regimes, which we define as the probability of the stock decreasing below 10% B_0 over a 100-year simulation. The population with annual stochastic recruitment fell below 10% B_0 in only one of 100 simulations. However, the risk of falling below 10% B_0 for the population showing

episodic recruitment was 89% (Fig. 2). In addition, all simulated trajectories for the episodically recruiting population dropped below 25% B_0 at some point of the 100-year simulation.

Discussion

Recruitment variability considerably influences risk of stock collapse. Beddington and May (1977) first showed that constant harvest strategies, particularly near the point of MSY, were prone to stock collapse in the face of random recruitment variability. These results led to greater consideration of risk minimization in management models and to incorporation of stochastic variability within the recruitment function (e.g. Getz *et al.*, 1987). However, variability in the marine environment generally is not random; rather it is autocorrelated on a number of time scales (Steele, 1985). Not surprisingly, recruitment to marine fisheries also displays a variety of patterns, mostly non-random (Caddy and Gulland, 1983). Autocorrelated recruitment variability increases risk of stock collapse to a degree depending upon the amplitude and frequency of the variability (Koslow, 1989).

Murphy (1968) pointed out that highly variable mortality in the early life history tends to be associated with increased longevity in relation to the pilchard, which is subject to notably prolonged periods of good and poor recruitment. Episodic recruitment is an extreme form of non-random variability, and fishes such as *Sebastes* spp. and orange roughy, which exhibit highly episodic recruitment, are among the most long-lived marine fishes.

Fishing substantially increases the risk of stock collapse of fishes subject to episodic recruitment, particularly under a constant quota management strategy, even if quotas are maintained well below MSY and might therefore be considered conservative. Clearly there is risk that such species may be fished to dangerously low levels before there is another burst of recruits. The recent collapse of the Challenger Plateau orange roughy and the continued decline of many other orange roughy stocks around New Zealand and Australia appear to exemplify this process. Further evaluation of management strategies for such fisheries needs to explicitly incorporate episodic, rather than stochastic variability. A more conservative management strategy seems warranted, whereby fishing ceases at biomass levels between 30 and 50% B_0 , rather than continuing at reduced levels, based on the assumption that the stock will rebuild with a steady input of recruits at long-term mean levels. The myth of the 'long-term mean equilibrium' may be a convenient assumption in ecosystem and population models, but, unfortunately, it is a dangerous one and should be abandoned in management practice.

References

- ANON. 2000. Cuts in roughy. *Fishing News International*, **39**(10): 7.
- BAX, N. J. 2000. Stock assessment report 2000, orange roughy (*Hoplostethus atlanticus*). South East Fishery Stock Assessment Group.
- BEDDINGTON, J. R., and R. M. MAY. 1977. Harvesting natural populations in a randomly fluctuating environment. *Science*, **197**: 463-465.
- CADDY, J. F., and J. A. GULLAND. 1983. Historical patterns of fish stocks. *Marine Policy*, **7**: 267-278.
- CLARK, M. 2001. Are deepwater fisheries sustainable? - the example of orange roughy in New Zealand. *Fisheries Research*, **51**: 123-135.
- CLARK, M. 1999. Fisheries for orange roughy (*Hoplostethus atlanticus*) on seamounts in New Zealand. *Oceanologica Acta*, **22**: 593-602.
- CLARK, M. R. 1995. Experience with the management of orange roughy (*Hoplostethus atlanticus*) in New Zealand, and the effects of commercial fishing on stocks over the period 1980-1993. Hopper, A. G. Deep-Water Fisheries of the North Atlantic Oceanic Slope. 251-266. 95. Dordrecht, Kluwer Academic Publishers. NATO ASI Series.
- CLARK, M. R., O. F. ANDERSON, R. I. C. C. FRANCIS, and D. M. TRACEY. 2000. The effects of commercial exploitation on orange roughy (*Hoplostethus atlanticus*) from the continental slope of the Chatham Rise, New Zealand, from 1979 to 1997. *Fisheries Research*, **45**: 217-238.
- CLARK, M. R., and D. M. TRACEY. 1994. Changes in a population of orange roughy, *Hoplostethus atlanticus*, with commercial exploitation on the Challenger Plateau, New Zealand. *Fishery Bulletin*, **92**: 236-253.
- FRANCIS, R. I. C. C. 2001. Stock assessment for 2001 of orange roughy on the northeast Chatham Rise, 3-27.

