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**Cod today and none tomorrow:
The Economic Value of a Marine Reserve**

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TABLE OF CONTENTS

Abstract	3
1. Introduction	4
2. The Mismanagement and Collapse of Fisheries	6
3. Modeling a Marine Reserve for the Northern Cod Fishery	8
4. The Value of a Marine Reserve	12
5. Caveats and Implications	20
6. Concluding Remarks	22
References	23

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. The 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: raised the resource rent even if harvesting had been 'optimal'; decreased the recovery time for the biomass to return to its former state and smoothed fishers' harvests and resource rents; and lowered the chance of a catastrophic collapse following a negative shock.

JEL codes: C61; Q22;

Key words: Marine reserves; Stochastic control; Fisheries

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Many catastrophes have occurred in fisheries around the planet ..., but none is more devastating as the closing of the fish banks from Cape Cod to Newfoundland along the northeast coast of North America.

Michael Berrill (1997), p. 114.

1. 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 (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 *et al.*, 1997; Pauly *et al.*, 2002). Reserves are justified on theoretical grounds because they can increase yields when population levels are overexploited (Pezzey *et al.*, 2000; Sanchirico and Wilen, 2001), reduce the variance of the population (Conrad, 1999) and harvest (Sladek Nowlis and Roberts, 1998; 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, Mosquera 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’ areas (Halpern and Warner, 2003). The concern is that reserves will reduce their harvests, increase costs and restrict when and where they can go fishing. 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 in the order of 70-80% of a fishing area to generate yield and conservation benefits to fishers equivalent to optimal harvesting (Hannesson, 1998), and that reserves can increase sustainable yields and revenues only when the population is overexploited (Holland, 2000; Pezzey *et al.*, 2000).

To address the question of what is the economic value of marine reserves, 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.

2. 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 *et al.*, 1993). For example, the world's largest fishery ever in terms of harvests was the Peruvian *anchoveta* that, according to official statistics, had total catches peak at an unsustainable 12 million tons per year, but which suddenly collapsed following an *El Niño* event in 1972-73. 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 that had yielded harvests of between 300,000 and 1 million tons/year in the first half of the twentieth century, but also collapsed in the early 1970s because of over harvesting 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 a 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 collapse has been so profound that the sub-species 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 to 1960 (Hannesson, 1996).

The decline began with the arrival of large factory stern trawlers in the late 1950s when 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/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 onwards 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).

3. 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 *et al.* (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. Gu  nette *et al.* (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 in their simulations, do not include the period 1973 when a large negative shock struck the fishery.

Following Grafton *et al.* (2000) we estimate a generalised density dependent growth function for the northern cod fishery of the following form:

$$f(x) = rx\left(1 - \frac{x}{K}\right)^\alpha \quad (1)$$

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 *et al.* 2000) and 5.6 million tons (Gu  nette *et al.*, 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. A full list of parameters values are provided in Table 1.

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 percent 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 *et al.* (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.²

We use the implicitly spatial approach to modeling marine reserve employed by Grafton *et al.* 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, with a reserve, the growth functions of the population in and outside of 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 in and outside of the reserve.

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

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

where h is harvest, $p(h)$ is the inverse demand function and $c(h, \frac{x_{NR}}{(1-s)K})$ is the aggregate

cost function. The inverse demand is defined as $p(h) = ah^\varepsilon$ and the cost function by

$$c(h, \frac{x_{NR}}{(1-s)K}) = \frac{bh(1-s)K}{x_{NR}}. \text{ Both functions are derived from Grafton } et al. (2000) \text{ where } a$$

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: one, environmental stochasticity that may be either positive or negative due to temporal variation in the habitat (Shaffer, 1981) and, two, a negative shock that occurs randomly over time.³ We define environmental stochasticity by a Wiener diffusion process (Brownian motion) defined by W_t and negative shocks as a jump process (q) that follows a Poisson distribution defined by the parameter λ that is the arrival rate of the negative shock.

