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# Optimal Rebuilding of Fish Stocks in Different Nations: Bioeconomic Lessons for Regulators

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**Abstract** *Under the rubric of sustainable fisheries, nations are mandated to rebuild overfished stocks. Although rebuilding strategies are almost universally directed by the available biological information, approaches vary depending on fishery laws, management objectives, and technical guidelines. For example, rebuilding schedules in the United States are primarily designed to achieve rapid rebuilding of biomass and spawning stocks consistent with the biological characteristics of the resource. In contrast, New Zealand has greater flexibility in rebuilding stocks in order to consider economic, social, and cultural needs. In this paper we investigate potential economic costs to the fishery that result by limiting the US manager's flexibility in choosing a recovery trajectory. Using numerical models for moderate- and long-lived stocks, the analysis reveals that depending on productivity of the stock and the discount rate, extending the rebuilding timeframe can substantially increase annual harvests and economic benefits. The results underscore the importance of economic analysis in crafting flexible rebuilding schedules that account for the unique characteristics of the fisheries, including economic and social needs.*

**Key words** Fisheries economics, fisheries management, K-selective species, rebuilding.

JEL Classification Codes Q22, C61.

## Introduction

Under the rubric of sustainable fisheries, fishery managers are required to rebuild overfished stocks. Although rebuilding strategies are almost universally directed by

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the available biological information, approaches vary depending on national laws and technical guidelines. As one comparative example, the United States and New Zealand are mandated by their respective fisheries laws—the 1996 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) and the 1996 New Zealand Fisheries Act—to rebuild "overfished" stocks (NOAA Fisheries 1996; New Zealand Ministry of Fisheries 2002). The MSFMCA requires the preparation of a recovery plan for overfished stocks so that stock levels are able to support maximum sustainable yield (MSY) levels within 10 years if biologically feasible, or 10 years plus one generation if not.[1] In contrast, the New Zealand Fisheries Act does not require a specific time limit for rebuilding even though stocks are also required to reach levels that can produce MSY. The New Zealand Fisheries Act does, however, require the rebuilding plan to consider relevant social, cultural, and economic factors. Thus, New Zealand fishery managers have considerably more legal scope to set an optimal recovery trajectory for a depleted or overfished stock compared to their counterparts in the US who are restricted to biologically determined schedules.

Fishery managers in the US and New Zealand have been slow to adopt standard resource economic approaches to assist with stock management and the design of recovery strategies. The reasons for this may include a lack of familiarity with appropriate methodologies, inadequate economic data, perceptions that economic models are too complex to be a routine part of decision making, and poorly defined economic or social objectives. At best, fisheries managers are ignoring important decision support tools, and, at worst, managers are neglecting their responsibilities to make decisions with the best available information.

This paper aims to demonstrate that resource economics provides practical tools and insights in exploring stock-recovery issues and developing harvest strategies that improve social welfare. To support this assertion, a stylized bioeconomic model is developed that is consistent with key aspects of legislated stock rebuilding mandates, such as those found in the US and New Zealand. Given the intertemporal nature of sustainable resource use, and the frequent need to evaluate relatively long-lived stocks, a dynamic programming bioeconomic model is constructed to estimate optimal harvesting and rebuilding strategies for both a "moderate-lived" and a "long-lived" stock. The model is used to compare the effects of rebuilding on different "assemblages," as recently recommended by NOAA Fisheries (2005), and is consistent with the recommendation by King and McFarlane (2003) to group species by "strategist" groups for management. The model is also used to simulate the effects of alternative regulatory actions designed to capture key differences in legislative mandates for rebuilding between the two nations. Such differences include assumptions regarding the rights of future generations, the rebuilding timeframe, and supplemental output controls. Results are intended to provide insight into economic outcomes associated with alternative approaches to rebuilding depleted commercial fish stocks.

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[1] The exact intent of the U.S. Congress in mandating rebuilding of overfished stocks is unclear, as are the implementing guidelines developed by the National Marine Fisheries Service (NMFS). In particular, there is confusion about conflicting objectives if stocks must be rebuilt "in the shortest time period possible" while considering the "needs of fishing communities." The intent is even more uncertain for stocks that cannot be rebuilt within 10 years, which can result in perverse rebuilding strategies, such as increased harvests for stocks at relatively low levels (*e.g.*, Natural Resources Defense Council vs. NMFS (2005) provides an interpretation to rebuilding moderate- and long-lived stocks of West Coast rockfish).

## Bioeconomic Model

Bioeconomic models are generally used to determine the efficient use of resources over time by simultaneously considering biological and economic factors. In fisheries, empirical bioeconomic models have been used to evaluate resource management problems and develop policy options (*e.g.*, setting annual harvest quotas or allocations) that could better satisfy management objectives (Gilbert 1988; Kellogg, Easley, and Johnson 1988; Önal *et al.* 1991; Milliman *et al.* 1992; Sylvia and Enriquez 1994; Sandberg, Bogstad, and Røttingen 1997; Larkin and Sylvia 2004). For a depleted stock, a dynamic bioeconomic analysis can reveal economic and biological tradeoffs associated with different rebuilding timeframes and can provide rebuilding schedules that best achieve management objectives.

The biological and economic variables in this paper are defined across time ($t$), which represents years. The stock is assumed to consist of multiple cohorts that are distinguished by age in years ($a$). Greek letters are used to represent exogenous parameters. Uppercase letters are used to represent the endogenous variables. The model is structured to determine the time path of harvest that maximizes the social welfare generated by the fishery subject to the biological dynamics of the stock, economic conditions, and rebuilding requirements. Social welfare is represented as the discounted dollar value of net economic benefits derived from the commercial use of the resource.

The biological component of the model is based on conventional, age-structured population dynamics (Ricker 1975). The number of fish in each cohort that is vulnerable to fishing effort is assumed exogenous in the first year (*i.e.*, $N_{t=1,a}$ known). This initial stock size was constructed assuming an initial recruitment level (*i.e.*, $N_{t=1,a=1}$ known), instantaneous natural mortality rate ($\omega$), and average life span with the following equation:

$$N_{t=1,a+1} = N_{t=1,a} \cdot \exp(-\omega). \tag{1}$$

Equation (1) generates an initial stock that declines in numbers by age; that is, the youngest (oldest) cohort is the most (least) abundant. To account for fish that would otherwise disappear from the model after reaching the oldest cohort ($A$), an accumulator equation was used to augment the initial size of $A$ (*i.e.*, create a "plus-group" terminal age class; Haddon 2001).

