ON THE OPTIMALITY OF A FISHERY MORATORIUM

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ABSTRACT

While a moratorium that completely closes an overharvested fishery may best facilitate stock recovery, such a policy can be particularly costly for economies dependent on fish consumption for sustenance, or on fishing and fishing-related industries for income and economic well-being. Nevertheless, even if a fishing moratorium is a policy option that should be reserved only for the most dire of circumstances, it is useful to understand the economic consequences both of potentially failing to prevent such a worst-case scenario, and having already mismanaged fisheries to the point of collapse.

In this Master's thesis, we develop a bioeconomic model to evaluate the optimality of a fishing moratorium when costs to labor and capital are taken into consideration. We first present our model analytically, drawing parallels and distinctions between the optimal Faustmann-Wicksell forest rotation and optimal fishery moratorium with *ex gratia* unemployment relief and vessel depreciation payments, deriving an analytic solution for the case of logistic growth, and extending the model to allow for time-varying prices. We subsequently apply our model to a numerical case study of the ongoing moratorium instituted on the Northern Atlantic cod fishery off the Canadian province of Newfoundland and Labrador beginning in 1992.

Under our model and baseline parameter assumptions calibrated to fishery conditions in 1992, we find that the cod moratorium is economically inefficient if the option value of the alternative "business-as-usual" policy to refrain from imposing a moratorium is zero: the costs of annual *ex gratia* unemployment relief significantly outweigh the benefits of increased revenues from greater sustainable post-moratorium harvests. The cod moratorium may become optimal if (i) the intrinsic growth rate of the Northern cod stock is sufficiently high; (ii) the anticipated future net dockside

price of cod is sufficiently high; (iii) the social discount rate is sufficiently low; (iv) the unemployment benefits paid to fishermen during the moratorium are sufficiently low; or (v) the option value of the alternative “business-as-usual” no moratorium policy is severely negative, possibly owing to the risk of potential collapse or even extinction of the stock. However, in the baseline scenario, when compared to an alternative “business-as-usual” policy with an expected economic value of zero, the cod moratorium remains economically inefficient even with cod prices that vary or are forecast using actual price data from Newfoundland over 1990-2016.

BIOGRAPHICAL SKETCH

Brian Bennett Shin received his Artium Baccalarius (A.B.) in Economics from Cornell University in 2011. Post-graduation, he completed a Master of Social Science (M.Soc.Sc.) in Global Political Economy, specializing in the "Global Economy in Politics", at the Chinese University of Hong Kong in 2014, and worked as a research assistant in the same department thereafter. In 2015, Brian returned to Cornell to pursue an additional Master of Science (M.S.) in Applied Economics and Management, concentrating in Environmental, Energy, and Resource Economics, in order to further develop his theoretical research and bioeconomic modeling skills. He plans to continue onward to complete a Ph.D. and pursue an academic career.

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Closer to home, I wish to express the sincerest appreciation and deepest gratitude to my advisors and members of my Special Committee, Prof. Jon Conrad and Prof. C.-Y. Cynthia Lin Lawell, without whose kindness and unwavering patience, guidance, and encouragement during the research and writing process this thesis would not be complete. In particular, I would like to note it was taking Prof. Conrad's undergraduate course in resource economics nearly a decade ago that first ignited my interest in the field, and that I am greatly honored to have been one of Prof. Conrad's last official students before his well-deserved retirement.

I pause here to also acknowledge the memory of the late Prof. Greg Poe, who previously accepted an invitation to serve on my Committee, but sadly and very much unexpectedly passed away early last year. I had looked forward to spending many fruitful years learning from and working together with Prof. Poe, and I dearly hope the work in this thesis reflects some small kernel of the knowledge and values he tried to communicate to me and the other students in his graduate environmental economics class, during the short time I was fortunate to know him.

Lastly, I must of course mention my parents, Paul and Medy Shin, and my sister, Caren. Above all, their unconditional love and support has made my pursuit of this Master's degree possible.

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CHAPTER 1

INTRODUCTION

Fish provide a major and valuable source of nutrition for the global population. According to the Food and Agriculture Organization of the United Nations' most-recent 2018 *State of the World Fisheries and Agriculture Report*, in 2015, fish comprised more than one-sixth (about 17%) of worldwide animal protein consumption; for more than 3 billion persons, fish made up almost one-fifth of their average diet. Although the last two to three decades have seen a rapid expansion in aquaculture whereas capture or wild fisheries production has remained comparatively static, the latter still accounted for just over half (53%; 90.9 million tons) of total world fisheries and aquaculture production (170.9 million tons) in 2016 (FAO, 2018).

Beyond the direct consumption of wild-caught fish, the existence of such capture fisheries is also economically important for the substantial indirect economic benefits that spillover from their presence; especially within those coastal communities best-located to receive these harvests. For example, to preserve freshness until the fish are processed or reach the point of sale requires a ready supply of ice, ensuring a relatively steady source of demand for ice manufacturers. Subsequently, after the fish are landed, they must be sent to appropriate processing facilities onshore if fish-derivative products (e.g., canned sardines or tuna) are desired. Likewise, the vessel construction, upkeep, and repair activity required to maintain a robust fishing fleet is likely to sustain a similarly healthy shipbuilding industry (FAO, 2018).

Unfortunately, it has been well-known for some time that capture fisheries face a serious and global crisis due to long periods of continuous overexploitation, with a number of pessimistic forecasts already made in the 2000s. Most famously, extrapolating the current trend of fisheries collapses ("catches dropping below 10% of the recorded maximum"), a 2006 study by Worm *et al.* projected the complete collapse of *all currently fished taxa* before the middle of the century. While this utmost catastrophic scenario was challenged by other scientists, who cited successful examples of fishery recovery (Buchen, 2009), a later consensus report (Worm *et al.*, 2009) still predicted a "significant fraction" of stocks would remain collapsed without management intervention. Nearly a decade hence, the situation has not much improved: fully one-third (33.1%) of assessed fish stocks monitored by the Food and Agriculture Organization are estimated to be *overfished* ("fished at a biologically unsustainable level") in 2015, with a further 59.9% being fished at *maximally sustainable* (or "fully") fished levels, leaving just 7.0% of marine fisheries *underfished* and with room for further sustainable development (FAO, 2018).