We identify only one significant negative shock on the biomass that occurs in 1973 — equivalent to about 30% reduction of the total biomass for that year. Thus in our simulations we incorporate the actual shock in 1973 and set λ or the arrival rate to be 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 over harvesting without reference to negative environmental shocks — a result consistent with the findings of both Hutchings and Myers (1994) and Myers *et al.* (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 *et al.* (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:

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

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

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

For the northern cod fishery we set the discount rate $\rho = 0.05$, the initial population (x_0) as the sum of the population in and outside of the reserve in 1962 and equal to 2.977 million tons, and $\phi(1-s)K(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K})$ as the transfer function 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 the difference in population densities in the reserve and outside of the reserve. A higher density promotes out migration, but for a given difference in density, the larger is the reserve the smaller is 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. Its actual value would depend on the size, number and location of marine reserves established in the fishery.

Environmental stochasticity is represented by $g(x_R) = 0.05x_R$ and $g(x_{NR}) = 0.05x_{NR}$ which implies that both the reserve and fishery are subject to 5% variation following a realization of dW 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: one, $\psi(x_R) = 0.0$ and $\gamma(x_{NR}) = -0.30403x_{NR}$ and, two, $\psi(x_R) = -0.30403x_R$ and $\gamma(x_{NR}) = -0.30403x_{NR}$. 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 fishery.

We employ Ito's Lemma to define Bellman's fundamental equation of optimality, described in detail in Grafton *et al.* (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.

4. 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 2 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/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 problem given by equations (5)-(8).

Where the fishery and the reserve have identical shock sensitivities, that is,

$\psi(x_R) = -0.30403x_R$ and $\gamma(x_{NR}) = -0.30403x_{NR}$, 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.⁴

4.1 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 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 is the shock, the greater is 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 is a reserve because the more highly valued are future net returns from increased harvests following a shock (Grafton *et al.* 2006).

The actual harvest in the fishery and optimal harvest with a 40% reserve is plotted in Figure 2. From 1964-1970 actual exceeds the optimal harvest and thereafter, with the exception of the years 1972-1973 and 1975, optimal harvest is greater than actual harvest. Table 2 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 draw down 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 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 is 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 3 and illustrated in Figure 4. We find that optimal harvesting and an optimal marine size that protects 40% of the population would have generated almost \$2 billion more in net returns than what actually occurred over the 1962-1991 period.⁵ 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 3. 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.

4.2 Optimal harvest and reserve size versus 20% harvest rule

Our results show the economic benefits of both optimal harvesting and a reserve of optimal size combined would have generated multi-billion dollar benefits for the northern cod fishery over the period 1962-1991. We now investigate what is the value of a reserve 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, p. 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 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).⁶ 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 socio-economic 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 3. 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 3 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 .

4.3 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 3 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 3, however, a marine reserve coupled with the 20% harvesting 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 3 — \$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 is relative to its optimal level, the larger is 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 sub-optimal 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.

4.4 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 4 represent the point estimate for the intrinsic growth rate of 0.27067 plus and minus 0.04, a value that exceeds its standard error of 0.0367.⁷ The lowest value for $\phi = 0.7$ in Table 4 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 $\phi = 1.0$ 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 4 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 4, 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 4. 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.

4.5 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 *et al.*, 1998; Lauck *et al.*, 1998). In our modeling we show that a reserve in the Northern Cod fishery would generate two other types of resilience: one, ‘Pimm-resilience’ or P-resilience (Pimm, 1984) such that a reserve reduces the time it takes for a harvested population to recover to its former state following a negative shock and, two, 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 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 (Roughgarden and Smith, 1996).⁸

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 (a) 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 (b) 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.

5. 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 simply 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 Ocean, 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. 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 centuries 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 CDN\$2 billion. We also show that even with optimal harvesting a reserve generates an extra payoff to fishers worth CDN\$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 the 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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Table 1: Parameter Values for Modeling a Marine Reserve in the Northern Cod Fishery

Parameter	Value
ρ	0.05
σ	0.08
	0.85
r	0.27067
α	0.24869
x_0	2.977
K	3.2
a	0.35
b	0.2
ε	-0.3
$\psi(x_R)$	0
$\gamma(x_{NR})$	-0.30403

Table 2: 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

Table 3: Cumulative net gain in resource rent (billions of 1991 Canadian dollars).