Growth of the individual fish is assumed to follow the von Bertalanffy specification for length-at-age (Haddon 2001):

$$L_a = L_\infty \cdot \left\{1 - \exp\left[-\mu \cdot (a - \lambda)\right]\right\}, \tag{2}$$

where $L_\infty$ is the average length at maximum age, $\mu$ is the growth rate coefficient, and $\lambda$ is age at which the species has zero length (*i.e.*, it is a hypothetical age that affects the position and steepness of the growth curve). Then, using the common power relationship, length is used to determine weight-at-age (Haddon 2001):

$$W_a = \gamma \cdot L_a^{\phi}, \tag{3}$$

using a constant for scaling ($\gamma$) and the allometric growth parameter ($\phi$).

Using the initial stock size and growth equations, the initial biomass is calculated:

$$B_{t=1,a} = N_{t=1,a} \cdot W_a. \tag{4}$$

The biomass is the total weight of all fish in the stock. This measure is contrasted with the spawning biomass (*SB*) that only contains mature cohorts ($a \geq a_m$). Spawning biomass can be measured in numbers or weight:

$$SB\_N_t = \sum_{a=a_m}^{A} N_{t,a} \text{ or } SB\_W_t = \sum_{a=a_m}^{A} B_{t,a}, \text{ respectively.} \tag{5}$$

Recruitment is defined as the number of fish of the youngest age added to the stock in each year ($R_t$):

$$N_{t,a=1} = R_t. \tag{6}$$

The model also identifies the youngest harvestable age (age at full selectivity). This is important for moderate- and long-lived stocks since length of time to maturity and reproduction can be significant relative to the rebuilding mandates and planning horizons of managers.

Employing the common Beverton-Holt specification ensures that recruitment is a function of spawning biomass (Haddon 2001):

$$R_t = \frac{\alpha \cdot SB\_N_t}{1 + SB\_N_t / \beta}. \tag{7}$$

The parameter $\alpha$ is important in determining both the productivity of the stock and the stock size at which productivity is maximized (Campbell, Hand, and Smith 1993). $\beta$ is the size of the spawning stock that produces half the maximum recruitment. The Beverton-Holt curve rises steadily from zero but the slope becomes less steep, and as the spawning stock grows proportionally large, the recruitment approaches the upper limit of $\alpha \cdot \beta$. For our stylized model we assume values for $\alpha$ that represent growth for 20- and 70-cohort stocks, and then use equation (7) with the assumed initial recruitment and spawning biomass to solve for $\beta$. This approach generates the pristine stock size; that is, the stable stock level in the absence of fishing that will be used to generate an overfished stock size to begin rebuilding scenarios.

To move the stock into subsequent years, the model must advance the age of each cohort:

$$N_{t+1,a+1} = N_{t,a} \cdot \exp(-Z_{t,a}). \tag{8}$$

The stock size in year $t + 1$ is determined by the stock size in year $t$ and the total instantaneous mortality rate in year $t(Z_{t,a})$, which varies by cohort. The total instantaneous mortality rate is composed of natural mortality and fishing mortality ($F$):

$$Z_{t,a} = \omega + F_{t,a}. \tag{9}$$

For simplicity the natural mortality rate is assumed equal across cohorts.

The number of fish harvested is determined by multiplying the proportion of mortality from fishing by the total number of fish that died during the period:

$$H_{t,a} = \left(\frac{F_{t,a}}{Z_{t,a}}\right) \cdot N_{t,a} \cdot \left[1 - \exp(-Z_{t,a})\right]. \tag{10}$$

The total annual harvest, in weight, which is referred to as the total allowable catch (*TAC*), is determined by multiplying the catch in numbers by the weight-at-age:

$$TAC_t = \sum_a (H_{t,a} \cdot W_a). \tag{11}$$

The net present value is calculated as the sum of annual net benefits (*i.e.*, gross revenues less variable and fixed costs) discounted at $\delta$:

$$NPV = \sum_{t=1}^{T} \left(\frac{1}{1+\delta}\right)^t \cdot \left\{TAC_t \cdot \left[P_t(TAC_t) - VC_t(SB\_W_t)\right] - \chi_t\right\}, \tag{12}$$

where $P$ is an endogenous price specification that can account for the product market effects of rebuilding:

$$P_t(TAC_t) = \theta - \tau \cdot TAC_t. \tag{13}$$

Conversely, the additional costs fishers must face to search for fish when stock levels are low can be incorporated by specifying that variable costs are inversely related to the spawning biomass:

$$VC_t(SB\_W_t) = \psi - \eta \cdot SB\_W_t, \tag{14}$$

which allows higher biomass levels to reduce harvest costs.[2] $\chi$ is the annual fixed cost associated with all capital used in the fishery.

## Models and Management Scenarios

Two stylized empirical models were created to capture differences of biological stock characteristics including the rate of individual growth and average life span. The first model represents a stock with moderate longevity. The second model depicts a long-lived species with low productivity. Each model was first used to ascertain the effects of alternative discount rates and rebuilding timeframes. The long-lived stock was then used to evaluate the effects of using supplemental output controls including a minimum size limit, multi-year closures of the fishery, and more restrictive harvest quotas. Such controls are routinely used to ensure the success of rebuilding programs.

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[2] The assumed effect on the variable economic parameters ultimately depends on the value assigned to the parameters. In this study, the parameters are positive and ensure the price and variable costs are inversely related to the TAC and SB, respectively (table 1).

