Cod Today and None Tomorrow: The Economic Value of a Marine Reserve

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ABSTRACT. *Using data from what was once one of the world's largest capture fisheries, the northern cod fishery, the economic value of a marine reserve is calculated using a stochastic optimal control model with a jump-diffusion process. Counterfactual analysis shows that with a stochastic environment an optimal-sized marine reserve in this fishery would have prevented the fishery's collapse and generated a triple payoff: raising resource rents even if harvesting was "optimal"; decreasing recovery time for the biomass to return to its former state, smoothing fishers' harvests and resource rents; and lowering the chance of a catastrophic collapse following a negative shock.* (JEL Q22, Q57)

> *Many catastrophes have occurred in fisheries around the planet . . . , but none is quite as devastating as the closing of the fish banks from Cape Cod to Newfoundland along the northeast coast of North America.* (Michael Berrill 1997, 114)

I. INTRODUCTION

Capture fisheries face problems of both biological and economic overfishing, and many stocks are in decline (Malakoff 1997; Schiermeier 2002). For the period 1974–1999, the Food and Agricultural Organisation of the United Nations (FAO) calculates that the proportion of fisheries harvested beyond the estimated maximum yield tripled from around 10% to 30% of surveyed stocks (FAO 2000), while Myers and Worm (2003) estimate that the stocks of predatory fish in the world's oceans have declined by over 90% in the past 50 years. In Europe, several cod stocks have declined precipitously in the previous two decades, and some important stocks are at their lowest levels ever (European Environment Agency 2003).

To overcome excess fishing, both managers and scientists have argued for a more holistic approach to management and the greater use of marine reserves (Botsford, Castilla, and Peterson 1997; Pauly et al. 2002). Reserves are justified on theoretical grounds because they can increase yields when population levels are overexploited (Pezzey, Roberts, and Urdal 2000; Sanchirico and Wilen 2001), reduce the variance of the population (Conrad 1999) and harvest (Sladek Nowlis and Roberts 1999; Mangel 2000; Hannesson 2002), and provide a hedge against management failure (Lauck et al. 1998). Empirical studies of reserves also indicate that they can raise the spawning biomass and mean size of exploited populations (Gell and Roberts 2002), increase abundance (Côté, Mosquiera, and Reynolds 2001), and, relative to reference sites, raise population density, biomass, fish size, and diversity (Halpern 2003). Reserves have also been shown to generate positive spillovers to fishers in adjacent areas subject to harvesting (Roberts et al. 2001; Bhat 2003; Gell and Roberts 2003).

Despite the apparent benefits of marine reserves, they remain a controversial management tool, and measures to establish or enlarge reserves are often met with protest by fishers (National Research Council 2001). Indeed, many fishers are strongly opposed to all but the smallest "no-take"

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areas (Halpern and Warner 2003). The concern is that reserves will reduce their harvests, increase costs, and restrict when and where they can fish. The reluctance of harvesters to support reserves has also found some support in the economics literature, which has used deterministic models to show that if effort (and harvests) can be perfectly controlled, then reserves are of little or no value (Holland and Brazee 1996); reserves need to be on the order of 70% to 80% of a fishing area to generate yield and conservation benefits to fishers equivalent to optimal harvesting (Hannesson 1998); and reserves can increase sustainable yields and revenues only when the population is overexploited (Holland 2000; Pezzey, Roberts, and Urdal 2000).

To address the question of what the economic value of marine reserves is, and how they might assist in preventing declines or collapses in fish populations, we use data and estimates from what was once one of the world's largest capture fisheries—the northern cod fishery of Newfoundland and Labrador. This resource has been commercially exploited for centuries, and, until the 1950s, fish were found in such large numbers that harvesting was considered to have no material impact on yields (Berrill 1997). Beginning with the arrival of the first freezer-factory trawler in 1958, however, harvesting grew dramatically, reaching a peak of over 800,000 tons in 1968. Despite extension of Canadian fisheries jurisdiction over most of the fishing grounds in 1977, coupled with the use of input and total harvest controls, the fishery collapsed in the early 1990s and still has yet to recover.

Using data from the fishery we address four principal questions: What would have been the economic value of a marine reserve if a no-take harvesting area of optimal size had been established in the fishery in 1962? Even with optimal harvesting that tries to maximize the discounted net returns from fishing, is it possible for a marine reserve to generate an extra economic return to harvesters, given the shocks that occurred in the fishery? What is the consequence for optimal reserve size of harvesting from a smaller than optimal biomass? Could an economically optimal marine reserve have prevented the collapse of the fishery if the harvesting rule used by the regulator had been successfully implemented? The answers we provide generate important insights for the management of renewable resources.

II. THE MISMANAGEMENT AND COLLAPSE OF FISHERIES

Many of the world's exploited fisheries are managed on the presumption that maximizing the sustainable yield from the fishery is both possible and desirable. In reality, there exists a wealth of evidence that fisheries are subject to environmental stochasticity, where populations can widely fluctuate over time (Caddy and Gulland 1983), and variability that can hide evidence of overexploitation (Ludwig, Hilborn, and Walters 1993). For example, the world's largest fishery ever in terms of harvests was the Peruvian *anchoveta*, which, according to official statistics, had total catches peak at an unsustainable 12 million tons, but which suddenly collapsed following an *El Niño* event in 1972–1973. Various reasons have been given for the collapse, but undoubtedly overharvesting was a major contributing factor, despite controls on the total harvest (Pauly et al. 2002). A similar story occurred with the North Sea herring fishery, which had yielded harvests of between 300,000 and 1 million tons per year in the first half of the twentieth century but also collapsed in the early 1970s because of overharvesting that was, in part, a consequence of overestimation of the size of the population by fishery biologists (Hilborn and Walters 1992). More recently, half of the major cod stocks in Europe have fallen below critical biomass thresholds where recruitment is expected to decline and the risk of collapse is greatly increased (European Environment Agency 2003).