	(1) Optimum harvest & 40% reserve Vs. Year actual harvest	(2) Optimum harvest & 40% reserve Vs. optimum harvest & no reserve	(3) Optimum harvest & 40% reserve Vs. 20% harvest rule & no reserve	(4) Optimum harvest & 40% reserve Vs. 20% harvest rule & 40% reserve	(5) 20% harvest rule & no reserve Vs. actual harvest	(6) 20% harvest rule and 40% reserve Vs. actual harvest	(7) 20% harvest rule & 40% reserve Vs. 20% harvest rule & 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

Table 4: Sensitivity Analysis of Optimal Reserve Size and Resource Rent

	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)			
	Transfer coefficient											
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

End Notes:

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

² Dissimilarity scores for each year are available from the authors and were obtained from the software OutFish.

³ Sethi *et al.* (2005) identify two other forms of uncertainty in fisheries management that include stock measurement error and inaccurate implementation of harvest quotas.

⁴ Figures of the effects and value of a reserve assuming equal shocks are available from the authors upon request. 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.

⁵ All \$ values are in 1991 Canadian dollars.

⁶ The estimates we use for the exploitable biomass come from a series that corrects for past inaccuracies.

⁷ A full range of sensitivity analysis based on 90% confidence intervals for the estimated parameters are available upon request.

⁸ Sumaila (1998) shows that reserves can provide good protection in the face of negative shocks while Mangel (1998) shows that there is a minimum reserve size to ensure sustainability of a population. 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.