**Table 1**
Variable and Parameter Definitions and Values

| Description | Symbol | Stock Longevity: Moderate | Stock Longevity: Long |
|---|---|---|---|
| Discount Rate | $\delta$ | 0%–24% | 0%–24% |
| Time Horizon | $T$ | 40 years | 60 years |
| Number of Cohorts | $A$ | 20 | 70 |
| Initial Recruitment | $N_{t=1,a=1}$ | 1 million | 1 million |
| Natural Mortality Rate | $\omega$ | 0.20 | 0.05 |
| von Bertalanffy Growth: | $L_a$ | | |
| Maximum length (cm) | $L_\infty$ | 90.0 | 40.0 |
| Growth rate coefficient | $\mu$ | 0.24 | 0.07 |
| Intercept if $L_a$=0 | $\lambda$ | –1.10 | –0.30 |
| Weight (*g*) | $W_a$ | | |
| Direct coefficient | $\gamma$ | 0.005 | 0.09 |
| Power coefficient | $\phi$ | 2.90 | 2.70 |
| Initial Spawning Biomass: | | | |
| Numbers of fish | $SB\_N_{t=1}$ | 4.5 million | 6.2 million |
| Weight of fish | $SB\_W_{t=1}$ | 5,239 mt | 9,753 mt |
| Age at Full Maturity[a] | $a_m$ | 1 | 25 |
| Age at Recruitment[a] | $a$ | 1 | 1 |
| Age at Full Selectivity[a] | $a$ | 1 | 1, 25 |
| Beverton-Holt recruitment: | $R_t$ | | |
| Productivity coefficient | $\alpha$ | 2.2 | 0.75 |
| Stock size coefficient | $\beta$ | 505.4 | 1,430.8 |
| Price: | $P$ | | |
| Intercept coefficient | $\theta$ | $11,200 | $11,200 |
| Slope coefficient | $\tau$ | $9.20 | $9.20 |
| Variable Cost:[b] | $VC$ | | |
| Intercept coefficient | $\psi$ | $7,200 | N/A |
| Slope coefficient | $\eta$ | $1.50 | N/A |
| Fixed Cost | $\chi$ | $1,500,000 | $1,500,000 |

[a] Age at full maturity is the youngest age included in the calculation of the spawning biomass. The spawning biomass determines the number of recruits, which is the number of fish in the youngest cohort that enter the model in each year. Age at selectivity is the youngest cohort that can be harvested; this age is increased to $a_m$ under the minimum size scenario (*i.e.*, this is an added constraint to the optimization).
[b] The 70-cohort model could not be solved with the endogenous variable cost specification, so a constant unit cost of $2,000/mt (the average from the endogenous specification in the baseline run) was assumed.

Assumptions for the parameter values are summarized in table 1. The moderate and long-lived stocks are assumed to have 20 and 70 cohorts, respectively, which are modelled under 40- and 60-year timeframes.[3] The relative differences in the natural mortality, growth, weight, age at full maturity, and recruitment are characteristic of *K*-strategists species with different life cycles (King and McFarlane 2003). To better isolate the effects due to species longevity and discount rates, and to facilitate comparisons among scenarios, fish price and harvesting costs are assumed identical between species.

[3] The modeling horizon for the long-lived cohort was restricted to less than one generation due to software constraints. An optimal solution to the 60-year model could not, however, be found with the endogenous cost specification, so these model runs only use $\psi$.

The starting point for each scenario is a depleted fishery that was determined by "fishing down" the pristine stock under a 24% discount rate, which was the highest observed in empirical studies published in *Marine Resource Economics* from 1985–99 that were summarized in Harte *et al*. (2000). The resulting stock sizes were 7% and 10% (362 mt and 962 mt) of the pristine stock sizes for the moderate- and long-lived stocks, respectively. The effects of alternative rebuilding timeframes were then examined under the assumption that the size of the spawning biomass will return to the level that can produce MSY within a specified period of time and that the stock size will remain above that level for the duration of the modelling horizon. The spawning biomass level was used as the rebuilding target instead of the total biomass level because the age at sexual maturity is an important factor in the determination of whether a relatively long-lived stock has been rebuilt.

All equations are solved simultaneously using the MINOS solver in the General Algebraic Modelling System (GAMS) (Brooke, Kendrick, and Meeraus 1988) to maximize *NPV* [equation (12)], which essentially solves for fishing mortality (*F*). Rebuilding scenarios were optimized across different time horizons (*T*) with explicit rebuilding requirements [the spawning biomass requirement on equation (5) discussed above] using discount rates ranging from 0 to 24%. This wide range was selected for analysis to account for diverse preferences regarding the appropriate level of discount rates between countries and to illustrate the effects of low relative to high discount rates. For instance, New Zealand is required to manage fish stocks for the "foreseeable needs of future generations," which supports the use of a relatively low discount rate (New Zealand Ministry of Fisheries 2002). That said, a study of quota transfer prices that included New Zealand harvest rights revealed implied discount rates of up to 50% (Asche 1999), and another study calculated rates up to 20% (Akroyd *et al.* 1999). The subjective nature of the discount rate used in New Zealand is in contrast to the prescribed rates for federally funded projects in the US, which are specified by the Office of Management and Budget (OMB). The real treasury rates published by the OMB ranged from 2.8% to 7.9% during the 1979 to 2005 period. To simplify the comparative analysis, we only present the results associated with the 4% and 24% rates, which reflect a range of observed and derived discount rates under a variety of market and regulatory conditions.

## Results and Discussion

### *Moderate Stock Rebuild*

To examine alternative rebuilding scenarios for a moderate-lived stock, the depleted 20-cohort stock (*i.e.*, 362 mt) is used to begin a new 40-year time horizon. Requiring the stock to rebuild to the spawning biomass that would produce MSY (*i.e.*, 1,912 mt) within 10 years would generate a *NPV* of $5.6 million with a 24% discount rate. Delaying the rebuilding requirement to 20 or 30 years with a 24% discount rate would increase *NPV* by 17.7% to 19.4%, respectively. Table 2 summarizes the changes in *NPV* and average *TAC* during the rebuild period from requiring rebuilding within 10, 20, and 30 years at the two discount rates. Discounting at higher rates has larger impacts, as rebuilding timeframes are delayed.

From an economic, social, and regulatory perspective an important issue is the path the stock takes to reach the MSY target. Figure 1a shows the stock recovery and the corresponding *TAC* requirements to rebuild in 10 years under a 4% discount rate. The spawning biomass increases steadily to the required MSY stock size, which indicates that this 20-cohort species is able to rebuild within 10 years. Just