- FRANCIS, R. I. C. C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.*, **49**: 922-930.
- FRANCIS, R. I. C. C., and D. C. SMITH. 1995. Mean length, age, and otolith weight as potential indicators of biomass depletion for orange roughy, *Hoplostethus atlanticus*. *New Zealand Journal of Marine and Freshwater Research*, **29**: 581-587.
- GETZ, W. M., R. C. FRANCIS, and G. L. SWARTZMAN. 1987. On managing variable marine fisheries. *Can. J. Fish. Aquat. Sci.*, **44**: 1370-1375.
- GUNDERSON, D. R. 1977. Population biology of Pacific Ocean perch, *Sebastes alutus*, stocks in the Washington-Queen Charlotte Sound region, and their response to fishing. *Fishery Bulletin*, **75**: 369-403.
- KOSLOW, J. A. 1996. Energetic and life-history patterns of deep-sea benthic, benthopelagic and seamount-associated fish. *Journal of Fish Biology*, **49**(Supplement A): 54-74.
- KOSLOW, J. A. 1989. Managing non-randomly varying fisheries. *Can. J. Fish. Aquat. Sci.*, **46**: 1302-1308.
- KOSLOW, J. A., N. J. BAX, C. M. BULMAN, R. J. KLOSER, A. D. M. SMITH, and A. WILLIAMS. 1997. Managing the fishdown of the Australian orange roughy resource. Hancock, D. A., Smith, D. C., Grant, A., and Beumer, J. P. Developing and Sustaining World Fisheries Resources: the state of science and management: 2nd World Fisheries Congress proceedings. 558-562. Collingwood, Victoria, CSIRO Publishing.
- KOSLOW, J. A., G. W. BOEHLERT, J. D. M. GORDON, R. L. HAEDRICH, P. LORANCE, and N. PARIN. 2000. The impact of fishing on continental slope and deep-sea ecosystems. *ICES Journal of Marine Science*, **57**: 548-557.
- LEAMAN, B. M. 1991. Reproductive styles and life history variables relative to exploitation and management of *Sebastes* stocks. *Environmental Biology of Fishes*, **30**: 253-271.
- LUDWIG, D., R. HILBORN, and C. WALTERS. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science*, **260**: 17-36.
- MACE, P. M., AND I. J. DOONAN. 1988. A generalized bioeconomic simulation model for fish population dynamics. New Zealand Fisheries Assessment Research Doc., No. 88/4, December 1988, N.Z. Ministry of Agriculture and Fisheries.
- MURPHY, G. I. 1968. Pattern in life history and the environment. *American Naturalist*, **102**: 391-403.
- SMITH, D. C., G. E. FENTON, S. G. ROBERTSON, and S. A. SHORT. 1995. Age determination and growth of orange roughy (*Hoplostethus atlanticus*): a comparison of annulus counts with radiometric ageing. *Can. J. Fish. Aquat. Sci.*, **52**: 391-401.
- SMITH, D. C., S. G. ROBERTSON, and A. K. MORISON. 1998. Age composition of orange roughy in the eastern and southern management zones. 98. Queenscliff, Victoria, Marine and Freshwater Resources Institute.
- SMITH, A. D. M., A. E. PUNT, S. E. WAYTE, and N. L. KLAER. 1996. Evaluation of harvest strategies for eastern gemfish (*Rexea solandri*) using Monte Carlo Simulation. In: Evaluation of harvesting strategies for Australian fisheries at different levels of risk from economic collapse. A. D. M. Smith (ed.). FRDC T93/238, p. 120-164.
- STEELE, J. H. 1985. A comparison of terrestrial and marine ecological systems. *Nature*, **313**: 355-358.
- TUCK, G., T. SMITH, A. CONSTABLE, X. HE, S. KUIKKA, and N. KLAER. 2000. An initial evaluation of management strategies for Macquarie Island toothfish fishery. In: Ecologically sustainable development of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island: population parameters, population assessment and ecological interactions. X. He and D. M. Furlani (eds.) *Final Report to the Fisheries Research Development Corporation*. (Project No. 97/122).
- WAYTE, S., and N. BAX. 2001. Assessment of eastern zone orange roughy. Orange roughy assessment group document.