In the pioneering dynamic bioeconomic model of the fishery, first presented by Clark and Munro (1975), society wishes to find the optimal harvest path that maximizes the economic rent derived from fishing. Adopting the seminal work of Schaefer (1954), the population dynamics of the fish stock are described by the differential equation:

$$\frac{dx}{dt} = F(x(t)) - h(t),\ x(0) = x_0 \text{ given,} \tag{1.1}$$

where $x(t)$ is the total fish biomass at time t; $F(x)$ the density-dependent natural net recruitment function of the fish population prior to harvesting; and $h_{\max} \geq h(t) \geq 0$ the rate of harvest, taken to equal fish consumption, and bounded above by the fishing industry's maximum capacity to harvest. It is typically assumed $F(0) = F(K) = 0$, with $F(X)$ continuous and concave such that $F''(X) < 0$, and where $F(X) > 0$ for $0 < X < K$. K denotes the natural carrying capacity or the maximum fish population sustainable by the environment, embodying the tendency of the fish population to grow toward the stable equilibrium at $X = K$ in the absence of harvest (Clark and

Munro, 1975; Clark, 2010).

Additionally, Clark and Munro make the further "standard" assumptions that harvest increases linearly with respect to fishing effort, denoted $E(t)$, and also increases (although perhaps not linearly) in biomass, $x(t)$:

$$h(t) = qE(t)x(t)^{\beta}, \tag{1.2}$$

with $q, \beta > 0$ constant; and that the total cost of harvest, $c^h(\cdot)$, is directly proportional to effort:

$$c^h(E(t)) = aE(t), \tag{1.3}$$

with a being the unit cost of effort. Rearranging (1.2) to make fishing effort a function of harvest, these production and cost functions imply

$$h(t) = qE(t)x^{\beta} \quad \Leftrightarrow \quad E(t) = \frac{h(t)}{qx(t)^{\beta}} \quad \Rightarrow \quad c^h(h(t)) = \frac{ah(t)}{qx(t)^{\beta}};$$

that is, harvesting costs are themselves also linearly increasing in $h(t)$, but a decreasing function in $x(t)$. If the demand for fish is infinitely elastic (as in a large market supplied by many relatively smaller-scale fisheries) such that the price of fish, p, is constant, society faces the following *linear optimal control problem*, wherein the net present value of the fishery is the sum total of harvest revenues discounted at an instantaneous social rate of discount, δ, over an infinite time horizon:

$$\max_{\{h(t)\}} \int_0^{\infty} e^{-\delta t}[p - c^h(x(t))]h(t)\, dt, \tag{1.4}$$

subject to the biological constraint (1.1). The solution is easily obtained by applying the Maximum Principle of optimal control theory (for a detailed proof and exposition of the Maximum Principle, see Weitzman, 2003). Following Clark and Munro (1975), by the Maximum Principle, maximizing the objective functional (1.4) under (1.1) is equivalent to maximizing the *current-value Hamiltonian*:

$$\begin{aligned} H(t) &\equiv [p - c^h(x(t))]h(t) + \psi(t)[F(x(t)) - h(t)] \\ &= [p - c^h(x(t)) - \psi(t)]h(t) + \psi(t)F(x(t)) \\ &= \sigma(t)h(t) + \psi(t)F(x(t)), \end{aligned} \tag{1.5}$$

in which $\psi(t)$ is termed the adjoint or co-state variable; and $\sigma(t) = [p - c^h(x(t)) - \psi(t)]$ a "switching function". There is an optimal steady-state equilibrium x^* determined at the singular solution $\sigma(t) \equiv 0$ to this problem:

$$\sigma(t) = p - c^h(x^*) - \psi(t) = 0 \quad \Leftrightarrow \quad p = c^h(x^*) + \psi(t);$$

for an overharvested fishery, given $x(t) < x^*$ and decreasing harvest costs in biomass $x(t)$ (in other words, at low stock biomass $x(t)$, harvest costs $c^h(x(t))$ are *higher*), it must be that $p < c^h(x^*) + \psi(t)$ or $\sigma(t) < 0$, and the optimal management strategy (which maximizes $H(t)$) is to impose an outright moratorium on fishing until the stock rebuilds to x^*.

However, while completely closing the fishery might best enable a depleted fish stock to recover, Clark and Munro themselves later emphasized how embracing such an extreme, even "draconian" measure might very well entail serious drawbacks (Clark and Munro, 2017; particularly underscoring that the optimality of this "most rapid recovery path" is more a mathematical artifact of the *linear* and *autonomous* nature of their somewhat stylized optimal control problem). Most immediately, human populations dependent on fish consumption for sustenance may be subject to higher food prices and hunger if all fishing must stop. Furthermore, because inputs to harvest cannot be shifted costlessly both into and out of the resource industry (Bjørndal and Munro, 2012), a prolonged moratorium is likely to significantly burden affected economic sectors and communities predominantly dependent on fishing harvest, income, or on downstream fishing-related industries, as we have previously discussed.

Nevertheless, even if a fishing moratorium represents a policy option that should be reserved only for the most dire of circumstances, it is useful to understand the economic consequences both of potentially failing to prevent such a worst-case scenario, and having already mismanaged fisheries to the point of collapse.

In this thesis, we develop a dynamic fishery model to analyze the optimality of a harvest moratorium when costs to labor and capital are taken into consideration. As neither the social benefits nor costs of a moratorium policy are incurred at once in their entirety, but accrue gradually over a potentially substantial or even infinite time horizon, our dynamic model emphasizes the need to account for the temporal dimension of resource management. Rather than limiting our calculus to the immediate benefits and costs of a moratorium, we must instead conduct a dynamic benefit-cost analysis that compares the present discounted value of the entire stream of benefit and cost flows that a moratorium entails.[1]

Drawing upon the classic Faustmann-Wicksell dynamic optimization model of rotational forestry, one can analogously conceive of the optimal length or duration of a fishery moratorium t^* as that which maximizes the net present value of expected future resource rent less moratorium costs from labor unemployment and capital depreciation. Under the capital-theoretic interpretation of fish as productive capital, such a harvest moratorium is equivalent to a capital investment in the resource (Clark and Munro, 1975, 2017). To evaluate whether undertaking this investment is in fact economically efficient therefore requires comparing the value of the optimized moratorium, $NPV(t^*)$, to the value of the alternative "business-as-usual" policy to refrain from imposing a moratorium, when the fishery stays open and fishermen need not be paid *ex gratia* relief,[2], but which risks the potential collapse or even extinction

[1]Such a dynamic cost-benefit analysis is a crucial element in the current debate over the optimal climate change abatement policy (see, e.g., Auffhammer *et al.*, 2016).

[2]An *ex-gratia* ("by favor") payment does not involve the recognition of liability or legal obligation.

of the stock.

We subsequently apply our model to a numerical case study of the ongoing moratorium instituted on the Northern Atlantic cod fishery off the Canadian province of Newfoundland and Labrador beginning in 1992. Under our model and baseline parameter assumptions calibrated to fishery conditions in 1992, we find that the cod moratorium is economically inefficient if the option value of the alternative "business-as-usual" policy to refrain from imposing a moratorium is zero: the costs of annual *ex gratia* unemployment relief significantly outweighs the benefits of increased revenues from greater sustainable post-moratorium harvests.