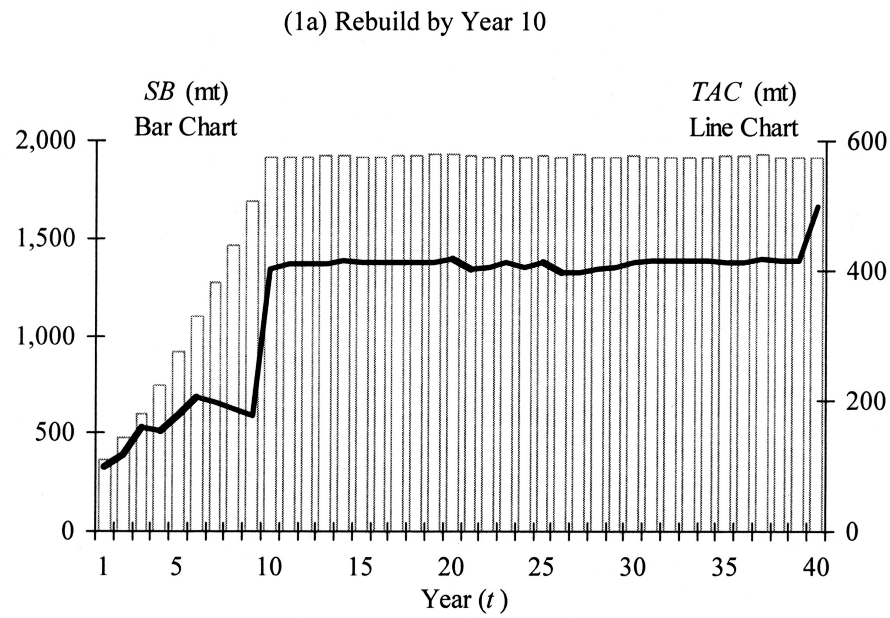
**Table 2**
Maximized *NPV* and Corresponding Average *TAC* during the Rebuild Period for the Moderate-lived Stock under Alternative Rebuilding Timeframes and Discount Rates

| | Rebuilding Timeframe[a] | | |
|---|---|---|---|
| Discount Rate (δ) | 10 Years | 20 Years | 30 Years |
| *NPV*: | | | |
| 4% | \$36.6 million[b, d] | \$37.9 million (3.5 %) | \$38.0 million[c] (3.9 %) |
| 24% | \$5.6 million[b] | \$6.6 million (17.7 %) | \$6.7 million[c] (19.4 %) |
| Average *TAC* during Rebuild: | | | |
| 4% | 163.4 mt[b] | 250.0 mt (53 %) | 321.9 mt[c] (97 %) |
| 24% | 141.8 mt[b] | 207.0 mt (46 %) | 249.6 mt[c] (76 %) |

[a] Parentheses contain the percentage change from the 10-year rebuild scenario. Scenarios require the spawning biomass to reach 1,912 mt during the rebuilding timeframe and remain at or above that level through the end of the modelling horizon (*i.e.*, 40 years).
[b] The corresponding annual spawning biomass and *TAC*s are shown in figure 1.
[c] The corresponding annual spawning biomass and *TAC*s are shown in figure 2.
[d] Although not explicitly discussed, the consumer surplus changes across rebuilding plans are not trivial. For example, for the 4% case, the consumer surplus losses from the 10-year recovery are in the range of \$3 million compared to 20 years and \$6 million compared to 30 years.

before the 10-year rebuilding deadline approaches, annual *TAC*s drop slightly to ensure the spawning biomass requirement is met. Following the 10-year rebuild, annual *TAC*s remain steady at approximately 400 mt and *NPV* totals \$36.6 million. Note that the harvest increases in the final year since there is no spawning biomass level to maintain in the following year. If the rebuilding mandate is extended to 30 years, the effects of that action are shown in figure 1b. Although the stock is capable of rebuilding in 10 years, a 30-year mandate allows recovery to occur gradually over time. In response, the *TACs* increase over the first eight years and then stabilize briefly before falling just prior to the 30-year deadline. Again, *TACs* stabilize at approximately 400 mt following the rebuild. Under the delayed rebuilding schedule, *NPV* increases just 3.9% but likely minimizes the potentially negative impacts imposed on coastal communities from aggressive rebuilding schedules, which are not captured in this analysis.

Figure 2a shows that under a 24% discount rate, the stock can also be rebuilt in ten years but produces only \$5.6 million in *NPV* (table 2). A comparison of figures 1a and 2a reveals that the higher discount rate produces significant reductions in *TAC* in the years immediately preceding the deadline. This effect is even more severe when the rebuilding deadline is delayed as shown in figure 2b. The annual *TAC* stabilizes at approximately 300 mt in years 10 through 20, but falls to just 100 mt in year 29, returning to the 400 mt harvest level in years 30 through 40. Again, the stock rebuild is delayed as long as possible. This scenario increases *NPV* by 19.4% compared to the 10-year rebuild plan depicted in figure 2a.



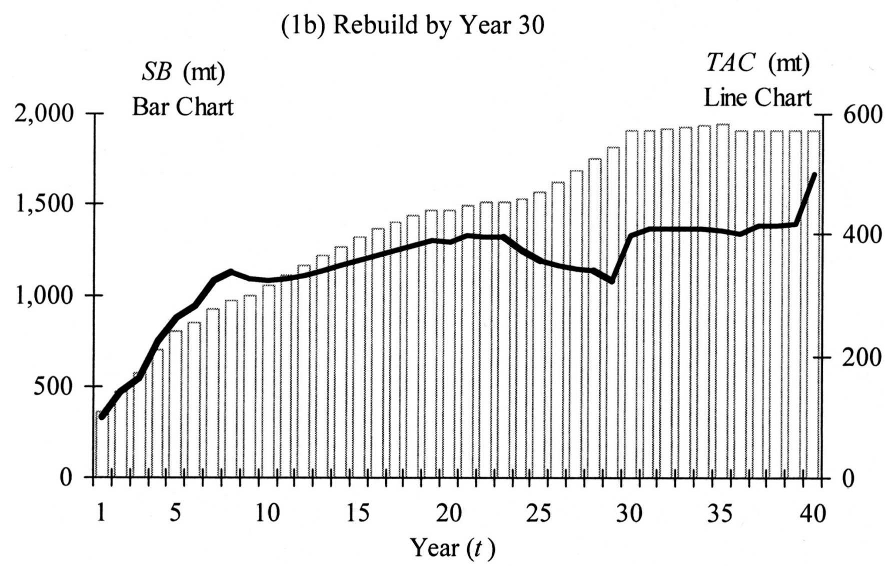
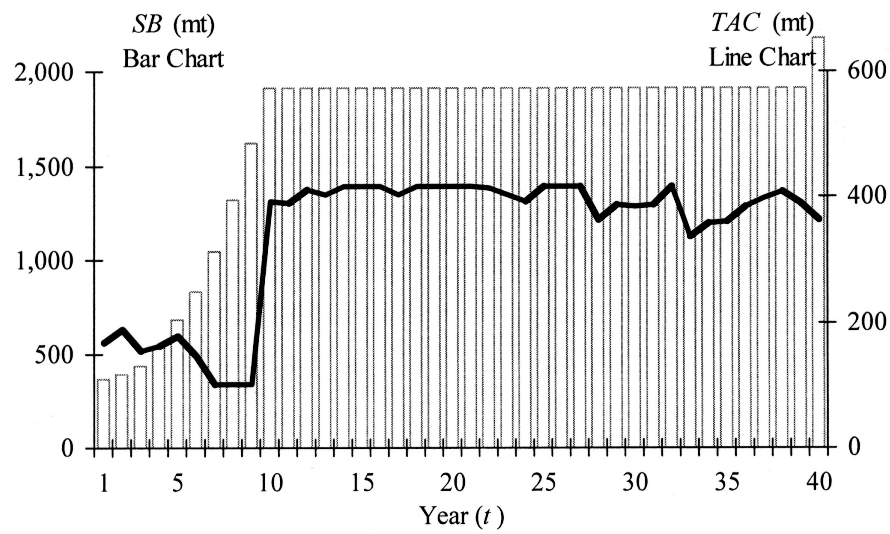