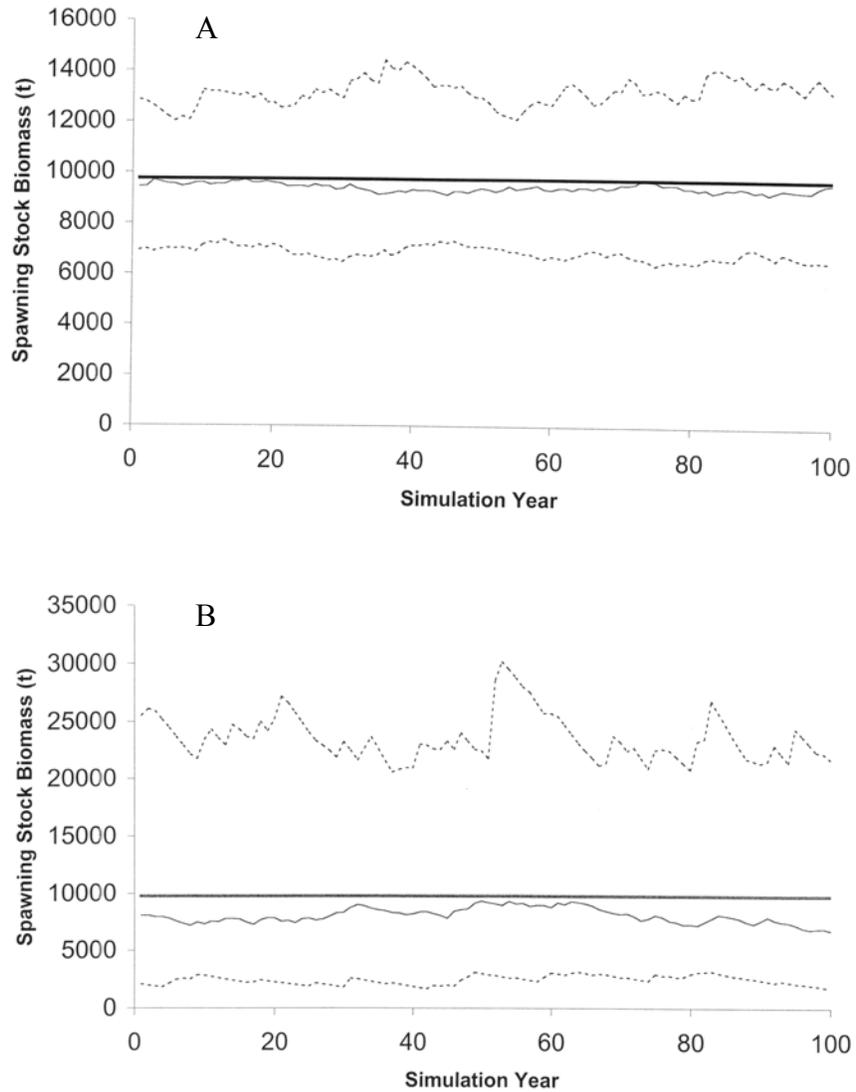


Fig. 1. The median trajectories of simulated orange roughy spawning stock biomass (in tons) without fishing over 100 years, based on deterministic recruitment (heavy solid lines) compared with a) stochastic recruitment (solid light line) and b) episodic recruitment (solid light line). 5% and 95% percentiles shown as broken lines.