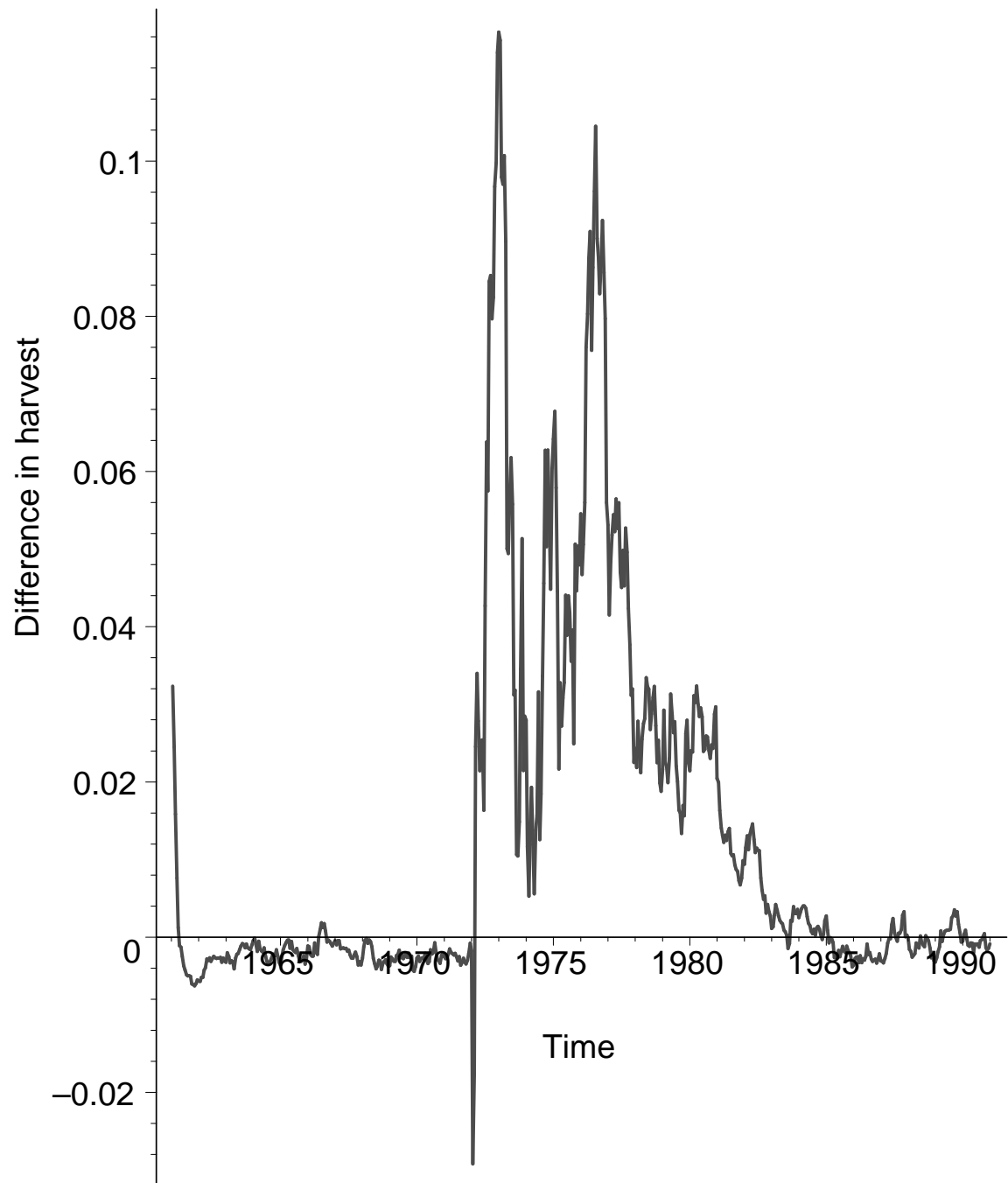


Figure 1: The difference in harvest between the case of optimum harvest with a 40% reserve and optimum harvest with no reserve

