On The Optimal Moratorium in an Overfished Fishery: The Case of Canadian Cod

by

Jon M. Conrad*, C.-Y. Cynthia Lin Lawell, and Brian B. Shin

January 9th, 2020

Abstract

In the linear model in Clark (1976), if a fish stock is below its optimal level, x^*, a moratorium on fishing is optimal. The moratorium remains in effect until the stock increases and reaches x^*. At that time, harvest is resumed at a rate equal to net biological growth. By restricting harvest to net biological growth, the stock is maintained at its optimal level for the rest of time. In this paper we explore the optimal moratorium when a government makes unemployment insurance (UI) payments to fishers idled by the moratorium. How does the payment of UI affect the length of the optimal moratorium? This was the question faced by the federal government of Canada after the declaration, on July 2nd, 1992, of a moratorium on the commercial harvest of Northern cod in the coastal waters off Newfoundland and Labrador. In calibrating the model with UI payments to the Canadian cod fishery, we determine that the optimal moratorium with no UI payments is 23 years and that the optimal moratorium is only shortened slightly by positive UI payments.

JEL codes: Q2, Q22
Keywords: Overfished fisheries, Optimal moratoria, Canada's cod fishery.

*Corresponding Author. Conrad is Professor Emeritus, Lin Lawell is Associate Professor, and Shin is a graduate student. All are in the Charles H. Dyson School of Applied Economics and Management within the Cornell College of Business, Cornell University, Ithaca, New York, 14853. Email Addresses: Conrad: jmc16@cornell.edu, LinLawell: clinlawell@cornell.edu, Shin: bbs62@cornell.edu

1 Introduction and Overview

On July 2nd, 1992, the Canadian federal government declared a moratorium on commercial fishing for cod in the waters off Newfoundland and Labrador. The cod stocks in these waters had been harvested under open access conditions in the 1960s and 1970s, prior to the declaration of the 200-mile economic zone authorized under the Third United Nations Law of the Sea Conference in 1977. In 1968 it was estimated that foreign, distant-water fleets had harvested 700,000 metric tons of cod (*Gadhus morhua*) on top of the 120,000 metric tons harvested by Canadians [Baird et al. (1991)].

The exclusion of foreign vessels raised hopes that the Canadian federal government would be able to rebuild the cod stock and manage the fishery in a sustainable fashion. Unfortunately, scientists overestimated the rate of recovery and the size of the potential stocks in NAFO (North Atlantic Fisheries Organization) zones 2J, 3K, and 3L, which after 1977 fell within Canada's Exclusive Economic Zone (EEZ) [Bishop and Shelton (1997)].

Overestimation of the speed and scale of recovery buoyed the expectations and investment behavior of both fishers and processors. Between 1976 and 1981 the cod fishery saw (1) the number of registered fishers increase from 14,000 to 34,000, (2) a doubling in the number of inshore vessels, and (3) a tripling in the freezing capacity at fish processing plants [Schrank (2005)]. Domestic overcapitalization replaced foreign overcapitalization before the cod stock could recover.

In this paper we develop a model to determine the optimal moratorium in an overfished fishery when a government pays unemployment insurance (UI) to idled fishers. With no UI payments, Clark (1976) has shown that if (1) the current-value Hamiltonian is linear in harvest and (2) the current fish stock is less than the steady-state optimum, x^*, then the optimal approach to x^* is most rapid, requiring a moratorium until the stock has increased to x^*. When x^* is reached, harvest is restricted to net biological growth, which maintains the stock at x^* for the rest of time.

We develop expressions for the net present value of a moratorium with and without the payment of UI to fishers idled by the moratorium. The question of interest becomes: "How does the payment of UI affect the duration of the optimal moratorium, and thus the size of the fish stock and rate of harvest, when fishing resumes?"

In the next section we review the linear fishery from Clark (1976) and show how the optimal moratorium might be determined in two ways: (1) using the steady-state golden rule to determine x^* and then deriving an expression for the length of the moratorium based on the time it takes to go from $x(0)$ to x^* when harvest, $h(t)$, is zero, and (2) maximizing the net present value of a moratorium of length T. This second approach is more straightforward and *has* to be used when annual UI payments are positive. The second approach also allows one to determine the sensitivity of the optimal moratorium to the rate of UI payments per unit time. Intuitively, one would expect that making positive UI payments would *shorten* the optimal moratorium. The empirical question becomes "How sensitive is the optimal moratorium to the rate of UI payments?"