The cod moratorium may become optimal if (i) the intrinsic growth rate of the Northern cod stock is sufficiently high; (ii) the anticipated future net dockside price of cod is sufficiently high; (iii) the social discount rate is sufficiently low; (iv) the unemployment benefits paid to fishermen during the moratorium are sufficiently low; or (v) the option value of an alternative "business-as-usual" no moratorium policy is severely negative, possibly owing to the risk of potential collapse or even extinction of the stock. Interestingly, on the other hand, neither the initial stock level nor the marginal cost of capital depreciation significantly affect moratorium net present value. Moreover, in the baseline scenario, when compared to an alternative "business-as-usual" policy of no moratorium with an expected economic value of zero, the cod moratorium remains economically inefficient when the dynamic benefit-cost analysis is conducted using cod prices that vary or are forecast using actual price data from Newfoundland over 1990-2016; the cod price never reached nor maintained a sufficiently high level for the moratorium to attain a positive net present value.

The remainder of this thesis is organized as follows. In Chapter 2, we present our theoretical model, drawing parallels between the optimal Faustmann-Wicksell forest rotation and an optimal fishery moratorium with *ex gratia* unemployment relief and vessel depreciation payments, deriving an analytic solution for the case of logistic growth, extending the model to allow for time-varying prices, and extending the benefit-cost analysis to include real options considerations. Chapter 3 applies our model to a numerical analysis of the famous Northern cod moratorium to investigate (i) the economic efficiency of the moratorium; (ii) the comparative statics of optimal moratorium length; and (iii) the effect of allowing for prices that vary or are forecast using actual price data from Newfoundland over 1990-2016. Chapter 4 concludes.

CHAPTER 2

THEORETICAL MODEL AND ANALYSIS

2.1 The Optimal Faustmann-Wicksell Forest Rotation

Prior to formally introducing our dynamic fishery moratorium model, we review as inspiration the Faustmann-Wicksell problem of optimal forestry rotation, drawing heavily on the presentations of forestry in the field of resource economics (Conrad, 2010) and the Faustmann-Wicksell solution in Weitzman (2003). This classic model focuses on the sole owner of a land parcel recently cleared and homogeneously re-planted with tree seedlings, who desires to maximize the net present value π of the ensuing even-aged forest.

In the variant of the optimal forest management problem attributed to Wicksell, after the present stand has been harvested, the land is to be converted to some other, non-forestry, use. It is further assumed that *this future non-forestry use has no further economic interest for the present owner.* What is the optimal length of this *single rotation*?

Let $t = 0$ be the time of reseeding and $Q(t)$ be the volume of merchantable timber as a function of time t, with $Q'(t) > 0$ and $Q''(t) < 0$. The *Wicksell single rotation problem*, which we identify with a subscript w, is then typically stated as if the landowner faces a known, constant net price $p_{\text{net}} > 0$ per unit volume of wood, and discount rate δ, so that the optimization problem of interest seeks to:

$$\max_{t} \pi_w(t) = p_{\text{net}} Q(t) e^{-\delta t}. \tag{2.1}$$

We rewrite (2.1) slightly differently for reasons that shall eventually be apparent. Rather than *net* price, we disaggregate p_{net} into $p > 0$, the *sale* or *spot* price per unit volume of wood; and $c > 0$, the total economic cost of cutting, processing, and transporting the timber to market (as shorthand, we henceforth refer to these economic costs collectively as the *harvest cost*). Next, we recast the landowner as explicitly selling the land parcel once the rotation ends for its *site value* $v > 0$, which we take to be *exogenous* for the time being. Accordingly, the optimization problem becomes:

$$\max_t \pi_w(t) = [pQ(t) - c + v]e^{-\delta t}, \tag{2.2}$$

which reduces back to the traditional formulation (2.1) by subsuming c into p and for $v = 0$.

The optimal single rotation length t^* satisfies the following first-order condition:

$$\begin{aligned} \frac{d\pi_w(t^*)}{dt} &= pQ'(t^*)e^{-\delta t^*} + [pQ(t^*) - c + v](-\delta)e^{-\delta t^*} = 0 \\ \Leftrightarrow \quad & pQ'(t^*) = \delta[pQ(t^*) - c + v]. \end{aligned} \tag{2.3}$$

We observe that equation (2.3) has an important economic interpretation. The left-hand side is the *marginal benefit from waiting* an extra instant dt to cut, which is simply the marginal value of merchantable timber at t^*. On the other hand, the right-hand side of (2.3) is the *marginal cost of waiting* dt to cut; this is the amount earned from harvesting the stand and disposing of the land at t^*, and depositing the proceeds $[pQ(t^*)-c+v]$ in a risk-free bank account paying interest at the competitive rate δ. At the optimal single rotation length t^*, the marginal benefit of waiting equals the marginal cost of waiting, and the landowner is indifferent between the two courses of action.

Equation (2.3) also permits us to examine how the optimal single rotation is affected by changes in p, c, v, and δ. Dividing both sides by p,

$$
\begin{aligned}
pQ'(t^*) = \delta[pQ(t^*) - c + v] \quad &\Leftrightarrow \quad Q'(t^*) = \delta\left[Q(t^*) + \frac{(-c+v)}{p}\right] \\
&\Leftrightarrow \quad \frac{Q'(t^*)}{\left[Q(t^*) + \frac{(-c+v)}{p}\right]} = \delta. \qquad (2.4)
\end{aligned}
$$

When $(-c+v)$ is positive (negative), an increase in price p decreases (increases) the denominator on the left-hand side of (2.4), leading to an overall increase (decrease) on the left-hand side. Given our assumptions on the volume schedule $Q(t)$, to reestablish the equality, $Q'(t^*)$ must correspondingly decrease (increase), which requires a lengthening (shortening) of the single rotation t^*. Consequently, $\partial t^*/\partial p > 0$ if $(-c+v) > 0$, while $\partial t^*/\partial p < 0$ if $(-c+v) < 0$.

The logic underlying these comparative statics of t^* for changes in p is driven by the term $(-c+v)/p$ in the denominator of the left-hand side of (2.4), which represents the ratio of the net benefit $(-c+v)$ earned from rotation's end to the market price of wood p. At a higher p, the unharvested stand acquires a greater economic value relative to the rotation-capping gain or loss. Consider first $(-c+v) > 0$. The prospect of earning net income from the post-rotation land sale initially encourages the landowner to cut and capture it sooner. In this situation, the unharvested stand becoming more valuable through an increase in p provides a countervailing incentive to wait longer before doing so. If $(-c+v) < 0$, the landowner starts off preferring to prolong the rotation and postpone incurring the net expense of selling the bare land. Then an increase in p again effectively dampens the magnitude of this effect, motivating a quicker harvest.