One of the most recent and also most spectacular collapses of any fishery has been the catastrophic decline in the population of Canada's northern cod fishery. Indeed, the

TABLE 1
ACTUAL AND OPTIMUM HARVEST WITH OPTIMUM RESERVE (MILLIONS OF TONS)

Year	1 Actual Exploitable Biomass	2 Actual Harvest	3 Optimum Biomass	4 Optimum Harvest
1962	2.977	0.503	2.977	0.85309121
1963	2.655	0.509	2.42347432	0.37350931
1964	2.541	0.603	2.47517002	0.40391219
1965	2.39	0.545	2.60979768	0.49069243
1966	2.336	0.525	2.37307641	0.35091683
1967	2.382	0.612	2.40202432	0.36530523
1968	2.329	0.81	2.59490323	0.4790063
1969	2.006	0.754	2.56659628	0.46001592
1970	1.693	0.52	2.61925004	0.49564353
1971	1.601	0.44	2.61842344	0.49522417
1972	1.394	0.458	2.54388726	0.4443343
1973	0.983	0.355	2.10377814	0.24296733
1974	0.752	0.373	2.44857247	0.38857491
1975	0.568	0.288	2.13681133	0.27116593
1976	0.526	0.214	2.33601211	0.33528629
1977	0.526	0.173	2.27663654	0.31169336
1978	0.597	0.139	2.31584134	0.32562431
1979	0.695	0.167	2.24265689	0.29957699
1980	0.781	0.178	2.35903646	0.34533376
1981	0.882	0.171	2.39559685	0.36233135
1982	0.931	0.23	2.56969681	0.46146337
1983	1.007	0.232	2.52018798	0.43114364
1984	1.125	0.232	2.42224303	0.37392935
1985	1.06	0.231	2.54156966	0.44430831
1986	0.951	0.252	2.70627668	0.56275807
1987	0.812	0.235	2.31906297	0.32721533
1988	0.699	0.269	2.21147028	0.2901883
1989	0.569	0.253	2.37187835	0.3500142
1990	0.405	0.219	2.24827366	0.30152929
1991	0.242	0.171	2.60424519	0.48559519

collapse has been so profound that the subspecies of cod in the fishery has been listed by the independent Committee on the Status of Endangered Wildlife (COSEWIC) as endangered (Schiermeier 2003). This is despite the fact that the northern cod fishery has been commercially exploited since 1497 and consistently yielded annual catches of more than 200,000 tons per year over the period 1880–1960 (Hannesson 1996).

The decline began with the arrival of large factory stern trawlers in the late 1950s and the exploitation rate increased dramatically as these vessels were able to harvest cod offshore in winter months at times and at places where they were never previously caught. As shown in Columns 1 and 2 of Table 1, by 1968 harvests peaked at the unsustainable level of over 800,000 tons, and both the biomass and the harvest declined until 1977 when Canada assumed jurisdiction for almost the entire area of the fishery. Under Canadian jurisdiction, the total allowable harvest was reduced to 173,000 tons on the expectation that stocks would recover and eventually allow a sustainable yield of over 400,000 tons per year (Department of Fisheries and Oceans 1981). Although stocks did recover and peaked in 1984, the increase was not as much as expected. Despite a declining biomass over the 1980s, total catches did not decrease and reached a maximum of 269,000 tons in 1988. Thereafter, both catches and the biomass fell precipitously such that by 1992 a complete harvesting moratorium was imposed on the fishery.

From 1998 onward a very small amount of fishing was permitted, which peaked at 8,000 tons in 1999, dropping to 1,000 tons in 2003. Since April 2003 the fishery has been closed indefinitely and still has not recovered; indeed, its estimated biomass remains at 1% or less of its depleted size in the 1980s (Department of Fisheries and Oceans 2004a). Based on the available evidence, it would seem that the fishery has suffered serious harm that has led to a profound shift in the food web (Scheffer et al. 2001) and may have left the fishery in a "predator pit" that prevents recovery (Shelton and Healey 1999).

III. MODELING A MARINE RESERVE FOR THE NORTHERN COD FISHERY

Many authors have attempted to model the northern cod fishery, but very few have examined the issue of optimal harvesting from an economic perspective, or in terms of a marine reserve. Grafton, Sandal, and Steinshamn (2000) derive a deterministic optimal feedback rule for the fishery over the period 1962–1991 and show that such a rule would have led to much smaller harvests and the implementation of a harvesting moratorium three years earlier given the development of the biomass that actually took place over the period. Guénette, Pitcher, and Walters (2000) derive a spatial model of a marine reserve for the fishery and undertake simulations for the period 1984–1991 to compare the ability of a reserve to protect the fishery from collapse with no other management controls, with seasonal closures for trawl and gillnets, and with winter-season trawl closures. They find that a reserve of 80% size would have been sufficient to prevent the collapse that occurred in the early 1990s. Unfortunately, the model they use lacks an economic component, and they are unable to determine optimal harvest, an economically optimal reserve size, or consider the implications of a harvest rule on the fishery. Moreover, the data they use, and also their simulations, do not include the period 1973 when a large negative shock struck the fishery.

Following Grafton, Sandal, and Steinshamn (2000) we estimate a generalized density-dependent growth function for the northern cod fishery of the following form:

$$f(x) = rx\left(1 - \frac{x}{K}\right)^{\alpha}, \qquad [1]$$

where x is the population or biomass, $f(x)$ is its growth, r is the intrinsic growth rate, α is a parameter, and K is the carrying capacity. Using two different estimates of carrying capacity of 3.2 million (Grafton, Sandal and Steinshamn 2000) and 5.6 million (Guénette, Pitcher, and Walters 2000), and data for actual harvests and estimated exploitable biomass for the period 1962–1992, we estimate parameter values for [1] with a dummy variable for 1973. The estimates (with standard errors in parentheses) for the case where $K = 3.2$ million are $r = 0.27067$ (0.03670), $\alpha = 0.24869$ (0.12339), and $D73 = -0.3043$ (0.10928), and where $K = 5.6$ million are $r = 0.27734$ (0.04756), $\alpha = 0.65602$ (0.37303), and $D73 = -0.30132$ (0.11147).[1] Both sets of estimates are used in determining optimal harvest and optimal reserve size in our simulations and provide similar results.