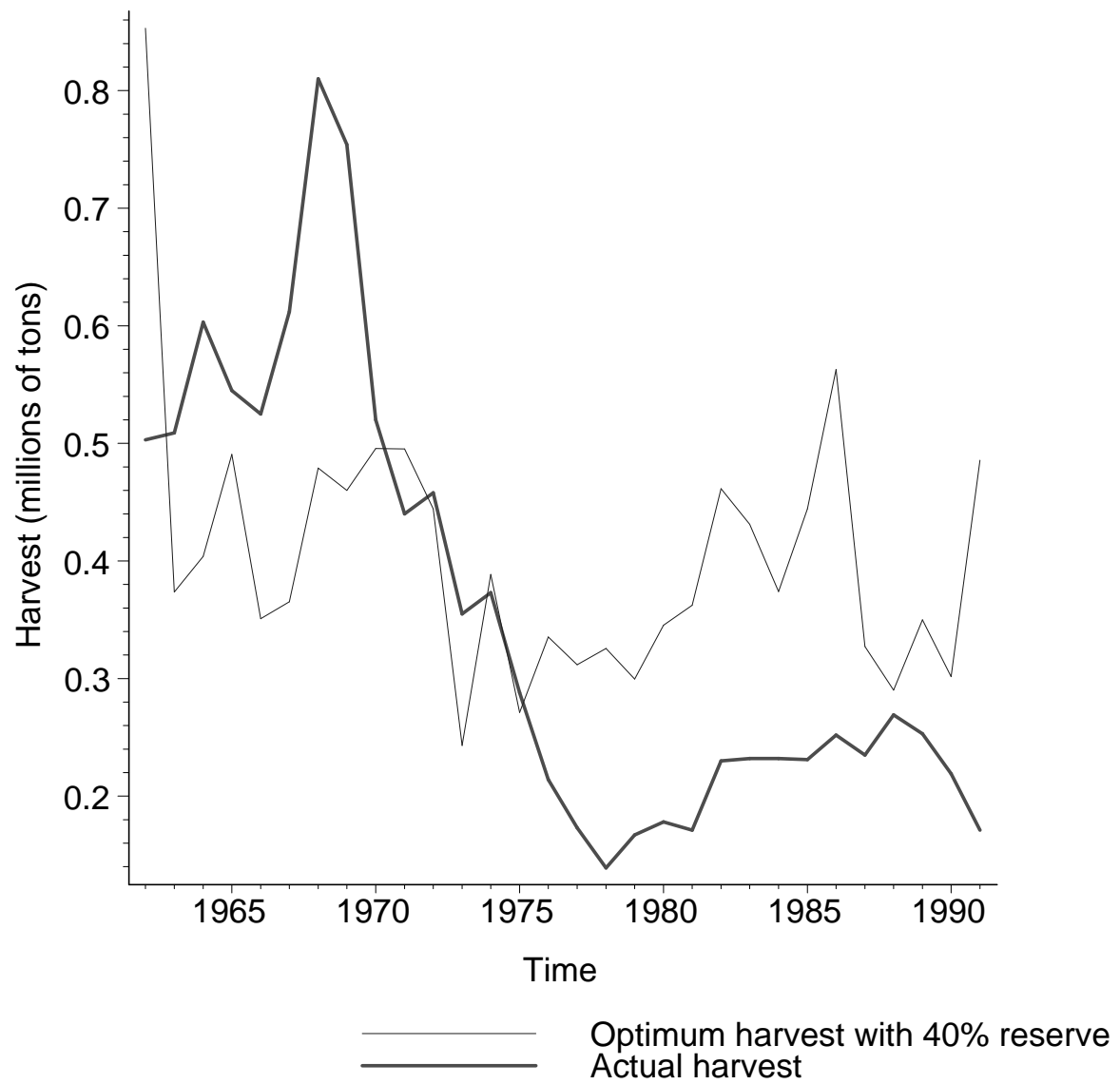


Figure 2: Relationship between the actual harvest and optimum harvest with 40% reserve