As they only appear once and together on the left-hand side with opposing signs, the effects of increases in harvest cost c and site value v are in unmistakably different directions, and we need only analyze one to deduce the other. An increase in c causes a decrease in the left-hand side denominator, and thereby an increase on the left-hand side proper. To maintain (2.4) we decrease $Q'(t^*)$, lengthening t^*, and implying that $\partial t^*/\partial c > 0$, and $\partial t^*/\partial v < 0$. This makes intuitive sense. A higher harvest cost can be offset by delaying harvest, whereas an increased post-rotation payment encourages a shorter single rotation.

The discount rate δ alone constitutes the entire right-hand side of (2.4), wherefore an increase in δ necessitates the same increase in $Q'(t^*)$ on the left-hand side, shortening t^*, so that $\partial t^*/\partial \delta < 0$. In terms of our prior interpretation of (2.3), a higher prevailing discount rate δ means other economic assets (especially the risk-free bank account paying interest on deposits at δ) offer improved returns on investment. As a capital stock whose own rate of return, as measured by its growth rate, is presumed to be declining in t, the forest is thence no longer competitive with alternative assets at an earlier time. We note this capital-theoretic approach to the forest management problem is most purely manifest in the first-order condition for (2.1); or for (2.2) with c absorbed into p_{net} and under such a circumstance that $v = 0$, for example, when land is abundant:

$$v = 0 \quad \Rightarrow \quad p_{\text{net}} Q'(t^*) = \delta[p_{\text{net}} Q(t^*)] \quad \Leftrightarrow \quad \frac{Q'(t^*)}{Q(t^*)} = \delta. \tag{2.5}$$

Recalling that $Q'(t^*)/Q(t^*)$ is the continuous-time analogue of the growth rate $\Delta Q/Q$, equation (2.5) states that should the land parcel have no intrinsic site value v, the optimal strike point t^* is exactly when the yield on the forest equals the discount rate, or the yield on money in the bank.

The natural extension of the Wicksell single rotation, first proposed by Faustmann, is to ask what the optimal rotation t^* would be if the land parcel were instead devoted to forestry *in perpetuity, for an infinite series of like rotations* of equal length T. Letting c include replanting costs (excepting those for the initial reseeding, which are sunk) in lieu of the "once-and-for-all" payment v, the landowner would receive a net revenue of $[pQ(T) - c]$ following each rotation, at times $t = T, 2T, 3T, \ldots$ ad infinitum. The optimal *Faustmann rotation* T^* is therefore given by the following optimization problem:

$$\begin{aligned} \max_{\{T\}} \pi_f(T) &= [pQ(T) - c](e^{-\delta T} + e^{-\delta 2T} + e^{-\delta 3T} + \ldots) \\ &= \frac{[pQ(T) - c]e^{-\delta T}}{1 - e^{-\delta T}} = \frac{[pQ(T) - c]}{e^{\delta T} - 1}, \end{aligned} \tag{2.6}$$

where $\pi_f(T)$ is the present discounted value of the entire stream of per-period payoffs to the landowner from using the land for forestry; and where we simplify the expression by using the sum to infinity $S_\infty = a/(1 - r)$ of the convergent geometric series of discount factors ($a = e^{-\delta T}$; $|r| = |e^{-\delta T}| < 1$ for all $T > 0$), and multiplying the resulting fraction by $e^{\delta T}/e^{\delta T}$.

Applying the quotient rule to (2.6), the Faustmann first-order condition is given by:

$$\frac{d\pi_f(T^*)}{dT} = \frac{pQ'(T^*)(e^{\delta T^*} - 1) - [pQ(T^*) - c](\delta e^{\delta T^*})}{(e^{\delta T^*} - 1)^2} = 0,$$

which, after dividing through by $(e^{\delta T^*} - 1)$, produces:

$$pQ'(T^*) = \frac{\delta[pQ(T^*) - c]e^{\delta T^*}}{e^{\delta T^*} - 1} = \delta \pi_f(T^*) e^{\delta T^*}. \tag{2.7}$$

But from (2.6), it turns out that:

$$\begin{aligned} \pi_f(T^*) = \frac{[pQ(T^*) - c]}{e^{\delta T^*} - 1} \quad &\Leftrightarrow \quad \pi_f(T^*)(e^{\delta T^*} - 1) = pQ(T^*) - c \\ &\Leftrightarrow \quad \pi_f(T^*)e^{\delta T^*} = pQ(T^*) - c + \pi_f(T^*), \end{aligned} \tag{2.8}$$

and inserting (2.8) back into the right-hand side of (2.7) finally yields:

$$pQ'(T^*) = \delta[pQ(T^*) - c + \pi_f(T^*)]. \tag{2.9}$$

Equation (2.9) reveals the optimality condition for the Faustmann rotation T^* to directly parallel its counterpart (2.3) for the Wicksell single rotation t^* with an explicit site valuation v, and having exactly the same interpretation of being the marginal benefit-cost equilibrium. The only difference is that the *exogenous* parameter v in (2.3) is replaced in (2.9) by the Faustmann formula for $\pi_f(T^*)$, the *endogenous* maximized net present value of freshly reseeded forest land (which is, therefore, the income that would be received from selling such land to another Faustmann forester). This elegant symmetry arises because the future looks exactly identical at the end of every rotation in an infinitude of like rotations.

As $\pi_f(T^*)$ is a function of δ, we return to (2.7) for comparative statics of T^*. Isolating terms involving δ on the right-hand side and then dividing the left-hand side through by p, we obtain:

$$pQ'(T^*) = \frac{\delta[pQ(T^*) - c]e^{\delta T^*}}{e^{\delta T^*} - 1} \quad \Leftrightarrow \quad \frac{pQ'(T^*)}{pQ(T^*) - c} = \frac{\delta e^{\delta T^*}}{e^{\delta T^*} - 1}$$
$$\Leftrightarrow \quad \frac{Q'(T^*)}{Q(T^*) - \frac{c}{p}} = \frac{\delta}{1 - e^{-\delta T^*}}. \tag{2.10}$$

Whilst we recognize (2.10) is distinguished by the disappearance of v from the left-hand side and division by a factor $(1 - e^{-\delta T^*})$ on the right-hand side, the time derivative of the latter is $(\delta e^{-\delta T^*})$, which will be small for realistic choices of δ on the order of a few percent. This justifies that (2.10) is sufficiently similar to (2.4) for the Wicksell rotation that we feel it unnecessary to repeat our previous comparative static analysis in detail. Just as in the Wicksell solution, where $\partial t^*/\partial p < 0$ when $(-c + v)$ is negative, $\partial T^*/\partial p < 0$ in the Faustmann rotation, as the model lacks the v term entirely; and $\partial T^*/\partial c > 0$. Finally, the numerator on the right-hand side of (2.10) dominates the denominator by increasing linearly in δ versus asymptotically to 1 with δ, and $\partial T^*/\partial \delta < 0$.