In our modeling, we test for the significance of environmental shocks over the 30-year period and find that the only year when a dummy variable is significantly different from zero at the 5% level of significance is 1973. In addition to testing for negative shocks in [1] using dummy variables, we also apply an index approach of absolute dissimilarity (Diewert 2002). This method, extended by Fox, Hill, and Diewert (2004), allows us to calculate mix, scale, and absolute measures of dissimilarity. We find that the decline in the growth in the biomass in 1973 is a clear outlier that generates a mix score of 7.00, while the next highest score in any year is just 0.71.[2]

We use the implicitly spatial approach to modeling marine reserve employed by Grafton, Kompas, and Ha (2006). In the case of a permanent reserve that protects proportion $s \in (0,1]$ of the population, the carrying capacity in the harvested or exploited area is defined by $(1 - s)K$. Thus,

[1] Further details and diagnostics of the estimated growth function are available from the authors.

[2] A list of the mix, scale, and absolute dissimilarity scores for each year are available from the authors.

with a reserve, the growth functions of the population inside and outside the reserve are defined by

$$f(x_R,s) = rx_R\left(1 - \frac{x_R}{sK}\right)^\alpha, \quad [2]$$

$$f(x_{NR},s) = rx_{NR}\left(1 - \frac{x_{NR}}{(1-s)K}\right)^\alpha, \quad [3]$$

where x_R and x_{NR} are the population of fish inside and outside the reserve.

The intertemporal rent from harvesting in the northern cod fishery is defined by

$$\Pi(h,x_{NR}) = p(h)h - c\left(h, \frac{x_{NR}}{(1-s)K}\right), \quad [4]$$

where h is harvest, $p(h)$ is the inverse C1 demand function, and $c(h, x_{NR}/(1-s)K)$ is the aggregate cost function. The inverse demand is defined as $p(h) = ah^\varepsilon$, and the cost function by $c(h, x_{NR}/(1-s)K) = bh(1-s)K/x_{NR}$. Both functions are derived from Grafton, Sandal, and Steinshamn (2000), where a and b are estimated to be 0.35 and 0.2 and ε is -0.3.

To analyze the effects of the marine reserve in the northern cod fishery we incorporate environmental instability as two types of stochasticity: (1) environmental stochasticity that may be either positive or negative due to temporal variation in the habitat (Shaffer 1981), and (2) a negative shock that occurs randomly over time. We define environmental stochasticity by a Wiener diffusion process (Brownian motion) that follows a normal distribution (W_t) and negative shocks as a jump process (q) that follows a Poisson distribution defined by the parameter λ.

We identify only one significant negative shock on the biomass, which occurred in 1973—equivalent to about a 30% reduction of the total biomass for that year. Thus, in our simulations we incorporate the actual shock in 1973 and set λ sufficiently large to ensure no further shock occurs over the period 1974–1991. In other words, our estimates indicate that the severe declines in the exploitable biomass in the late 1980s and early 1990s can be entirely explained by overharvesting without reference to negative environmental shocks—a result consistent with the findings of both Hutchings and Myers (1994) and Myers, Hutchings, and Barrowman (1996).

The optimization problem maximizes the discounted net returns in the northern cod fishery over the period 1962–1991 taking into account both environmental stochasticity and the negative shock that occurred in 1973. The solution provides a "counterfactual" of what the optimal harvest and optimal reserve size should have been in the northern cod fishery if the objective of the regulator had been to maximize the discounted net returns from fishing. The structure of the model follows Grafton, Kompas, and Ha (2006) and is defined below.

$$V(x_R,x_{NR}) = \max_h \int_0^\infty e^{-\rho t}\Pi(h,x_{NR},s)\,dt, \quad [5]$$

subject to

$$dx_R = \left[f(x_R,s) - \phi(1-s)K \times \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right)\right]dt + g(x_R)dW + \psi(x_R)\,dq, \quad [6]$$

C2

$$dx_{NR} = \left[f(x_{NR},s) + \phi(1-s)K \times \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}\right) - h\right]dt + g(x_{NR})dW + \gamma(x_{NR})\,dq, \quad [7]$$

$$x_0 = x(0). \quad [8]$$

For the northern cod fishery we set the discount rate $\rho = 0.05$, the initial population (x_0) as the sum of the population inside and outside the reserve in 1962 and equal to 2.96 million tons, and $\phi(1-s)K(x_R/sK - x_{NR}/(1-s)K)$ as the transfer function C3 that governs migration from the reserve to the exploited areas of the habitat. The transfer function is consistent with existing diffusion models in fisheries (Kramer and Chapman 1999) where migration between the reserve and exploited populations depends on relative population densities. A higher density promotes out migration, but for a given difference in density, the larger the reserve the smaller the transfer (Beverton and Holt 1957). We specify a value for ϕ that corresponds to a migration level of about 5% of the reserve population in the absence of a negative shock, and about 25% immediately following the negative shock.

Environmental stochasticity is represented by $g(x_{\mathrm{R}}) = 0.05x_{\mathrm{R}}$ and $g(x_{\mathrm{NR}}) = 0.05x_{\mathrm{NR}}$, which implies that both the reserve and fishery are subject to 5% variation following a realization of dW that is either +1 or −1 and that occurs with equal probability. The functions ψ and γ represent shock sensitivities in the reserve and fishery. They differ to allow for the *possibility* that harvesting, especially trawling in offshore areas in the winter months, may have had a deleterious impact on the age structure and habitat (Turner et al. 1999) such that, for a given negative shock, the consequences are greater for the exploited than the reserve population. However, we also examine the case where the shock sensitivities are the same for the reserve and harvested population. In our specification, we impose only the negative shock that actually occurred in the fishery in 1973 and examine two cases: the first, $\psi(x_{\mathrm{R}}) = 0.0$ and $\gamma(x_{\mathrm{NR}}) = -0.30403x_{\mathrm{NR}}$, and the second, $\psi(x_{\mathrm{R}}) = -0.30403x_{\mathrm{R}}$ and $\gamma(x_{\mathrm{NR}}) = -0.30403x_{\mathrm{NR}}$. In the first case, the negative shock is assumed not to occur in the reserve, while in the second it occurs equally in both the reserve and the fishery.