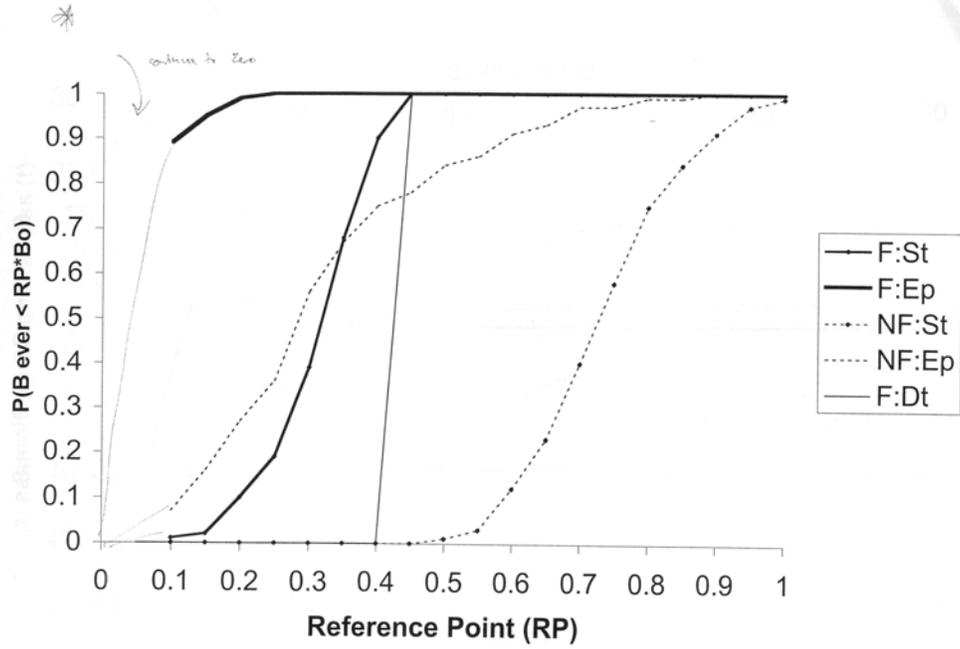


Fig. 2. The probability (P) that biomass during a simulation will decline below reference point proportions (RP) of virgin biomass, B_0 . F: with fishing; NF: without fishing; St: stochastic recruitment; Ep: episodic recruitment; Dt: deterministic recruitment.