One last remark concerning the model of optimal forestry management presented in this section. The optimal Wicksell and Faustmann rotation periods t^* and T^* are frequently misleadingly framed as a study in contrasts. By this point, it should be evident that our reformulation (2.2) of the former was intended to stress the actual complementarity between the two. In fact, substituting $v = \pi_f(t)$ into (2.2), the Wicksell problem becomes:

$$\begin{aligned}
\max_t \pi_w(t) &= [pQ(t) - c + \pi_f(t)]e^{-\delta t} \\
&= \left\{ [pQ(t) - c] + \frac{[pQ(T) - c]}{e^{\delta t} - 1} \right\} e^{-\delta t} \\
&= [pQ(t) - c] \left(1 + \frac{1}{e^{\delta t} - 1} \right) e^{-\delta t} \\
&= [pQ(t) - c] \left(\frac{e^{\delta t}}{e^{\delta t} - 1} \right) e^{-\delta t} \\
&= \frac{[pQ(t) - c]}{e^{\delta t} - 1} = \pi_f(t).
\end{aligned} \tag{2.11}$$

Thus, the Wicksell and Faustmann rotations are precisely equivalent when land value is properly determined and accounted for in the economic calculus. Our section nomenclature of "Faustmann-Wicksell" *erat demonstratum*.

2.2 The Optimal Fishery Moratorium with *Ex Gratia* Unemployment Relief and Vessel Depreciation Payments

Drawing parallels between the optimal Faustmann-Wicksell forest rotation and an optimal fishery moratorium with *ex gratia* unemployment relief and vessel depreciation payments, we now develop a dynamic model of a fishery wherein the future stream of increased revenues from greater sustainable harvests in post-moratorium steady-state over an infinite horizon are traded off against the foregone harvest income and moratorium costs.

Consider a fishery severely overexploited to the point of being candidate for immediate moratorium. Suppose the decision to impose a (perfectly enforceable) fishing moratorium of finite length T is proposed. We model this by taking $t = 0$ to indicate the time of closure, with biomass $x = x(t)$ and $x(0) = x_0$ as before in (1.1), but now:

$$h(t) = 0 \quad \Rightarrow \quad \frac{dx}{dt} = F(x(t)),\ 0 \leq t \leq T, \tag{2.12}$$

because harvesting ceases during the moratorium.

To assess the optimality of a fishing moratorium, we must first quantify its social benefits and costs. In doing so, it is imperative to recognize that neither of these benefits nor costs are immediately incurred in their entirety, but accrue gradually over time. Accordingly, a proper benefit-cost accounting necessitates comparing the present discounted value of the entire stream of benefit and cost flows that a moratorium policy entails. On a broader scale, our resulting dynamic model emphasizes the need to account for the fundamentally temporal nature of resource management.

As a renewable resource, if we define harvest to be *indefinitely sustainable* (abbreviated as "sust.") only when it is strictly constrained by the productivity of the stock, i.e., $h_{\text{sust.}}(t) \leq F(x(t))$, we might describe the goal of a moratorium as finding the optimal trade-off from delaying a smaller sustainable harvest today (as $F'(X) > 0$ for X low), in order to reap a stream of greater sustainable harvests tomorrow.[1]

While there will be no economic benefits derived from the fishery until the moratorium is lifted at the future instant $t = T$, it seems a reasonable post-moratorium objective to maintain the fish stock in a steady-state at its post-moratorium level $x(T)$ thereafter. Under such a policy, the maximum sustainable harvest $h_{\text{sust.}}{}^{*}(t)$ will be bounded above by the population growth (stock productivity) at T, $F(x(T))$. Assuming for simplicity that the owner of the fishery is subject to a constant dockside

[1] A moratorium completely eliminates the risk of unsustainable harvests $h_{\text{unsust.}}(t) > F(x(t))$ causing a population crash or extinction, but this consideration does not enter our present derivation of the fishery net present value in our deterministic model.

price p per unit harvest, and social rate of discount δ, the maximum gross discounted economic benefits from the fishery over an infinite time horizon will be the integral of the revenues from the constant maximum sustainable harvest from time $t = T$ to $t = \infty$, as given by:

$$\int_T^\infty pF(x(t))e^{-\delta t}\, dt. \tag{2.13}$$

The economic costs to a moratorium are more concrete in the sense that, for a real-world fishery, they could be calculated from the specific micro- and macro-economic circumstances of the affected dependent sectors, and the details of any government programs that provide *ex-gratia* monetary compensation or other forms of economic relief. For our simple model, however, we restrain consideration of moratorium costs solely to *ex gratia* unemployment payments to labor and those necessary to restore depreciated physical capital.

Specifically, suppose that before they accede to stop fishing, the fishermen demand unemployment relief at a constant rate $u > 0$ during the moratorium $[0, T)$. Moreover, let $A(0) = A^*$ be the minimum capital stock required to safely fish. The capital stock degrades at a rate γ when left unused, so that the cost to re-establish A^*, once the moratorium is lifted, is $c(1 - e^{-\gamma t})$, at a unit capital cost $c > 0$. With a moratorium length T, the gross discounted moratorium costs are given by:

$$\begin{aligned}\int_0^T ue^{-\delta\tau}\, d\tau + cA^*(1 - e^{-\gamma T})e^{-\delta T} &= u\left[\frac{e^{-\delta\tau}}{-\delta}\right]_0^T + cA^*(1 - e^{-\gamma T})e^{-\delta T} \\ &= \frac{u(1 - e^{-\delta T})}{\delta} + cA^*(1 - e^{-\gamma T})e^{-\delta T}. \end{aligned} \tag{2.14}$$

As an overexploited fishery is often the culmination of excessive investment in fishing capacity, from a policy perspective, it is unclear whether the government should actually compensate private market participants for their short-sighted decision-making instead of letting them simply absorb the costs of capital depreciation. One counterargument is that bailing them out creates a situation of moral hazard and a perverse incentive for the fishing industry to continue ignoring long-term sustainability knowing that they are protected from low returns on capital by (essentially) the public purse. In our model, we are agnostic about who pays to restore depreciated physical capital after the moratorium is lifted, allowing the costs to be borne by, for example, either the government or fishermen. Regardless of whose responsibility it actually becomes in practice, this is an overall cost to society that we therefore include in our calculation of social net benefits.