We employ Ito's lemma to define Bellman's fundamental equation of optimality, described in detail by Grafton, Kompas, and Ha (2006), to solve for the optimal harvest trajectory for a given reserve size by using a modified form of the perturbation method developed by Gaspar and Judd (1997). The solution procedure allows us to solve the optimal harvest level for all possible reserve sizes and then choose the reserve size that generates the highest value of the value function from all possible reserve sizes.

IV. THE VALUE OF A MARINE RESERVE

The optimum biomass and harvest levels for all years over the period 1962–1991 are provided in Columns 3 and 4 of Table 1 using the estimated parameter values where $K = 3.2$ million with a 5% discount rate. The results indicate that a harvest level of about 400,000 tons per year, obtained from a fluctuating exploitable biomass of about 2.5 million tons, would maximize the discounted net returns from fishing.

We find that even with optimal harvesting, it is beneficial to have a marine reserve that protects about 40% of the total population, given a shock sensitivity of zero in the reserve. We emphasize that a reserve is not only beneficial to fishers relative to the actual harvesting that took place in the fishery, but would still have generated a positive economic payoff *even if harvesting had been optimal* as defined by the solution to the problem given by equations [5]–[8]. Where the fishery and the reserve have identical shock sensitivities, that is, $\psi(x_{\mathrm{R}}) = -0.30403x_{\mathrm{R}}$ and $\gamma(x_{\mathrm{NR}}) = -0.30403x_{\mathrm{NR}}$, then the optimal reserve size is 10%. We emphasize that in both cases (equal and different shocks in reserve and fishery) a marine reserve generates an economic payoff to fishers even with optimal harvesting.[3]

Optimal Harvest and Reserve Size versus Actual Harvest

The value of a marine reserve with optimal harvesting is that it allows the fishery to recover faster following the large negative shock in 1973, thereby increasing the harvest over what it would have been without a reserve. The trade-off is that in the absence of the shock a reserve reduces the harvest over what would be possible

[3] Figures of the effects and value of a reserve assuming equal shocks are available from the authors. As with the unequal shock case, a reserve generates a positive economic value relative to the actual harvest that took place, but also with optimal harvesting.

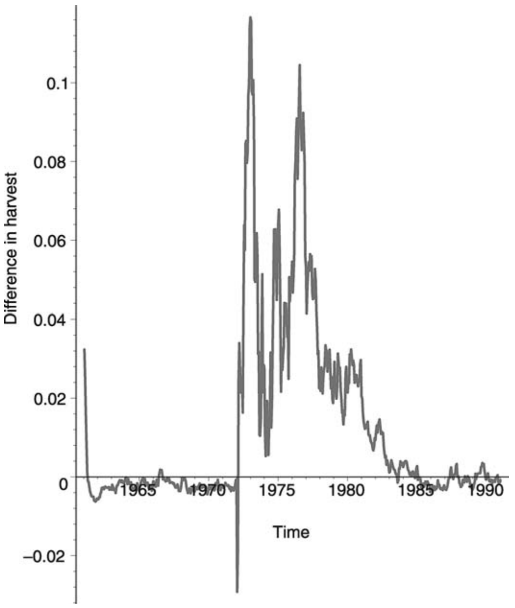

FIGURE 1
THE DIFFERENCE IN HARVEST BETWEEN THE CASE OF AN OPTIMUM WITH A 40% RESERVE AND AN OPTIMUM HARVEST WITH NO RESERVE

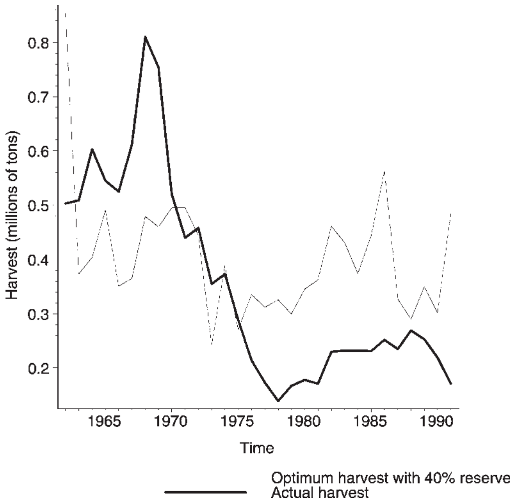

FIGURE 2
RELATIONSHIP BETWEEN THE ACTUAL HARVEST AND OPTIMUM HARVEST WITH A 40% RESERVE

with optimal harvesting. Thus, when an unexpected negative shock occurs, a reserve generates a positive economic benefit in that it allows for the spillover of fish out of the reserve and raises the harvest available to fishers. This spillover effect is shown in Figure 1, where a 40% reserve generates a much higher level of harvest than no reserve immediately following and for several years after the negative shock in 1973. This is despite the fact that in both cases (40% reserve and no reserve) harvesting is optimal. The trade off is that before the shock occurs in 1973 a reserve results in a *lower* harvest than what would have occurred if harvesting had been optimal but with no reserve. This is also illustrated in Figure 1, as is the gradual decline in the extra harvest with a reserve following the shock in 1973.

The economic payoff from a reserve represents a resilience effect that allows for a quicker recovery of the population following a negative shock. The more frequent and the larger the shock, the greater the payoff of a reserve because it acts like a buffer stock, allowing the population to recover faster. Similarly, the smaller the discount rate the more valuable a reserve is because the more highly valued are future net returns from increased harvests following a shock.