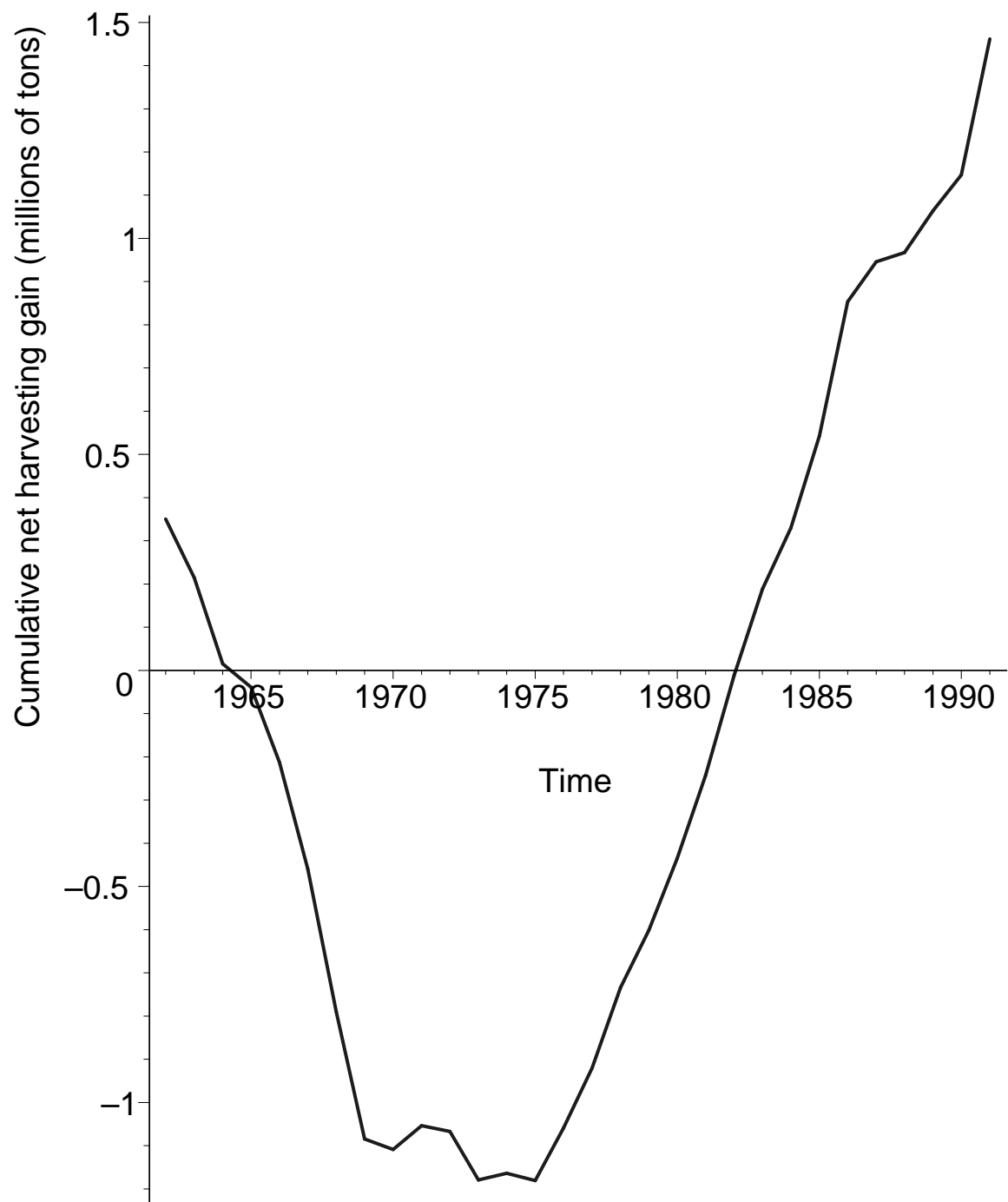


Figure 3: Cumulative net harvesting gain (millions of tons) from optimal harvesting and 40% reserve versus actual harvest.

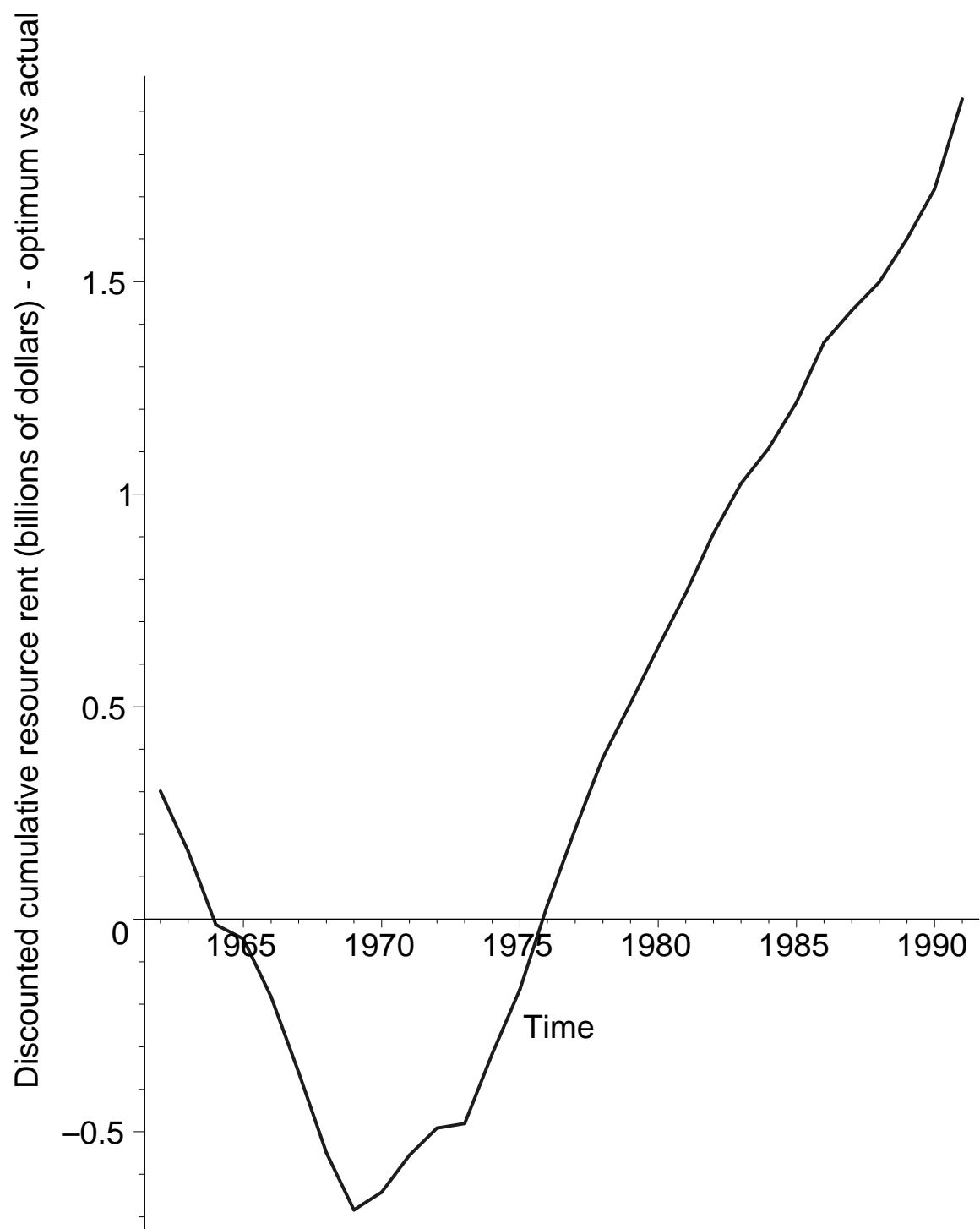


Figure 4: Discounted cumulative resource rent (billions of dollars) from optimal harvesting and 40% reserve versus actual harvest.