In Section 3, we specify functional forms for net revenue and net biological growth that allow the derivation of an analytic expression for the net present value of a moratorium of length T; with or without UI payments. In Section 4 we calibrate that specification to the Northern cod fishery in Canada. In Section 5 we solve for the optimal moratoria when the size of UI payments varies from \$0 to \$200,000,000 Canadian Dollars (CD) per year. The analysis reveals that positive UI payments shortens the length of the optimal moratorium, *but only slightly.* With no UI payments, the optimal moratorium is approximately 23.31 years, with a steady-state stock of 1,414,010 metric tons and an annual harvest of 127,081 metric tons, yielding annual net revenues of \$158 million CD. With UI payments of \$200,000,000 CD per year the optimal moratorium drops to 21.67 years with a steady-state stock and harvest of 1,209,720 metric tons and 122,725 metric tons, respectively, supporting a steady-state annual net revenue of \$150 million CD.

2 The Linear Model

Let $x = x(t)$ denote the stock (biomass) of fish at instant t, $\infty > t \geq 0$, $h = h(t)$ the rate of harvest, and $\dot{x} = dx/dt = F(x) - h$ the state equation, describing the change in the fish stock. $F(x)$ is a strictly concave net-growth function. We assume that net revenue is linear in harvest and given by $\pi(x, h) = [p - c(x)]h$, where $p > 0$ is the ex-vessel (dockside) price per metric ton of harvest, and $c(x)$ is the marginal cost of harvest, with $c'(x) < 0$ indicating that larger stocks lower marginal cost.

The optimal management of this fishery would seek to

$$\begin{array}{l} \underset{h}{\text{Maxmize}} \quad \pi = \int_0^\infty [p - c(x)]he^{-\delta t}dt \\ \text{Subject to } \ \dot{x} = F(x) - h \text{ and } \ x(0) > 0 \text{ given,} \end{array}$$

where $\delta > 0$ is the instantaneous rate of discount and $e^{-\delta t}$ is the continuous-time discount factor. The current value Hamiltonian for this dynamic optimization problem may be written as

$$H = [p - c(x)]h + \mu[F(x) - h] = [p - c(x) - \mu]h + \mu F(x). \tag{1}$$

where $\mu = \mu(t) > 0$ is the current-value shadow price on the marginal metric ton of fish in the water. The current-value Hamiltonian is linear in h and the term $[p - c(x) - \mu]$ represents price less "full marginal cost." If $[p - c(x) - \mu] < 0$, the optimal rate of harvest is zero, $h^*(t) = 0$, while if $[p - c(x) - \mu] > 0$, the optimal rate of harvest is the maximum feasible rate, $h^*(t) = h_{\max} > 0$. When $[p - c(x) - \mu] = 0$, price equals full marginal cost and, along with $\dot{x} = 0$ and $\dot{\mu} = 0$, implies

$$F'(x) + \frac{-c'(x)F(x)}{p - c(x)} = \delta, \tag{2}$$

as in Clark (1976, p.40). Equation (2) is often referred to as a "golden rule" because it requires each generation to harvest the fish stock so as to maintain it at $x(t) = x^*$. It also provides a single equation in x which may be solved to determine the optimal steady-state fish stock, $x = x^*$. When $x < x^*$, $[p - c(x) - \mu] < 0$ and $h^*(t) = 0$. Clark defines a fish stock as being *economically overfished* when $x(t) < x^*$, which in the linear model requires the adoption of a moratorium of length T until $x(T) = x^*$ for the first time.

During the moratorium, $\dot{x} = F(x)$. Suppose that $\dot{x} = F(x)$ has an analytic solution $x(t) = G(t)$. We then know that $x(T) = G(T) = x^*$ and for $t \geq T$ that $h^* = F(G(T))$. The analytic solution, $x(t) = G(t)$ will typically depend on the parameters of the net biological growth function, $F(x)$, and on the current size of the fish stock, $x(0)$. In the next section, we will specify logistic net biological growth, $F(x) = rx(1 - x/K)$, and where $r > 0$ is the intrinsic growth rate and $K > 0$ is the environmental carrying capacity. The logistic differential equation $\dot{x} = rx(1-x/K)$ has the well-known analytic solution $x(t) = G(t) = K/(1+\alpha e^{-rt})$, where $\alpha = [K - x(0)]/x(0)$. If one has computed x^* from Equation (2), then one can solve $x^* = K/(1 + \alpha e^{-rT})$ for T and show that