Setting T to be the choice variable t, the fishery manager is presented with the problem of finding the optimal moratorium length $t = t^*$ that maximizes the net present value $NPV(t)$ of the fishery, as given by the present discounted value of the gross benefits (2.13) minus costs (2.14) under (2.12):

$$\begin{aligned} \max_t \; NPV(t) &= -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \int_t^\infty pF(x(\tau))e^{-\delta\tau}\,\mathrm{d}\tau \\ &\text{subject to } \frac{dx}{dt} = F(x(t)) \text{ for } t < t^*,\; x(0) = x_0 \text{ given.} \end{aligned} \tag{2.15}$$

Since the value of the sustained stream of maximally sustainable harvests $pF(x(t))$ will itself be constant if the fish stock $x(t)$ is maintained in steady-state following the end of the moratorium at time t, it can therefore be factored out from the net benefit integral, so that the objective functional becomes:

$$\max_t \left[-\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + pF(x(t)) \int_t^\infty e^{-\delta\tau}\,\mathrm{d}\tau \right],$$

and using that $\int_t^\infty e^{-\delta\tau}\,d\tau = \lim_{T\to\infty} \left[\frac{e^{-\delta\tau}}{-\delta}\right]_t^T = \lim_{T\to\infty} \left[\frac{-e^{-\delta T} - (-e^{-\delta t})}{\delta}\right] = \frac{e^{-\delta t}}{\delta}$, the optimization problem simplifies to:

$$\max_t \left[-\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \frac{pF(x(t))e^{-\delta t}}{\delta} \right]. \tag{2.16}$$

With only one control variable and no constraint, we can directly obtain the first-order condition by differentiating (2.16) with respect to t:

$$\frac{dNPV(t^*)}{dt} = -ue^{-\delta t^*} - cA^*[-\delta e^{-\delta t^*} + (\gamma+\delta)e^{-(\gamma+\delta)t^*}] \\ + \frac{p}{\delta}\left[F'(x(t^*))x'(t^*)e^{-\delta t^*} + F(x(t^*))e^{-\delta t^*}(-\delta)\right] = 0,$$

and canceling common $e^{-\delta t^*} \neq 0$ factors:

$$\Leftrightarrow \quad \frac{pF'(x(t^*))x'(t^*)}{\delta} = pF(x(t^*)) + u + cA^*[(\gamma+\delta)e^{-\gamma t^*} - \delta]$$

$$\Leftrightarrow \quad pF'(x(t^*))x'(t^*) = \delta\left\{pF(x(t^*)) + u + cA^*[(\gamma+\delta)e^{-\gamma t^*} - \delta]\right\}. \qquad (2.17)$$

The structural parallel between the optimal fishery moratorium with *ex-gratia* relief payments for unemployment and vessel depreciation, and the optimal Faustmann-Wicksell rotation as reviewed in Section 2.1 is now very clear. In each case, the respective net present value-maximizing owners wish to ascertain in the present how long to defer the realization of economic gain from the effective conversion of a natural resource into its discounted cash value. For the forester, the endogenously-determined maximized site value $\pi_f(T^*)$ is defined in (2.6) by the infinite stream of discounted net revenues $[pQ(T^*) - c]$ following each like rotation at $t = T, 2T, 3T, \ldots$; similarly, the fishery manager enjoys the post-moratorium infinite stream of maximized indefinitely sustainable harvests with discounted net present valuation $pF(x(t))e^{-\delta t}/\delta$.

A careful examination of the first-order condition (2.17) for the optimal moratorium length with *ex-gratia* relief, t^*, demonstrates that it is analogous to conditions (2.3) and (2.9) for the optimal Faustmann-Wicksell rotation. Consider what would occur if the moratorium were to be extended by an extra instant dt. The marginal benefit from the fishery remaining closed for an additional increment dt is a further increase in the stock of $x'(t)$, which itself causes a rise in the maximally sustainable post-moratorium harvest of $F'(x(t))x'(t)$. The value of this marginal harvest is exactly the left-hand side of (2.17).

The right-hand side of (2.17) reiterates the theme that the opportunity cost of waiting is the foregone interest payment on the income receivable from ending investment in the moratorium "rotation" now. The amount that could be deposited is comprised of the instantaneous value of the current maximum indefinitely sustainable harvest $pF(x(t^*))$, plus the avoided marginal costs of unemployment relief u and capital depreciation $cA^*[(\gamma+\delta)e^{-\gamma t^*}-\delta]$. Thus we conclude that the optimal moratorium length t^* balances the marginal benefits and costs of waiting in a comparable manner to the optimal Faustmann-Wicksell rotation.

We are able to analytically conduct comparative statics of t^* for changes in p and δ. From (2.17), the first-order condition with $c = 0$ is given by:

$$pF'(x(t^*))x'(t^*) = \delta[pF(x(t^*)) + u]$$

and the now-routine operation of dividing through by p and separating δ on the right-hand side yields:

$$\frac{F'(x(t^*))x'(t^*)}{F(x(t^*)) + \frac{u}{p}} = \delta. \qquad (2.18)$$

This has the familiar appearance of the Wicksell condition rearranged for comparative statics (2.4), where in place of $(-c+v)$ we now have the unemployment benefit $u > 0$, so our interpretation of $\partial t^*/\partial p > 0$ for the Wicksell rotation with $(-c+v) > 0$ applies. In essence, the predominant economic pressure on the fishery manager is to end the moratorium earlier and save unemployment costs. When the net dockside price per unit fish p increases, the stream of indefinitely sustainable post-moratorium harvests becomes more relatively valuable, which intensifies the counterbalancing incentive to wait for the fishery to become even more productive. Similarly, just as in both the Wicksell and Faustmann forestry solutions, $\partial t^*/\partial\delta < 0$: an increase in the discount rate decreases the optimal moratorium length.

2.3 The Stock Effect on Harvest Cost

A fishery departs from the analogy of rotational forestry in one potentially important detail: for fish, there is a possibility that there exists some *stock effect*, whereby the cost to harvest is sensitive to the current stock level. The basic intuition underlying this hypothesis is that if there are fewer fish in the water, and fish are or tend to be more uniformly distributed spatially, then fishing vessels will need to expend extra effort to catch the same amount of fish. In contrast, the *sessile* or immobile nature of a forested land parcel ensures that rotational forestry harvest costs should not be density-dependent in this manner (i.e., the cost of cutting down a tree is unlikely to be affected by the number of trees per unit area).