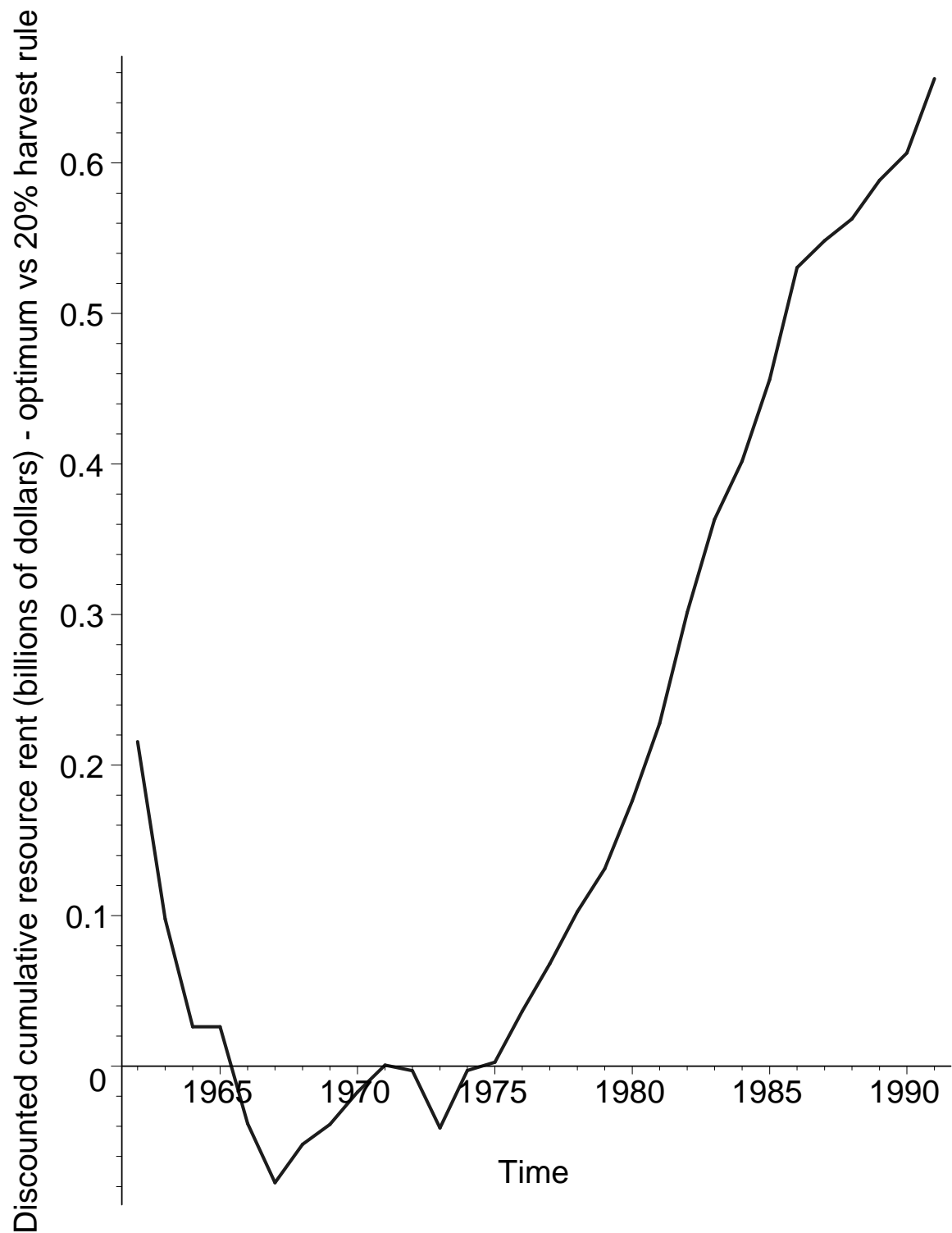


Figure 5: Discounted cumulative resource rent (billions of dollars) from optimal harvesting and a 40% reserve size versus a 20% harvest rule with no reserve.