The actual harvest in the fishery and optimal harvest with a 40% reserve is plotted in Figure 2. From 1964 to 1970 actual harvest exceeds optimal harvest, and thereafter, with the exception of the years 1972–1973 and 1975, optimal harvest is greater than actual harvest. Table 1 shows that even with optimal harvesting and a 40% reserve, it pays to draw down the biomass from its initial level of almost 3 million tons to a desired level of about 2.5 million tons and, thereafter, adjust the harvest in response to environmental stochasticity and the negative shock in 1973, to return to this level. By contrast, the actual harvest pattern indicates there was a major drawdown of the biomass, hastened by the negative shock in 1973, until the biomass levels out in 1976. The advent of Canadian jurisdiction in 1977 coincides with a lower harvest level and a gradual rebuilding of the fishery until 1984, thereafter, as shown in Figure 2, unsustainable harvests bring

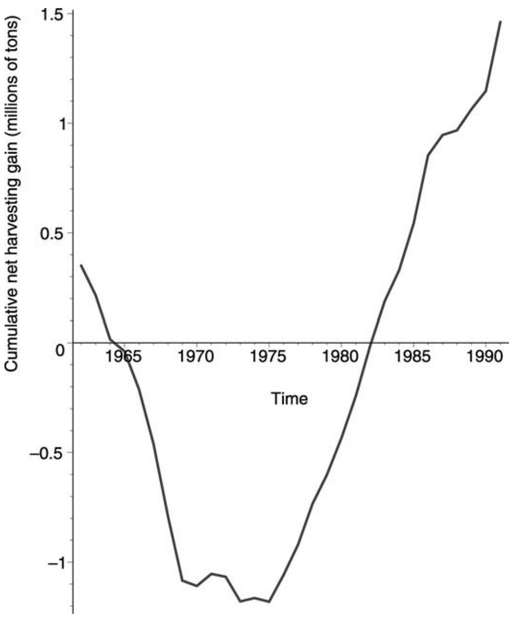

FIGURE 3
CUMULATIVE NET HARVESTING GAIN (MILLIONS OF TONS) FROM OPTIMAL HARVESTING AND A 40% RESERVE VERSUS ACTUAL HARVEST

about the collapse of the stock by the end of 1991.

The cumulative difference between the optimal and actual harvest over the entire period 1962–1991 is illustrated in Figure 3. It shows that by 1982 optimal harvesting and a 40% reserve are able to generate a higher cumulative harvest than what actually took place in the fishery. By 1991, the extra landings of fish associated with an optimal harvest and marine reserve exceed 1.5 million tons—an amount that would be expected to continue to increase beyond 1991 without a collapse in the fishery.

The cumulative resource rent from optimal harvesting and a reserve, relative to the actual harvest, can be calculated using the estimated inverse demand and cost function for the fishery. This extra payoff for each year is presented in Column 1 of Table 2 and illustrated in Figure 4. We find that optimal harvesting and an optimal marine size that protect 40% of the population would have generated almost $2 billion more in net returns than what actually occurred over the 1962–1991 period.[4] Although this is a very large economic benefit, it grossly underestimates the payoff from optimal harvesting and a reserve because any resource rent beyond 1991 is not included in the calculation. Our value also does not account for the $3.9 billion spent by the government of Canada over the period 1992–2001 to provide income support and industry adjustment following the harvesting moratorium in 1992 (Department of Fisheries and Oceans 2004b). Moreover, the payoff from optimal harvesting and a reserve assigns no value to the ecosystem benefits associated with a viable northern cod fishery, nor does it include the social and economic costs of a harvesting moratorium on fishers, processing workers, families, and fishing communities over and above any compensation they may have received from the government of Canada.

The economic payoff associated with a marine reserve versus no marine reserve, but with optimal harvesting, is given in Column 2 of Table 2. It shows that even with optimal harvesting, a marine reserve generates a cumulative resource rent of $162 million. The extra return from a reserve with optimal harvesting occurs because of the large negative shock in the fishery in 1973. A reserve would have helped buffer the fishery from the shock via spillovers of fish to the harvested area and, thus, allowed for a higher harvest level and resource rent than would otherwise have occurred. This payoff, however, would have declined over time, as no statistically significant negative shocks occurred over the period 1974–1991, but if there had been, the value of the reserve would have increased because of its ability to raise the harvest level immediately following such shocks.

Optimal Harvest and Reserve Size versus the 20% Harvest Rule

Our results show the economic benefits of both optimal harvesting and a reserve of

[4] All monetary values are in 1991 Canadian dollars.

TABLE 2
CUMULATIVE NET GAIN IN RESOURCE RENT (BILLIONS OF 1991 CANADIAN DOLLARS)