The presumption of a stock effect is typically made for demersal (bottom-dwelling) stocks (e.g., cod), that are considered not as prone to aggregation, unlike pelagic (open water) species (e.g., herring), which are more likely to exhibit schooling behavior as a defense against predators. It is often assumed that harvest costs are independent of stock size for such schooling species, as the unit harvest cost for a targeted school of fish is unrelated to the overall stock level. On the other hand, a smaller stock of a pelagic species might too equally require fishermen to expend extra effort in locating suitable schools of fish (see, e.g., Hannesson, 2007 for a more detailed discussion). A natural outcome of production costs rising as the stock declines is that, theoretically, a stock effect should *increase* the optimal steady-state biomass relative to a scenario where there is no stock effect (Clark, 2010).

Previous empirical research has indeed found a significant stock effect in both demersal and pelagic fisheries, although its strength varies with species' differing ecological characteristics, and the type of gear used in the fishery. For example, Sandberg (2006) reports a stock effect for coastal vessels fishing Norwegian herring, a schooling species, but not for pelagic trawlers or purse seiners, hypothesized to be due to the coastal vessels' lower geographical range. As these boats are restricted to operating in coastal waters, their costs may significantly reduce as the stock becomes more robust, if this means they can spend less time searching for herring schools. Similarly, Hannesson (2007) estimates a significant stock effect in the Norwegian bottom trawling fisheries for haddock, cod, and saithe. Grafton, Kompas, and Hilborn (2007) suggest that overharvested fisheries may especially benefit from rebuilding due to the stock effect: comparing four different fisheries (the Western and Central Pacific big eye tuna and yellowfin tuna, and Australian northern prawn and orange roughy fisheries), they find that the more exploited fisheries would enjoy even greater marginal economic gains from stock rebuilding, with the stock effect notably large at current overexploited biomasses.

To extend our model to incorporate a potential stock effect, we allow our fishery to be subject to the same harvest production and effort cost functions (1.2) and (1.3) assumed by Clark and Munro (1975) reviewed in Section 1. We specifically choose $\beta = 1$, again for simplicity:

$$c^h(h(t)) = \frac{ah(t)}{qx(t)},$$

recalling that a is the unit cost of effort, and q the constant of proportionality in the harvest production function (1.2), often called the (species- or stock-specific) *catchability coefficient*. The profit $\pi(h, x)$ per unit fish is then:

$$\pi(h, x) = R(h) - c^h(h, x) = ph - \frac{ah}{qx} = \left(p - \frac{C}{x}\right) h,$$

and such production-cost dynamics imply a cost of harvest that is simply inversely proportional to the stock level, with $C = a/q$ being a cost parameter specific to each fishery (as it is the ratio of the unit cost of effort, a, to the catchability coefficient, q, which are dependent on the particular fishery, and the species and fishing gear used, respectively). As the inclusion of a stock effect just modifies the net dockside price per unit fish from p to $(p - C/x)$, we may directly make this substitution in (2.16) to give the moratorium optimization problem with a stock effect (abbreviated as the subscript "sto. eff."):

$$\max_t NPV_{\text{sto. eff.}}(t) = \left\{ -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \left[p - \frac{C}{x(t)} \right] \frac{F(x(t))e^{-\delta t}}{\delta} \right\}. \tag{2.19}$$

Evidently, the first-order optimal condition for (2.19) will be nearly identical to (2.17), as the only difference between the two expressions for $NPV(t)$ is in the value of the post-moratorium revenue stream. To understand the impact of a stock effect on t^*, therefore, it is sufficient to compare the derivative with respect to moratorium length t of the present discounted value of the entire stream of post-moratorium revenues when there is no stock effect, to that when a stock effect does exist.

In our earlier derivation of the first-order condition (2.17) for the optimal moratorium length t^* *ignoring any stock effect*, we computed:

$$\begin{aligned} \frac{d}{dt}\left[\frac{pF(x(t))e^{-\delta t}}{\delta}\right] &= \frac{p}{\delta}\left[F'(x(t))x'(t)e^{-\delta t} + F(x(t))e^{-\delta t}(-\delta)\right] \\ &= e^{-\delta t}\left[\frac{pF'(x(t))x'(t)}{\delta} - pF(x(t))\right]. \end{aligned} \tag{2.20}$$

Ignoring the common discount factor $e^{-\delta t}$, we recall from our subsequent discussion of optimality that the first term within the square brackets in (2.20), $pF'(x(t))x'(t)/\delta$, may be interpreted as the marginal *benefit* (to revenue) from extending the moratorium an extra instant dt, being the value of the associated marginal increase in post-moratorium harvest. Conversely, the second term within the square brackets in (2.20), $pF(x(t))$, is the marginal opportunity *cost* (to revenue) of lengthening the moratorium: it represents the foregone income from fishing which would otherwise be received if the moratorium were to be lifted without further delay.

Now compare (2.20) to the first time derivative of the revenue term in the extended moratorium model (2.19), *accounting for a stock effect*, which we evaluate using the product rule:

$$\begin{aligned}
&\frac{d}{dt}\left\{\left[p-\frac{C}{x(t)}\right]\frac{F(x(t))e^{-\delta t}}{\delta}\right\}\\
&=\frac{1}{\delta}\left\{\left[p-\frac{C}{x(t)}\right]\left[F'(x(t))x'(t)e^{-\delta t}-\delta F(x(t))e^{-\delta t}\right]+\frac{d}{dt}\left[p-\frac{C}{x(t)}\right]\left[F(x(t))e^{-\delta t}\right]\right\}\\
&=e^{-\delta t}\left\{\left[p-\frac{C}{x(t)}\right]\frac{F'(x(t))x'(t)}{\delta}-\left[p-\frac{C}{x(t)}\right]F(x(t))+\frac{d}{dt}\left[-\frac{C}{x(t)}\right]\frac{F(x(t))}{\delta}\right\}.
\end{aligned} \tag{2.21}$$

By inspection, the first two terms within the curly braces in (2.21) are clearly analogous to the marginal benefit and cost terms in (2.20), just with the constant net dockside price of fish, p, in the former (with no stock effect), replaced by the variable price $(p - C/x)$ that arises when harvest costs are subject to a stock effect in the latter.