**Figure 1.** Annual Spawning Biomass and Optimal Harvest Levels for the 20-cohort Stock with a 4% Discount Rate under 10- and 30-year Rebuilding Timeframes

(2a) Rebuild by Year 10




(2b) Rebuild by Year 30

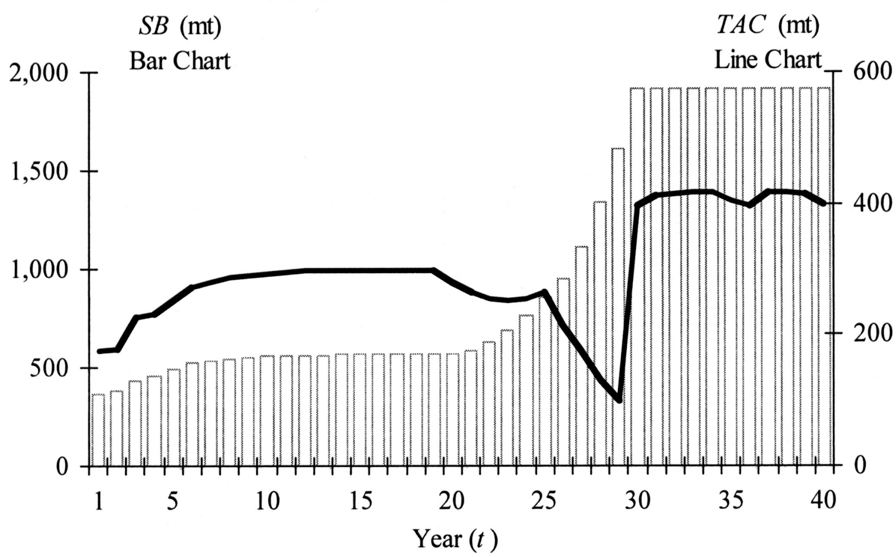



**Figure 2.** Annual Spawning Biomass and Optimal Harvest Levels for the 20-cohort Stock with a 24% Discount Rate under 10- and 30-year Rebuilding Timeframes

In summary, annual harvest quotas fall rapidly in the years immediately preceding a rebuilding deadline. This decline allows the spawning biomass to increase. At higher discount rates the pre-deadline *TAC* reduction is more pronounced, as the spawning biomass increase is delayed as long as possible. The decision to delay rebuilding allows the harvests to remain higher in the early years when the discount rate has a smaller effect. The *NPV*-effect of a delayed rebuilding schedule was, however, quite small at a low discount rate (despite a lower average harvest level).

These results are consistent with *a priori* expectations for non-linear fishery models (with respect to the control variable) with no stock effects. The model maintains the stock at the long-run bioeconomic optimum as long as possible before it rapidly increases the stock (and decreases harvests) to meet MSY constraints—behaviour consistent with "turnpike" properties of constrained optimizations—see Clarke (1985). At higher discount rates the adjustment paths are even steeper, since high discount rates provide less incentive to smooth out nonlinear adjustment costs over time.

### *Long-lived Stock Rebuild*

To examine alternative rebuilding scenarios for a long-lived stock, the depleted 70-cohort stock (*i.e.*, 962 mt) is used to begin a new 60-year time horizon. Table 3 summarizes the optimal *NPV* and corresponding average *TAC*'s during rebuild from requiring the stock to reach MSY (*i.e.*, 2,953 mt) within 40, 50, and 60 years at discount rates of 4% and 24%. In general, the long-lived stock is less productive during rebuild and less valuable (in terms of *NPV* from the commercial sales) than the moderate-lived stock.

**Table 3**
Maximized *NPV* and Corresponding Average *TAC* during the Rebuild Period for the Long-lived Stock under Alternative Rebuilding Timeframes and Discount Rates

| | Rebuilding Timeframe[a] | | |
|---|---|---|---|
| Discount Rate (δ) | 40 years | 50 years | 60 years |
| *NPV*: | | | |
| 4% | $6.5 million[b] | $10.3 million (58 %) | $14.7 million[c] (126 %) |
| 24% | $0.93 million[b] | $3.3 million (255 %) | $5.9 million[c] (534 %) |
| Average *TAC* during Rebuild: | | | |
| 4% | 22.1 mt[b] | 42.6 mt (93 %) | 72.7 mt[c] (229 %) |
| 24% | 15.9 mt[b] | 26.2 mt (65 %) | 42.2 mt[c] (178 %) |

[a] Parentheses contain the percentage change from the 40-year rebuild scenario. Scenarios require the spawning biomass to reach 2,953 mt during the rebuilding timeframe and remain at or above that level through the end of the modelling horizon (*i.e.*, 60 years).
[b] The corresponding annual spawning biomass and *TAC*s are shown in figure 3.
[c] The corresponding annual spawning biomass and *TAC*s are shown in figure 4.

Figure 3 shows the stock recovery and the annual *TAC* requirements to rebuild in 40 or 60 years under a 4% discount rate. With a 40-year rebuild mandate, the spawning biomass declines before increasing at a decreasing rate to the required minimum spawning biomass in year 40 (fig. 3a). Small harvests occur in years 1 and 2 and years 12 through 20; harvests begin to rapidly increase in year 30. The increase in spawning biomass from year 17 to year 40 indicates that this 70-cohort stock can be rebuilt in 23 years with a 4% discount rate. When the spawning biomass reaches approximately 85% of the MSY-generating level, harvests are reinitiated and increase steadily through the remainder of the modelling horizon.[4]

Figure 3b shows the effects of rebuilding within 60 years with a 4% discount rate. Again, the figure shows that the stock can rebuild within 23 years. The longer rebuilding mandate allows the stock to be further fished down (such that harvests can remain as high as possible as long as possible in the early years when discounting has less of an effect) before beginning to rebuild in year 17. At year 37 the annual harvests would decline and eventually stop before beginning again in year 46. Under this delayed rebuilding schedule and relatively low discount rate, *NPV* more than doubles to $14.7 million.