Year	1 Optimum Harvest and 40% Reserve vs. Actual Harvest	2 Optimum Harvest and 40% Reserve vs. Optimum Harvest and No Reserve	3 Optimum Harvest and 40% Reserve vs. 20% Harvest Rule and No Reserve	4 Optimum Harvest and 40% Reserve vs. 20% Harvest Rule and 40% Reserve	5 20% Harvest Rule and No Reserve vs. Actual Harvest	6 20% Harvest Rule and 40% Reserve vs. Actual Harvest	7 20% Harvest Rule and 40% Reserve vs. 20% Harvest Rule and No Reserve
1962	0.300	0.025	0.214	0.214	0.086	0.086	0.000
1963	0.159	0.017	0.096	0.104	0.063	0.055	−0.008
1964	−0.012	0.009	0.025	0.041	−0.038	−0.053	−0.015
1965	−0.048	0.006	0.025	0.048	−0.073	−0.096	−0.022
1966	−0.183	−0.001	−0.039	−0.006	−0.145	−0.174	−0.029
1967	−0.361	−0.004	−0.078	−0.039	−0.283	−0.322	−0.039
1968	−0.551	−0.007	−0.053	−0.005	−0.498	−0.543	−0.045
1969	−0.683	−0.013	−0.038	0.016	−0.645	−0.698	−0.054
1970	−0.644	−0.019	−0.019	0.044	−0.625	−0.684	−0.059
1971	−0.556	−0.024	0.000	0.067	−0.556	−0.623	−0.067
1972	−0.491	−0.029	−0.003	0.070	−0.488	−0.563	−0.074
1973	−0.481	−0.048	−0.041	−0.012	−0.440	−0.469	−0.029
1974	−0.316	0.025	−0.002	−0.032	−0.314	−0.283	0.030
1975	−0.165	0.038	0.002	−0.074	−0.167	−0.091	0.076
1976	0.034	0.080	0.035	−0.080	−0.003	0.115	0.118
1977	0.212	0.107	0.067	−0.084	0.143	0.297	0.154
1978	0.380	0.130	0.103	−0.080	0.277	0.461	0.184
1979	0.508	0.141	0.132	−0.079	0.376	0.587	0.211
1980	0.639	0.155	0.176	−0.058	0.463	0.698	0.235
1981	0.767	0.164	0.228	−0.029	0.540	0.796	0.256
1982	0.908	0.171	0.301	0.026	0.607	0.882	0.276
1983	1.024	0.172	0.363	0.070	0.661	0.955	0.294
1984	1.109	0.172	0.401	0.094	0.706	1.015	0.309
1985	1.216	0.172	0.456	0.134	0.760	1.082	0.323
1986	1.356	0.169	0.530	0.195	0.826	1.163	0.337
1987	1.432	0.168	0.548	0.203	0.885	1.230	0.346
1988	1.499	0.166	0.562	0.208	0.937	1.291	0.354
1989	1.601	0.165	0.589	0.227	1.013	1.375	0.362
1990	1.718	0.164	0.606	0.239	1.111	1.480	0.368
1991	1.930	0.162	0.655	0.282	1.274	1.649	0.374

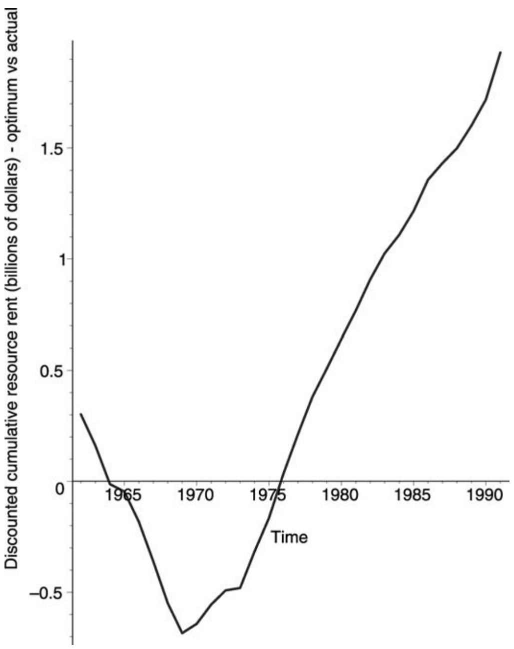

FIGURE 4
DISCOUNTED CUMULATIVE RESOURCE RENT (BILLIONS OF DOLLARS) FROM OPTIMAL HARVESTING AND A 40% RESERVE VERSUS ACTUAL HARVEST

optimal size combined would have generated multibillion dollar benefits for the northern cod fishery over the period 1962–1991. We now investigate what the value of a reserve is with optimal harvesting relative to an approximation of the harvesting rule that was supposed to have been used by the Canadian Department of Fisheries and Oceans over the period 1977–1991. This is a so-called 20% harvesting rule, whereby the current harvest is set at 20% of the previous level of the exploitable biomass and approximates the $F_{0.1}$ rule (Hannesson 1996, 93) commonly applied in developed fisheries.

Unfortunately, the 20% or $F_{0.1}$ rule that corresponds to a harvest slightly below the maximum yield per recruit was not properly applied in the northern cod fishery for two reasons. First, fisheries biologists overestimated the size of the exploitable biomass, and thus the harvest rate was actually a much higher rate than intended (Lane and Palsson 1996).[5] Second, successive federal fisheries ministers were unwilling to lower harvests due to worries over the social and economic costs of lower catches on fishing communities (Charles 1995). Immediate socioeconomic concerns associated with lower harvests are not unique to Canada. In Europe, for instance, a harvesting moratorium for the North Sea cod has been supported by the Scientific, Technical, Economic Committee on Fisheries since 2002, but harvesting is still allowed, albeit at reduced levels, because of the negative economic and social impacts of closures on the fishing industry (European Environment Agency 2004).

A comparison of the extra resource rent associated with optimal harvesting and an optimal reserve size versus a 20% harvesting rule and no reserve is given in Column 3 of Table 2. The results indicate that even if the fishery regulator had been able to successfully implement its desired harvesting rule, it would still have generated over $650 million *less* than what could have been obtained with optimal harvesting and a reserve size of 40%. This difference is illustrated in Figure 5. Column 4 of Table 2 shows that if a 20% harvesting rule and also a 40% reserve size had been implemented, then the net returns from harvesting would have been higher than with the 20% harvesting rule and no reserve—but still some $280 million less than a 40% reserve with optimal harvesting.

The 20% Harvest Rule versus Actual Harvest

We can also investigate the economic payoff associated with successfully implementing the 20% harvesting rule versus the actual harvest over the period 1962–1991. Column 5 of Table 2 shows that the 20% harvest rule offers a very substantial benefit, relative to actual harvest, of over $1.2 billion for the period 1962–1991. As shown in Column 6 of Table 2, however, a marine reserve coupled with the 20% harvesting

[5] The estimates we use for the exploitable biomass come from a series that corrects for past inaccuracies.