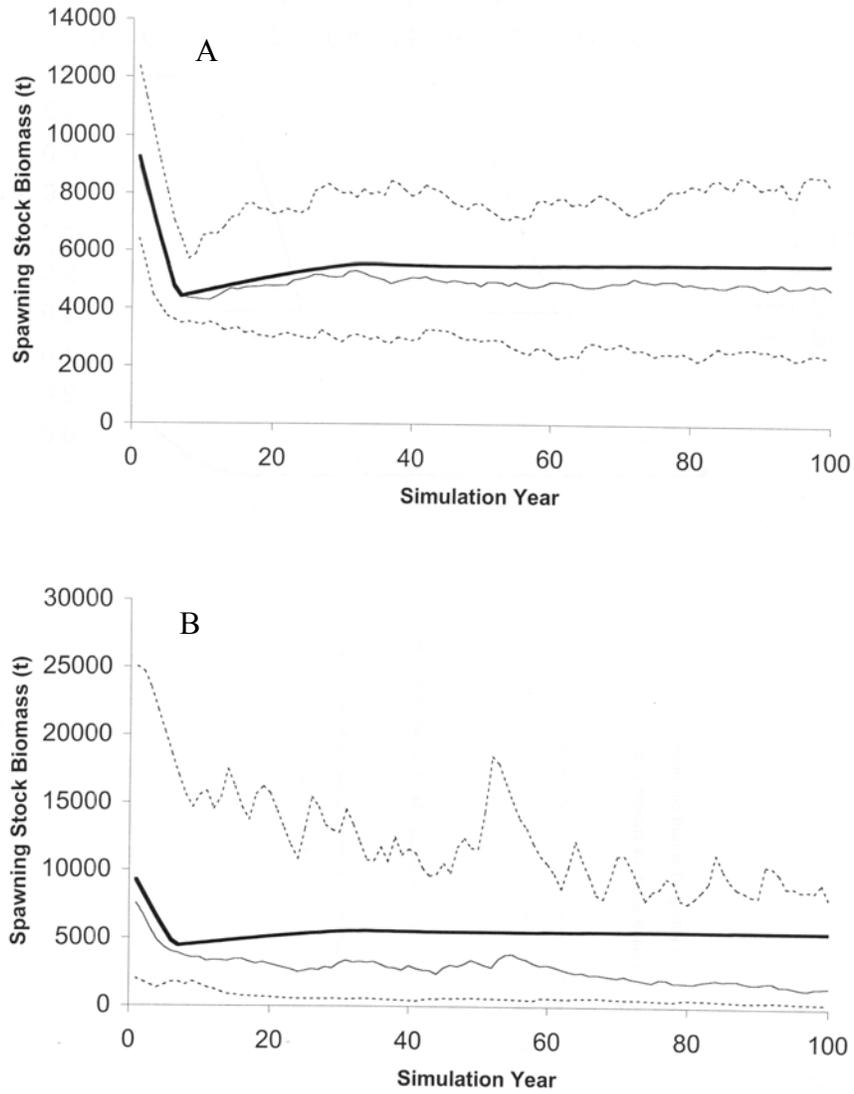


Fig. 3. The median trajectories of simulated orange roughy spawning stock biomass (in tons) with fishing over 100 years, based on deterministic recruitment (heavy solid lines) compared with a) stochastic recruitment (solid light line) and b) episodic recruitment (solid light line). 5% and 95% percentiles shown as broken lines.

Appendix: Recruitment models

The recruitment models follow a standard Beverton and Holt stock-recruitment relationship with the following form. The number of 0-year-olds in the population of sex k at the beginning of year y is given by,

$$N_{0,k}^y = 0.5\rho\tilde{B}^y(\alpha + \beta\tilde{B}^y)^{-1}e^{\varepsilon_y^r - \sigma_r^2/2} \quad \varepsilon_y^r \sim N(0, \sigma_r^2)$$

where

\tilde{B}^y is the female spawning biomass at mid-season of year y

ρ is a multiplying factor giving the increase in the number of recruits in a year of positive recruitment for the episodically recruiting population over an annually recruiting population

σ_r is the standard deviation of the natural logarithm of the multiplicative fluctuations in births, and

α and β are the parameters of the Beverton-Holt stock-recruitment relationship (see Mace and Doonan (1988) for details).

The deterministic annual recruitment model has $\sigma_r = 0$ and $\rho = 1$. The stochastic annual recruitment model has parameters $\sigma_r = 1.1$ and $\rho = 1$, while the stochastic episodic recruitment model has $\sigma_r = 1.1$ and $\rho = 10$ (Table 1).

Table 1 The biological parameters of the population model for orange roughy. The recruitment models are (i) deterministic annual recruitment, (ii) stochastic annual recruitment, and (iii) stochastic episodic recruitment.

Quantity		Values		
Natural mortality	M	0.05		
Von Bertalanffy growth parameters	L_{∞}	42.5cm		
	K	0.059		
	t_0	-0.3		
Length (cm) to weight (g)	a	0.0963		
	b	2.68		
Age at 50% maturity	A_m	30		
Gradual maturity	S_m	1		
Maximum age	x	70 years		
Steepness	h	0.75		
Length at full selection	s	35cm		
Recruitment models		(i)	(ii)	(iii)
Recruitment s.d.	σ_r	0	1.1	1.1
Recruitment multiplier	ρ	1	1	10