If the discount rate is increased to 24%, the general findings are unaffected as shown in figure 4; however, some interesting effects emerge. Figure 4a shows that the stock is capable of rebuilding in 23 years, as in figure 3b. As shown in table 3, the *NPV* of this scenario is $0.93 million. A comparison of figures 3a and 4a reveals that the higher discount rate results in higher *TAC*s in the first three years when the value of the harvests is discounted to a relatively greater degree.

For comparison, the effects of a 24% discount rate and 60-year rebuilding timeframe are shown in figure 4b. With a relatively high discount rate and the longest rebuilding timeframe, *NPV* is maximized by harvesting as much as possible as fast as possible. This harvest pressure causes the spawning biomass to first fall before beginning to rebuild in year 17. Under this scenario the fishery would be effectively closed from year 10 to year 43. Again, the spawning biomass is fished down from year 30 to year 43 before rebuilding a final time. With the higher discount rate, harvests are larger and the spawning biomass is smaller in early years (figure 3b versus 4b).

In the years preceding the rebuilding, the fishery for the long-lived species would need to be closed for a period of seven to 32 years. This is in contrast with the moderate-lived fishery that would not experience closures. In general, the longest closures occur under the highest discount rate, and the shortest closures occur with the delayed rebuilding mandate. The decision to delay rebuilding allows the harvests to remain higher in the early years when the discount rate has less of an effect.

Under a 60-year rebuilding mandate, the higher discount rate results in an optimal harvest plan in which harvests decline from approximately 375 mt in year 1 until an effective closure of the fishery in year 9. The fishery would then remain closed until year 43 before stabilizing at harvest levels that average 43 mt for nearly 15 years. Under a 4% discount rate by comparison, the *TAC* would average 70 mt and the fishery would not close until year 40. It would then remain closed for just seven years.

In summary, unlike the 20-year cohort scenarios summarized in table 2, the *NPV*-effect of a delayed rebuilding schedule for the 70-year cohort was significant.

[4] Similar to the rebuilding analysis for the moderate-lived stock, the significant increase in *TAC* levels in the final years is a modelling artefact reflecting surplus value at the end of the modelling horizon (*i.e.*, there is no minimum SB requirement to maintain the following year).

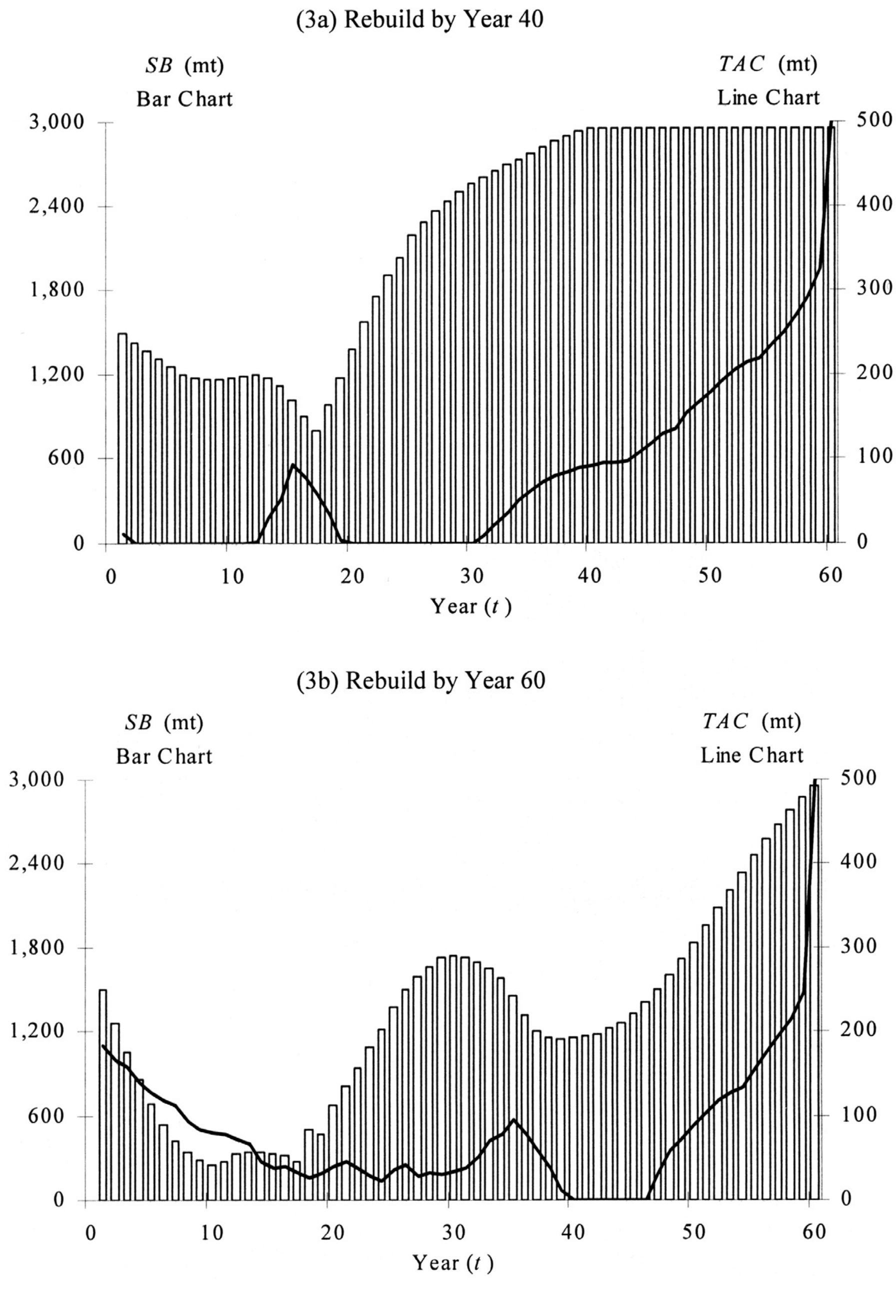



**Figure 3.** Annual Spawning Biomass and Optimal Harvest Levels for the 70-cohort Stock with a 4% Discount Rate under 40- and 60-year Rebuilding Timeframes