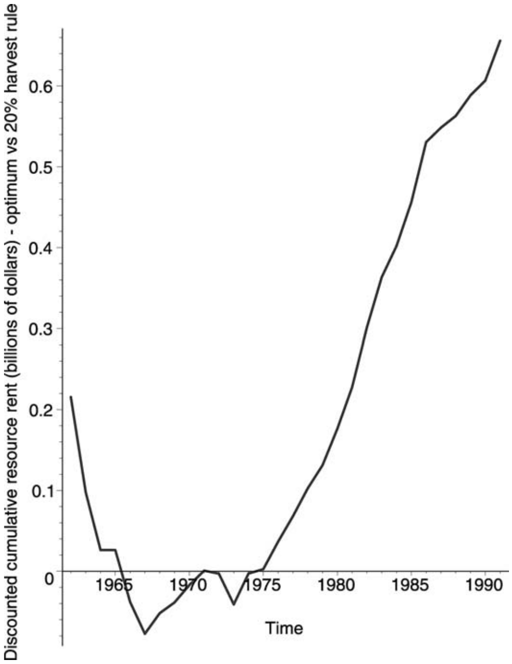

FIGURE 5
DISCOUNTED CUMULATIVE RESOURCE RENT (BILLIONS OF DOLLARS) FROM OPTIMAL HARVESTING AND A 40% RESERVE SIZE VERSUS A 20% HARVEST RULE WITH NO RESERVE

rule generates an even greater payoff. The extra benefit in terms of cumulative resource rent from a reserve with a 20% harvesting rule is given in Column 7 of Table 2—$374 million—and is more than twice as much as the extra benefit from having a reserve, but with optimal harvesting. In other words, the smaller the actual biomass relative to its optimal level, the larger the economic payoff of a reserve. Thus although a marine reserve gives a positive payoff with optimal harvesting, it gives an even higher payoff if a suboptimal harvesting rule is used, and would have given an even greater payoff with the development of the biomass that actually took place over the period 1962–1991.

Sensitivity Analysis

A problem with determining optimal reserve size is that the estimates of the economic and biological parameters may not be accurate representations of their true values. To examine the implications of changes in the economic parameters a and b on the results, we separately increased the value of each by 10%. The net effect of increasing a (the demand parameter) by 10% is to increase the economic value from having optimal harvesting and an optimal reserve size by some 12%, while raising b (the cost parameter) by 10% reduces the economic payoff by about 2%.

We also undertook a sensitivity analysis by changing the intrinsic growth rate (r) and the transfer coefficient (ϕ). The upper and lower values for r in Table 3 represent the point estimate for the intrinsic growth rate of 0.27067 ± 0.04, a value that exceeds its standard error of 0.0367. The lowest value for $\phi = 0.7$ in Table 3 corresponds to a very low transfer, equivalent to about 2% of the reserve population in the absence of a negative shock, while the upper value of ϕ

TABLE 3
SENSITIVITY ANALYSIS OF OPTIMAL RESERVE SIZE AND RESOURCE RENT

	Transfer Coefficient											
	Optimum Reserve Size (Proportion of Total Biomass)				Discounted Net Gain with Optimum Harvest and Reserve Size vs. Actual (Billions CDN 1991 Dollars)				Discounted Net Gain with Optimum Harvest and Reserve Size vs. Optimum Harvest with No Reserve (Billions CDN 1991 Dollars)			
	1	2	3	4	5	6	7	8	9	10	11	12
Growth Coefficient	0.7	0.8	0.9	1	0.7	0.8	0.9	1	0.7	0.8	0.9	1
0.23	0.6	0.7	0.8	0.9	0.84	0.87	0.90	0.93	0.20	0.23	0.26	0.29
0.27	0.4	0.5	0.6	0.6	1.79	1.91	1.93	1.95	0.04	0.16	0.18	0.20
0.31	0.4	0.4	0.5	0.5	2.83	2.88	2.94	2.95	0.03	0.07	0.13	0.15

= 1.0 represents a transfer of a little less than 5% of the reserve population. Further increases in ϕ beyond 1.0 would raise both the optimal reserve size and the economic payoff of a reserve.

In Columns 1–4 of Table 3, under the heading Optimum Reserve Size, we find that the optimum reserve size is sensitive to both r and ϕ. This suggests that resource managers need to pay careful attention to estimating these key parameters. In Columns 5–8 of Table 3, under the heading Discounted Net Gain with Optimum Harvest and Reserve Size, we find that the net economic benefit associated with optimal harvesting with a reserve, relative to the harvesting that actually occurred, is robust to changes in ϕ. The net gains from having a 40% reserve, but with optimal harvesting, are given in Columns 8–12 of Table 3. Overall, the sensitivity analysis shows that for a wide range of parameter values there exists a large economic payoff to a marine reserve, whether harvesting is optimal or whether the comparison is made to the actual harvest that occurred over the period 1962–1991.

Resilience

Several authors have shown that a marine reserve creates resilience in the sense that it increases population persistence by raising its level above the minimum viable level (Apostolaki et al. 2002; Guénette, Pitcher, and Walters 2000; Lauck et al. 1998). In our modeling we show that reserves also generate two other types of resilience: "Pimm resilience (Pimm 1984), or P-resilience, such that a reserve reduces the time it takes for a harvested population to recover to its former state following a negative shock; and a Holling resilience (Holling 1973), or H-resilience, such that a reserve helps the population stay within a stable attractor following a shock.

P-resilience is the reason why a reserve generates an economic payoff with environmental stochasticity, even when harvesting is optimal. It also explains a result by Conrad (1999) that with environmental

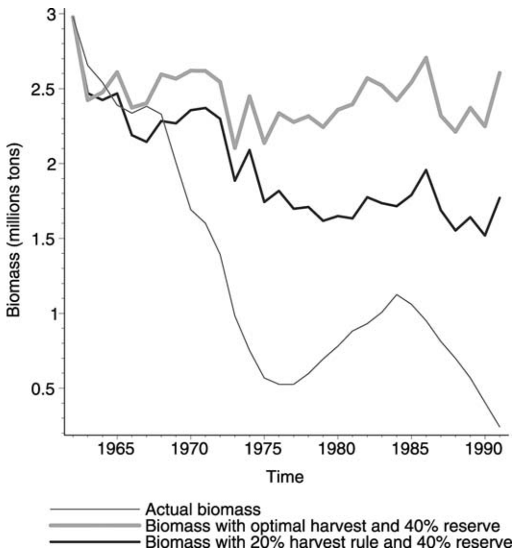

FIGURE 6
BIOMASS WITH OPTIMUM HARVEST WITH A 40% RESERVE, A 20% HARVEST RULE WITH A 40% RESERVE, AND ACTUAL BIOMASS

instability a marine reserve reduces the variance of the population. Our model shows that if P-resilience is measured as the time it takes for the population to recover to within one standard deviation of its former level before a negative shock, then *recovery time* is monotonically *decreasing* in reserve size. It implies that apart from an increased resource rent that a reserve can generate, a reserve can also reduce the variation in the rent and that may also be valued by fishers.