$$T^* = (1/r)ln\left[\frac{x^*(K - x(0))}{x(0)(K - x^*)}\right] \tag{3}$$

Equation (3) assumes that there are no costs to the moratorium other than delaying the resumption of fishing. This will not be the case if a government pays UI to idle fishers. The longer the moratorium, the larger will be the present value of total UI payments. Suppose that UI payments are made at a constant rate $u(t) = u \geq 0$ for $T > t \geq 0$. Then, the present value of UI payments for a moratorium of length T would be

$$U = \int_0^T ue^{-\delta t}dt = u(1 - e^{-\delta T})/\delta \tag{4}$$

With $x(T) = G(T) = x^*$ being maintained by harvest $h^* = F(G(T))$ for $t \geq T$, we can compute the net present value of the fishery after a moratorium of length T as

$$\pi = \pi(G(T), F(G(T)))e^{-\delta T}/\delta. \tag{5}$$

Equations (4) and (5) imply that the net present value of a moratorium when making UI payments at rate $u \geq 0$ for $T > t \geq 0$ can be computed as

$$NPV(T) = \pi(G(T), F(G(T)))e^{-\delta T}/\delta - u(1 - e^{-\delta T})/\delta \tag{6}$$

The optimal moratorium will be $T = T^*$ that maximizes $NPV(T)$. When $u = 0$ (no UI payments) the value for T^* that maximizes $NPV(T)$ will be the same the value of T^* where $x^* = G(T)$. However, when $u > 0$, we need to determine the optimal moratorium as $T^* = \underset{\text{T}}{\text{ArgMax}}\ NPV(T)$.

3 A Specification

In addition to logistic net growth, $F(x) = rx(1 - x/K)$, we also adopt a marginal cost function taking the form $c(x) = c/x$, where $c > 0$ is a cost parameter. This marginal cost function implies that net revenue is given by $\pi(x, h) = [p - c/x]h$ and Equation (2) has the famous analytic solution for the steady-state optimal stock given by

$$x^* = \left[\frac{K}{4}\right]\left[\frac{c}{pK} + 1 - \frac{\delta}{r} + \sqrt{\left(\frac{c}{pK} + 1 - \frac{\delta}{r}\right)^2 + \frac{8c\delta}{pKr}}\right] \tag{7}$$

With parameter values for r, K, c, p, and δ, one can compute the numerical value of x^*. Knowing the current stock, $x(0)$, one can use Equation (3) to compute T^*, the optimal moratorium when $u = 0$. One can also compute $h^* = rx^*(1 - x^*/K)$ and $\pi(x^*, h^*) = [p - c/x^*]h^*$. The same value for T^* will be obtained when maximizing the right-hand side of Equation (6) when $u = 0$.

We now want to derive the specific form of Equation (6) by making use of the fact that during the moratorium that $x(t) = G(t) = K/(1 + \alpha e^{-rt})$. The moratorium ends at $t = T$ where $X(T) = G(T) = K/(1 + \alpha e^{-rT})$ and $h(T) = rx(T)(1 - x(T)/K) = \alpha K r e^{-rT}/(1+\alpha e^{-rT})^2$. Substituting the expressions for $G(T)$ and $F(T)$ into Equation (6) yields

$$NPV(T) = \left[p - \frac{c(1 + \alpha e^{-rT})}{K}\right] \left[\frac{\alpha K r e^{-(r+\delta)T}}{\delta(1 + \alpha e^{-rT})^2}\right] - \frac{u(1 - e^{\delta T})}{\delta} \tag{8}$$

When $u > 0$, and a government is paying unemployment insurance, we must use Equation (8) to determine the optimal moratorium. What does Equation (8) imply about the optimal moratorium in the case of the Canadian Northern cod fishery?

4 Calibration

The collapse of the Canadian Northern cod fishery raised serious questions about the ability to accurately estimate spawning biomass and to specify and enforce a total allowable catch (a TAC) which would not result in economic overfishing ($x < x^*$). Scientists within Canada's Department of Fisheries and Oceans were called to testify and explain how they could have missed the warning signs that the cod fishery was on the brink of collapse. The inquiry that ensued resulted a large literature attempting to specify and calibrate models that could explain the collapse based on estimates of historical landings and which would also predict the likely length of a moratorium that would allow the stock to "adequately" recover. From this literature we seek reasonable values for r, the intrinsic growth rate, K, the carrying capacity in NAFO zones 2J, 3K, and 3L, p, the ex-vessel price per metric ton of cod when fishing is resumed at the end of the moratorium, c, the cost parameter in the marginal cost function, c/x, and δ, the appropriate rate of discount when managing a fishery. Our base-case set of parameters is summarized in Table 1.