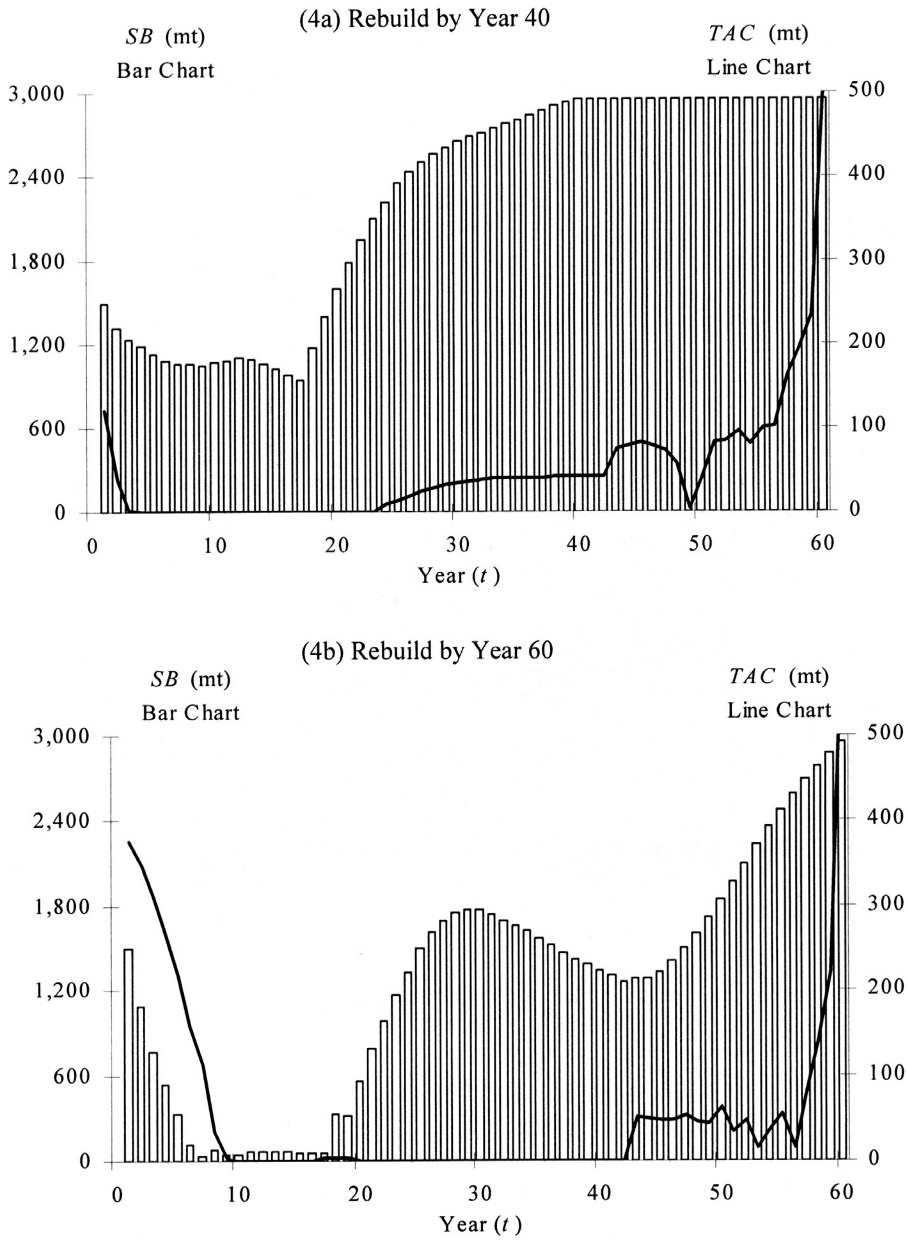



**Figure 4.** Annual Spawning Biomass and Optimal Harvest Levels for the 70-cohort Stock with a 24% Discount Rate under 40- and 60-year Rebuilding Timeframes

At higher discount rates the spawning biomass remained as low as possible and for as long as possible. This pattern is contrasted to the scenario involving a lower discount rate in which rebuilding occurs gradually over time. Higher *TAC*s in the face of imminent reductions (in order to rebuild in the time allotted) may appear counter-intuitive, but such harvest schedules are the direct result of discounting.

### *Long-lived Stock 40-year Rebuild with Additional Regulations*

Three additional regulations designed to further ensure the stock is rebuilt are examined under the two discount rates with the 70-cohort stock and 40-year rebuilding timeframe. The first scenario imposes a minimum size regulation by banning landings of cohorts younger than age 25. The second scenario begins the rebuilding timeframe with a 10-year closure. The third scenario places lower and upper bounds on annual landings of 10 mt and 350 mt, respectively. Although this constraint is less binding under a 4% discount rate than a 24% discount rate, this scenario illustrates the general effects of imposing some stability on the fishery (*e.g.*, in response to business and marketing costs associated with significant inter-annual variation). The resulting *NPV* and average *TAC* levels from these scenarios are summarized in table 4. As with the previous rebuilding analyses, the underlying MSY-based rebuilding target is maintained such that the additional management regulations may change the rebuilding pattern but do not affect whether the stock is rebuilt.

With a 4% discount rate the minimum size regulation decreased *NPV* by 37% and the average *TAC* by 39% due to lower *TAC*s. With a 24% discount rate, imposing a minimum size policy would decrease *NPV* by only 1% and the average *TAC* by just 3%. In contrast to the 4% discount rate scenario, the *TAC*s would be higher in

**Table 4**
Maximized *NPV* and Corresponding Average *TAC* for a 40-year Rebuilding Timeframe of the Long-lived Stock under Alternative Additional Regulations and Discount Rates

| | | Additional Management Regulations[a] | | |
|---|---|---|---|---|
| Discount Rate (δ) | Original Scenario[a] | Minimum Size | Fishery Opens Year 11 | *TAC* Range: 10–350 mt |
| *NPV*: | | | | |
| 4% | $6.50 mil. | $4.08 mil. (–37 %) | $6.50 mil. (0%) | $6.15 mil. (–5 %) |
| 24% | $0.93 mil. | $0.92 mil. (–1 %) | $0.09 mil. (–90 %) | $0.43 mil. (–54 %) |
| Average *TAC*: | | | | |
| 4% | 82.3 | 49.9 mt (–39 %) | 82.4 mt (0%) | 80.5 mt (–2 %) |
| 24% | 49.1 | 47.5 mt (–3 %) | 54.3 mt (11 %) | 36.0 mt (–27 %) |

[a] Parentheses contain the percentage change from the 40-year rebuild scenario. Scenarios require the spawning biomass to reach 2,953 mt within 40 years and remain at or above that level through the end of the modelling horizon (*i.e.*, 60 years)

the initial years with a 24% discount rate. Regardless of the assumed level of the discount rate, the lower *TACs* caused by regulatory discards did not increase average harvest levels or social welfare.