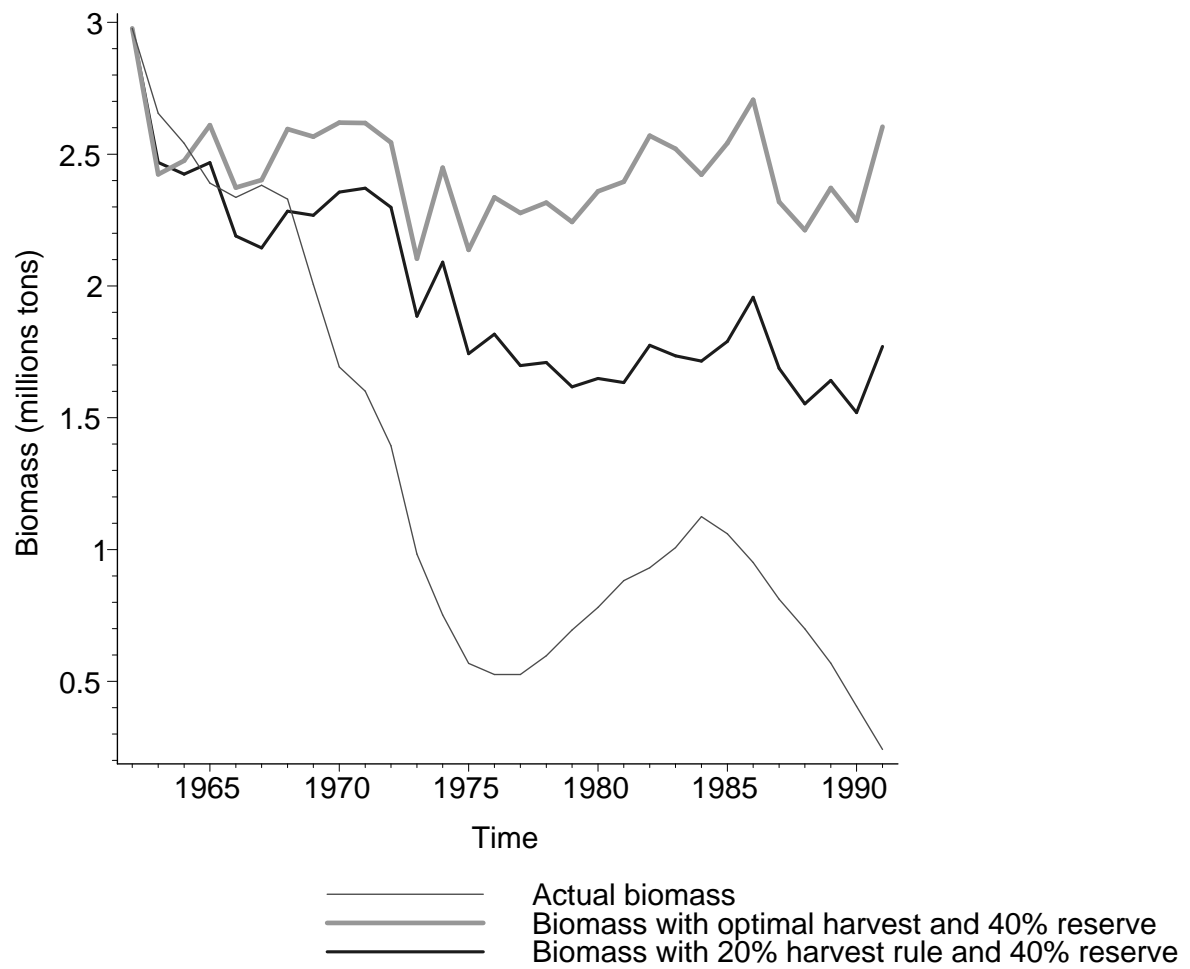


Figure 6: Biomass with optimum harvest with a 40% reserve, a 20% harvest rule with a 40% reserve, and actual biomass