H-resilience is more difficult to quantify because we must show that the population can be maintained in its present (but fluctuating) state indefinitely following a negative shock. Nevertheless, in Figure 6 we can illustrate the effects of three possible management scenarios—optimal harvesting with a 40% reserve, the 20% harvest rule with a 40% reserve, and the actual harvest—on the level of the biomass in the northern cod fishery. The actual harvest resulted in the complete collapse of the fishery by 1992, while both optimal harvesting and the 20% harvesting rule with a marine reserve allow the fishery to recover from the 1973 shock.

A reserve also helps keeps the biomass at higher levels than would otherwise be the case and, thereby, reduces the risk of the fishery dropping below a threshold point from which the stock may not recover.[6]

Our results do not imply that a reserve is a guarantee against population collapse but do suggest that an optimally sized reserve can reduce the chance of such an event. At least for the northern cod fishery, it appears there exists some threshold biomass level beyond which the fishery collapses and may not recover. This implies (1) a marine reserve, apart from the economic benefits it generates for fishers, also provides a higher level of the biomass and a buffer to negative shocks that gives a degree of protection from crossing a critical threshold, and (2) when specifying reserve size it is important to ensure a minimum number or biomass of fish in the reserve, irrespective of the proportion of the total biomass or population in a reserve.

V. CAVEATS AND IMPLICATIONS

Several caveats must be noted in terms of applying our results. First, we do not use an explicit spatial model and thus cannot translate the results into defined areas of the habitat, nor can we explicitly consider the spatial redistribution of fishing effort with a reserve (Smith and Wilen 2003; Wilen et al. 2002; Wilen 2004). Nevertheless, we may speculate that closure of fishing areas offshore, previously de facto reserves until the late 1950s, would be an obvious choice for at least part of a reserve. The experience from America's Georges Bank over the period 1994–1998 also indicates that a large offshore reserve may be easier to enforce than smaller seasonal areas and can also generate a high level of compliance (Murawski et al. 2000). Second, the optimal size of the reserve and optimal harvest levels depend on the parameters used in our simulations, although our general conclusion of the positive economic benefits of a reserve is robust to changes in both economic and biological parameters.

Our results have a number of important management implications for renewable resources. First and foremost, we find that managing a resource subject to environmental instability requires much more than adopting either a "conservative" harvest level or improved estimates of the relevant biological and economic parameters (Shelton and Rice 2002). By contrast to traditional management approaches, a reserve provides protection against management failure (Lauck et al. 1998) and also promotes population persistence, P-resilience, and H-resilience. Indeed, on the basis of our simulations, a reserve with optimal harvesting would have allowed the northern cod fishery to recover much faster following a negative shock in 1973 and would have kept the fishery above a threshold point below which the actual fishery fell in the early 1990s. The H-resilience associated with a reserve also has important implications for other fisheries that are explicitly managed to ensure that the spawning stock biomass is kept above a precautionary level.

Second, some of the economic concerns by fishers about marine reserves, at least for the northern cod fishery, are misplaced. We show that a marine reserve generates substantial economic benefits to fishers, even with optimal harvesting, in the form of increased resource rent and also reduces the variance of both the population and the harvest. In the case of the northern cod fishery where many harvesters have low incomes and there exist few employment opportunities beyond fishing-related activities (Department of Fisheries and Oceans 2004b), such income "smoothing" by reserves can be very valuable. The implication of our findings for resource managers is that appropriately sized reserves are able to generate economic payoffs to fishers while also providing some protection against management mistakes and environmental stochasticity.

[6] Sumaila (1998) and Mangel (1998) show an inverse relationship between reserve size and the size of negative shocks in a fishery. Doyen and Béné (2003) also find that the greater the level of uncertainty (size and/or probability of a negative shock), the greater the share of the population required in a reserve to maintain a minimum viable population.

VI. CONCLUDING REMARKS

The management of renewable resources is governed by irreducible uncertainties. Managers and regulators have either ignored environmental variation in their decision making or addressed uncertainty in a certainty-equivalent approach by employing conservative rates of exploitation. Using data from the northern cod fishery of Atlantic Canada that suffered one of the twentieth century's most spectacular resource collapses, we examine the economic value of a marine reserve with a stochastic optimal control model.

We find that a marine reserve with either optimal harvesting or with the harvesting rule that the regulator attempted to use in the fishery would have kept the biomass at much higher levels and reduced the risk of the stock collapse that occurred in the early 1990s. Our simulations also indicate that the economic value of a marine reserve and optimal harvesting in terms of cumulative resource rent over the period 1962–1991, relative to the actual harvest, is worth almost $2 billion. We also show that even with optimal harvesting a reserve generates an extra payoff to fishers worth $162 million. This extra benefit with a reserve occurs because a reserve allows for a spillover of fish and a higher harvest after a negative shock, although the trade-off is a lower harvest in the absence of a negative shock.

Our results show that if the regulator had been able to successfully implement its desired, but suboptimal, harvesting rule, then the economic value of the reserve would have been worth some $374 million. In addition to providing direct economic benefits to fishers, a marine reserve in the northern cod fishery would have provided a smoothing function for resource rents that would have been of considerable benefit to those fishers who have few employment options beyond cod fishing.

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