For the initial 10-year closure scenario, there was essentially no change in either *NPV* or the *TAC* pattern with a 4% discount rate. This occurs because the optimal economic solution for the original scenario requires the closure of the fishery for the first 12 years; thus, closures may be justified on a bioeconomic basis.[5] For the initial 10-year harvest closure under a 24% discount rate, *NPV* would decline 90%, although the average annual *TAC* would increase nearly 11%. The annual average *TAC* was higher due to an early surge in landings around year 10 and accelerated harvest rates in later years. *NPV* declines due to the higher discount rate and the fewer years of high *TAC*s around the year-10 peak.

For the TAC-bounded management scenario, *NPV* would fall 5% and the average *TAC* would decline just 2% under a 4% discount rate. Under the much higher 24% discount rate, however, *NPV* decreased 54% and the average *TAC* declined 27% following the imposition of minimum and maximum annual *TAC*s.

In summary, the imposition of additional fishing constraints designed to reduce the risk associated with the failure to rebuild to the MSY-supporting level did not increase *NPV* and had diverse effects on average landings. The diversity and magnitude of results highlights the importance of examining the implied rebuilding schedules, which are likely to be unique to each combination of management options. The magnitude of the effects was also heavily dependent on the assumed discount rate and underscores its importance in the determination of optimal rebuilding schedules.

## Conclusions

Implicit in the mandates of the New Zealand Fisheries Act and the US MSFCMA is the concept of an optimal rebuilding rate or trajectory for depleted stocks. For New Zealand fisheries, there is greater flexibility in designing a rebuilding process in order to meet economic, social, and cultural needs. In the US the fisheries manager is constrained by the requirement that stocks must be rebuilt within the "shortest possible time" and within 10 years if biologically possible (see footnote 1). The US fisheries manager can sacrifice economic benefits in order to achieve a biologically directed objective. Our analysis demonstrates that extending the rebuilding timeframe (as allowed under the New Zealand Act) could increase the net present value of commercial harvests from small to very significant levels depending on input and output prices, technology, productivity of the stock, and the discount rate. Corresponding harvest levels during a more flexible rebuilding plan could also more readily contribute to goals, such as meeting the needs of fishing communities.

Bioeconomic models can assist the fishery manager in making transparent the economic tradeoffs associated with alternative rebuilding timeframes, discount rates, and supplemental regulatory policy instruments. In addition, objective functions can be broadened to include other economic, social, or environmental objectives that may be important in maximizing national benefits. Models can also be used to evaluate distinct groupings or assemblages of species that "provide a foundation for developing conceptual management scenarios based on generalized

[5] Provided community impacts such as the employment rate, utilization of commercial fishing capital, and the viability of ports are not adversely affected to a large degree. These effects were not captured in this analysis. The underlying assumption is that such costs are identical across scenarios.

population dynamics," as most recently classified by King and McFarlane (2003, p. 254) and recommended by NOAA Fisheries (2005). In this study, the moderate- and long-lived species most closely resemble the "periodic strategist" and "equilibrium strategist" species groups (*e.g.*, rockfish and Pacific hagfish, respectively) identified by King and McFarlane (2003).

With respect to rebuilding strategies for stocks of moderate longevity as modelled in this paper, higher discount rates resulted in lower net present values, slower rebuilding rates (spawning stock increases are delayed as long as possible), and more pronounced harvest cutbacks as the rebuilding deadline approaches. However, at rates that are lower and closer to prevailing market rates of interest, the effects were less significant. Given the wide range of discount rates used for the moderate-lived species represented by this analysis, a rebuilding period of 10 years, as specified in the MSCFMA, would produce an economically inefficient outcome. In addition, social inefficiency may be underestimated since impacts on fishing communities are unaccounted for in this simplified analysis.[6]

Alternative rebuilding timeframes for the long-lived stock produced significantly larger changes in the value of the fishery, even though the rebuilding timeframe was shorter relative to the longevity of the species. In addition, the effect of the discount rate was larger with the long-lived species. The effects on the average annual quotas of alternative rebuilding timeframes were also different at the highest discount rate. Specifically, a delayed rebuilding timeframe for the long- (moderate-) lived species would increase (decrease) the average annual harvest quota during the first decade of rebuilding.

One major consideration not included in this analysis is the risk and uncertainty associated with rebuilding fish stocks. Given the significant uncertainties that characterize the dynamics of most fish stocks, there will be uncertainty in achieving expected stock trajectories by managing fishing effort. In the US, guidelines allow rebuilding schedules that may have as low as a 50% probability for achieving the MSY biomass at the terminal date. This has the effect of slowing down the rate of rebuild relative to higher probability levels. In other cases, it may be argued that given stock uncertainties, the manager needs to take a "precautionary approach" and decrease the rebuilding time by reducing fishing mortality. Placing the rebuilding problem within a risk-based economic framework, however, also requires analyzing the risks associated with achieving economic and social objectives, including the long-term effects on fleets, processing firms, and coastal communities.

The model presented in this paper is intended to function primarily as a heuristic device to explore economic issues associated with rebuilding moderate- and long-lived stocks. The model provides a platform for managers and analysts to identify potential economic tradeoffs resulting from alternative rebuilding schedules, including those based on biological criteria. The model can be expanded to explore a wide range of biological, economic, and management issues associated with rebuilding fish stocks.

In summary, the model demonstrates that dynamic bioeconomic analysis is a relevant policy tool for gaining insights into designing optimal rebuilding strategies. Because fish stocks are utilized to generate social welfare, and not simply biomass, rebuilding analysis should employ social and economic criteria. Although lawmakers may feel compelled to adopt relatively rigid rebuilding rules to meet sustainability requirements—possibly in response to inaction by regional fishery authorities—they must also recognize that such decisions may have real economic and

[6] If an actual fishery were being modelled, additional scenarios would be needed to better capture the community effects and the predicted changes in fish price and harvest costs.

social consequences. Exploring the potential of institutions and policies that create incentives to rebuild fish stocks, while also moderating economic and social costs, may be the model's best and highest use. Regardless, however, designing rebuilding plans that ignore the unique characteristics of each fishery—including social and economic considerations—may result in significant loss of social welfare.

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