Table 1: The Base-Case Parameters in the Canadian Northern Cod Fishery

Parameter	Description	Value	Source
r	Intrinsic Growth Rate	0.17	Myers and Mertz (1997)
K	Capacity of Zones 2J, 3K, and 3L	3,000,000 m.t.	Haedrich and Hamilton (2000)
$x(0)$	Estimated Biomass in 1992	50,000 m.t.	Haedrich and Hamilton (2000)
α	$\alpha = [K - x(0)]/x(0)$	59	Based on K and $x(0)$.
p	Ex-vessel price at T	\$1,387/m.t.	AR(1) Price Process, $t \to \infty$,
c	Cost parameter	\$200,857,000	Grafton et al. (2000)
δ	Annual Discount Rate	0.02	Weitzman (2001)

The Intrinsic Growth Rate

Myers and Mertz (1997) estimate the intrinsic growth rate for 20 cod populations in the North Atlantic. Their estimates vary from $r = 0.17$ for Newfoundland and Labrador (NAFO zones 2J, 3K, and 3L) to $r = 1.03$ in the Irish Sea (NAFO zone VIIa). With regard to the Canadian cod stocks in NAFO zones 2J, 3K, and 3L, the authors note:

Unfortunately, our results indicate that recovery could require a long period. Under average environmental conditions, our results suggest a doubling time of about 4 years. Given the severe depletion of these populations, (some are less than 5% of their maximum observed levels), recovery to desired levels of spawning biomass should not be expected for at least a decade of minimal mortality caused by fishing.

Carrying Capacity, Initial Stock Size, and α

Haedrich and Hamilton (2000) specify the discrete-time, logistic model, $x_{t+1} = [1 + r(1 - x_t/K) - f]x_t$, where f is the rate of fishing mortality. They adopt the intrinsic growth rate of $r = 0.17$ from Myers and Mertz (1997), a carrying capacity of $K = 3,000,000$ metric tons, and a current stock estimate of $x(0) = 50,000$ metric tons. Based on their analysis, they also come to a sobering conclusion "that the recovery would take more than 20 years" We adopt their parameter values for K and $x(0)$. In our continuous-time model, where during the moratorium $x(t) = K/(1 + \alpha e^{-rt})$, $\alpha = [K - x(0)]/x(0) = 59$.

Ex-vessel Price at $t = T$

Our value for $p = p(T)$ was based on an AR(1) regression $P_{t+1} = aP_t + b$, for prices (CD/mt) as reported in Table 2. The regression results were

$$\begin{array}{l} P_{t+1} = 0.6547951\ P_t + 478.931811 \\ \qquad\qquad (5.6313) \qquad\quad (3.1406) \\ \text{Adjusted } R^2 = 0.5513, \quad \text{F(1,24)} = 31.7114, \quad \text{D.W.} = 2.0015, \end{array}$$

where the t-statistics are given in parentheses below the coefficient. This difference equation has a closed-form solution given by

$$P_t = a^t P_0 + b \sum_{k=0}^{t-1} a^k.$$

As $t \to \infty$, $P_t \to P_\infty = b/(1-a) = \$1,387$. We assume this equilibrium price will be the ex-vessel price when fishing resumes at $t = T$, thus $p = P_\infty = \$1,387$/per metric ton as listed in Table 1.

The Cost Parameter c

The value of $c = \$200,857,000$ comes from Grafton *et al.* (2000, p.573), where they note that the marginal cost of harvest, $c(x) = c/x$, equalled \$353/metric ton in 1989 when the estimated cod stock was $x(1989) = 569,000$ m.t. This implies that c = (569,000 metric tons)(\$353/metric ton = \$200,857,000 CD.

The Discount Rate

Weitzman (2001) surveyed 2,160 economists asking them to indicate the appropriate discount rate for investments that would reduce global climate change. A declining schedule of discount rates best fit the survey data. If a single rate was to be used for public investments to slow climate change or manage fish stocks, Weitzman suggested that $\delta = 0.017$ would best represent that declining schedule. We round up to $\delta = 0.02$.

Table 2: Landings, Value, and Price for the Years 1990 - 2016.

Year	Landings (m.t.)	Value (CD)	Price (CD/m.t.)
1990	395,024	243,822,000	617.23
1991	309,923	227,916,000	735.40
1992	187,953	153,388,000	816.10
1993	76,645	66,325,000	865.35
1994	22,714	29,610,000	1,303.60
1995	12,489	18,133,000	1,451.92
1996	15,544	21,374,000	1,375.06
1997	29,899	35,320,000	1,181.31
1998	37,809	58,792,000	1,554.97
1999	55,478	81,082,000	1,461.52
2000	46,177	65,510,000	1,418.67
2001	40,440	58,459,000	1,445.57
2002	35,741	49,494,000	1,384.80
2003	22,768	33,540,000	1,473.12
2004	24,730	35,415,000	1,432.07
2005	25,156	34,001,000	1,351.61
2006	27,412	37,158,000	1,355.54
2007	26,732	42,868,000	1,603.62
2008	27,837	45,055,000	1,618.53
2009	19,948	24,697,000	1,238.07
2010	17,257	19,862,000	1,150.95
2011	13,038	17,221,000	1,320.83
2012	10,998	14,629,000	1,330.15
2013	10,518	11,997,000	1,140.62
2014	13,001	17,477,000	1,344.28
2015	12,234	17,980,000	1,469.67
2016	18,213	27,786,000	1,525.61

Source: Department of Fisheries and Oceans, Canada. (2017)

5 Optimal Moratoria

For the base-case parameters, when $u = 0$, we can use Equation (7) to determine that $x^* = 1,414,010$ metric tons after a moratorium of $T = 23.31$ years. This steady-state optimal cod stock supports a steady state harvest of $h^* = rx^*(1 - x^*/K) = 127,081$ metric tons. The net present value of the fishery, NPV^*, from the year of moratorium commencement, is \$4.96 billion CD.

These are the same values obtained from Equation (8) as reported in the first row of Table 3. As the annual rate of UI payments increases, the length of the moratorium decreases, *but only slightly*; from 23.31 years to 21.67 years. A longer moratorium supports a larger steady-state stock and harvest, with x^* declining from 1,414,010 mt when $u = \$0$ to 1,209,720 mt when $u = \$200$ million CD, while h^* declines from 127,081 mt to 122,725 mt. The steady-state annual net revenue, π^*, also declines, from \$158 million to \$150 million. NPV^* is the present value of the steady-state fishery net of the present value of UI payments. NPV^* declines from \$4.96 billion to \$1.34 billion as UI payments go from \$0 to \$200 million per year.

Table 3: Optimal Moratoria with UI Payments

u	T^*	x^*	h^*	π^*	NPV^*
0	23.31 years	1,414,010 mt	127,081 mt	\$158 million	\$4.96 billion
\$50 million	22.91 years	1,364,360 mt	126,457 mt	\$157 million	\$4.04 billion
\$100 million	22.52 years	1,314,040 mt	125,540 mt	\$155 million	\$3.12 billion
\$150 million	22.11 years	1,262,650 mt	124,308 mt	\$153 million	\$2.22 billion
\$200 million	21.67 years	1,209,720 mt	122,725 mt	\$150 million	\$1.34 billion

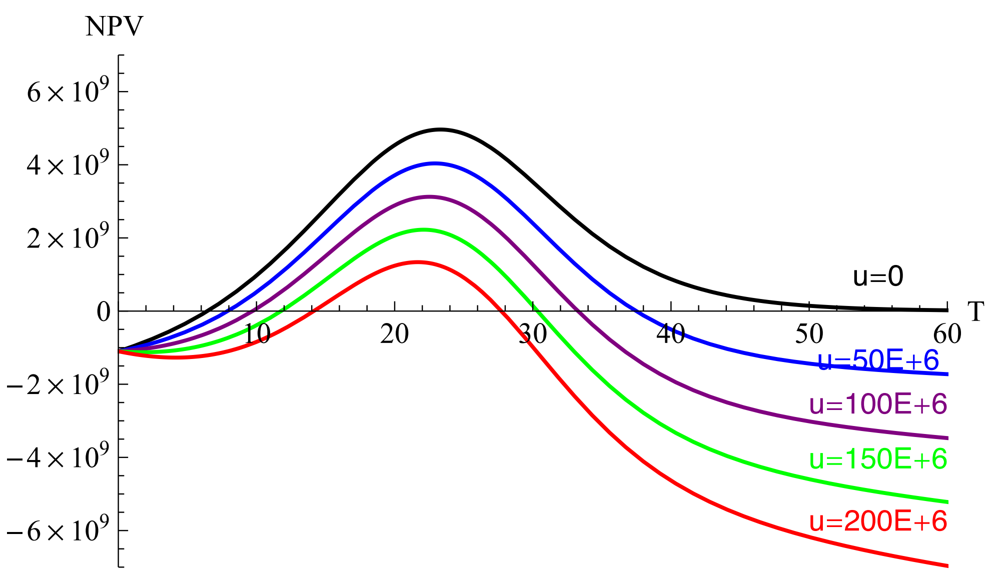

Figure 1: The NPV Curves as u goes from \$0 to \$200 million per year.

In Figure 1 we show the downward shift of NPV as UI payments increase from \$0 to \$200 million per year. Note that the peaks of the NPV curves, which correspond to the values of T^*, only move slightly to the left. If u increases to $u = \$277,054,907$, the optimal moratorium is $T^* = 20.97$, but net present value will have been driven to zero, $NPV^* = 0$.

6 Conclusion

In this article we developed an expression for the net present value of a moratorium in an overfished fishery. During a moratorium the state equation becomes $\dot{x} = F(x)$. If this equation can be solved for an analytic solution or numerical approximation, where $x(t) = G(t)$, then the net present value of a moratorium, net of the present value of UI payments, becomes $\text{NPV(T)} = \pi(G(T), F(G(T)))e^{-\delta T}/\delta - u(1 - e^{-\delta T})/\delta$ and the optimal moratorium is $T^* = \underset{T}{\text{ArgMax}}\ \text{NPV(T)}$. This expression was used to determine the optimal moratorium in the Canadian Northern cod fishery for varying levels of UI.

The data in Table 2 indicate that, in addition UI, the federal government of Canada permitted limited levels of harvest to fishers in isolated fishing communities whose economic livelihood depended critically on the cod fishery. While these positive levels of harvest could be justified on humanitarian grounds, they undoubtedly contributed to a slower recovery of cod stocks, necessitating a protracted moratorium which continues to this day.

Recovery of the cod stocks to a level which would end the moratorium has been further set back by what biologists regard as a significant increase in natural (*not fishing*) mortality that occurred during 2017 [Auld (2018)]. Fisheries biologists estimate that the spawning biomass of cod stocks in NAFO Zones 2J, 3K, and 3L has declined by nearly 30%. This decline appears to be the result of warming ocean waters and a decline in the stocks of capelin and shrimp, which are important prey species for northern cod. It now appears that climate change may be contributing to the earlier effects of overfishing and mismanagement to further imperil the Canadian cod fishery.

References

Auld, A. March, 23rd, 2018. Northern cod stocks show steep decline in once plentiful fishing areas. *The Canadian Press, CTV*.

Baird, J. W., C. A. Murphy, and E. F. Sudden. 1991. Sudden changes in the perception of stock size and reference levels for cod in the northeastern newfoundland shelves. Scientific Council Studies XVI:111-119., North Atlantic Fisheries Organization.

Bishop, C. A., and P. A. Shelton. 1997. A narraitive of nafo divisions 2J3KL cod assessments from extension of jurisdiction to moratorium. Canadian Technical Report of Fisheries and Aquatic Sciences 2199, Fisheries and Oceans Canada, Ottawa.

Clark, C. W. 1976. *Mathematical bioeconomics: the optimal management of renewable resources*. A Wiley-Interscience Publication. John Wiley and Sons.

Department of Fisheries and Oceans, Canada. 2017. Landings and landed value.

Grafton, R. Q., L. K. Sandal, and S. I. Steinshamn. 2000, August. How to improve the management of renewable resources: the case of canada's northern cod fishery. *American Journal of Agricultural Economics* 82:570–580.

Haedrich, R. L., and L. C. Hamilton. 2000. The fall and future of newfoundland's cod fishery. *Society and Natural Resources* 13:359–372.

Myers, R. A., and G. Mertz. 1997. Maximum population growth rates and recovery times for atlantic cod (gadus morhua). *Fishery Bulletin* 95:762–772.

Schrank, W. E. 2005. The Newfoundland fishery: ten years after the moratorium. *Marine Policy* 29:407–420.

Weitzman, M. L. 2001. Gamma discounting. *American Economic Review* 91:260–271.