The final term within the curly braces in (2.21), however, is entirely specific to the stock effect scenario:

$$\frac{d}{dt}\left[-\frac{C}{x(t)}\right]\frac{F(x(t))}{\delta}. \tag{2.22}$$

This, then, is the main marginal contribution of a stock effect to post-moratorium revenue. Should there exist such a stock effect, lengthening the moratorium a further instant dt results in a marginal reduction in harvest cost; or, equivalently, an effective increase in the net dockside price, of $d/dt[-C/x(t)]$. (By the quotient rule, $d/dt[-C/x(t)] = Cx'(t)/[x(t)]^2$, which is clearly positive, as $x'(t) \geq 0$ without harvest.) Multiplying this gain in unit price by the present value of the perpetuity of constant post-moratorium harvest $F(x(t))/\delta$ means that (2.22) represents the additional marginal *value* of a stock effect over the infinite horizon of the problem, beyond its impact on the net dockside price. Thus, the presence of a stock effect would augment the benefits from a moratorium, raising both the optimal moratorium length t^* and the optimum post-moratorium steady-state stock $x(t^*)$, as we naturally expect.

2.4 Analytical Derivation: Moratorium on Logistic Growth

We derive the analytical expression for the net present value $NPV_{\text{log.}}(t)$ of a moratorium as a function of time when imposed on a fish stock that exhibits deterministic logistic growth. Suppose that:

$$\frac{dx}{dt} = F(x(t)) = rx(t)\left(1 - \frac{x(t)}{K}\right),\ x(0) = x_0 \text{ given;} \tag{2.23}$$

where r is the intrinsic growth rate of the fish stock, and K the environmental carrying capacity.

Sans harvest, such a population is well-known[2] to follow a sigmoid trajectory:

$$x(t) = \frac{K}{1+\alpha e^{-rt}},\ \alpha = \frac{K - x_0}{x_0}.$$

Here, the maximally sustainable post-moratorium harvest is:

$$\begin{aligned} F(x(t)) = rx(t)\left(1 - \frac{x(t)}{K}\right) &= \frac{rK}{1+\alpha e^{-rt}}\left(1 - \frac{1}{1+\alpha e^{-rt}}\right) \\ &= \frac{rK}{1+\alpha e^{-rt}}\left(\frac{\alpha e^{-rt}}{1+\alpha e^{-rt}}\right) = \frac{\alpha r K e^{-rt}}{(1+\alpha e^{-rt})^2}; \end{aligned}$$

and inserting this into (2.16), the optimization problem becomes:

$$\max_t NPV_{\text{log.}}(t) = -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \frac{p\alpha r K e^{-(\delta + r)t}}{\delta(1+\alpha e^{-rt})^2}. \tag{2.24}$$

[2] By separation of variables (omitting intermediate steps for brevity),

$$\frac{dx}{dt} = rx(t)\left(1 - \frac{x(t)}{K}\right) \quad \Leftrightarrow \quad \int \frac{K}{x(t)(K - x(t))}\, dx = \int \left(\frac{1}{x(t)} - \frac{1}{K - x(t)}\right) dx = \int r\, dt$$

$$\Leftrightarrow \quad \ln\left|\frac{x(t)}{K - x(t)}\right| = rt + C \quad \Leftrightarrow \quad \frac{x(t)}{K - x(t)} = De^{rt},\ \text{and solving for } x(t) \text{ and } D = e^C.$$

In case there additionally exists a stock effect, substituting $P(x) = [p - C/x(t)]$ for p and the analytical expression for $1/x(t)$ into (2.24), the maximand of the optimization problem is further modified to:

$$\max_t NPV_{\text{log., sto. eff.}}(t) = -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \left[p - \frac{C(1+\alpha e^{-rt})}{K}\right] \frac{\alpha r K e^{-(\delta+r)t}}{\delta(1+\alpha e^{-rt})^2}. \tag{2.25}$$

With some careful algebra, we could arrive at the associated first-order condition, but the problem is clearly better suited to being implemented in any standard numerical solver. We take the latter approach in Chapter 3 below.

2.5 Incorporating Time-Varying Prices

We now allow for the possibility that the dockside price of fish, p, may possibly evolve over time during the moratorium. In particular, we examine the case in which p increases *exponentially* at a non-zero rate $g > 0$ over time, such that $p(t) = p_0 e^{gt}$, with $p(0) = p_0$ (given) being the price observed at moratorium's beginning, $t = 0$. Suppose first that the exponential price growth is determined to extend to the infinite horizon, and there is no stock effect on harvest costs. This simply modifies the gross economic benefits from the infinite stream of maximally sustainable post-moratorium harvests (2.13) to:

$$\int_t^\infty p(\tau)F(x(\tau))e^{-\delta\tau}\, d\tau = \int_t^\infty p_0 e^{gt} F(x(t))e^{-\delta t}\, dt = \int_t^\infty p_0 F(x(t))e^{-(\delta-g)t}\, dt, \tag{2.26}$$

and we can thereby define $(\delta - g) \equiv \rho$ as the "effective" discount rate; $p_0 F(x(t))$ still remains constant and can again be factored from the integral as before:

$$= p_0 F(x(t)) \lim_{T\to\infty} \left[\frac{-e^{-\rho T} + e^{-\rho t}}{\rho}\right].$$

The limit evaluates differently depending on the sign of ρ:

$$\lim_{T\to\infty}\left[\frac{-e^{-\rho T}+e^{-\rho t}}{\rho}\right]=\lim_{T\to\infty}\left[\frac{-e^{-\rho T}}{\rho}\right]+\frac{e^{-\rho t}}{\rho}=\begin{cases}\frac{e^{-\rho t}}{\rho}, & \rho>0 \quad \Leftrightarrow \quad \delta>g;\\ \text{divergent}, & \rho\leq 0 \quad \Leftrightarrow \quad \delta\leq g.\end{cases}$$

If $\delta > g$, assuming that price will rise in the future *decreases* the "effective" discount rate, as future discounting, which diminishes the present value of expected net benefits, is offset by price gains, that bolster the expected value of future harvests. Since an *increase* in the discount rate *decreases* the optimal moratorium length, an exponentially increasing fish price that decreases the effective discount rate increases the optimal moratorium length. All else equal, the higher the growth rate in fish price, the longer the optimal moratorium length. The analytic expression for moratorium net present value given logistic growth and exponential price (which we indicate by the subscript "log. x, exp. p" as shorthand) then only differs from (2.24) in having each instance of δ in the last term (representing post-moratorium revenues) replaced by ρ:

$$\begin{aligned} NPV_{\text{log. } x, \text{ exp. } p}(t) &= -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \frac{p\alpha r K e^{-(\rho+r)t}}{\rho(1+\alpha e^{-rt})^2} \\ &= -\frac{u(1-e^{-\delta t})}{\delta} - cA^*(1-e^{-\gamma t})e^{-\delta t} + \frac{p\alpha r K e^{-(\delta-g+r)t}}{(\delta-g)(1+\alpha e^{-rt})^2}. \end{aligned} \tag{2.27}$$

Otherwise, if $\delta \leq g$, i.e., the price of fish is expected to grow exponentially as fast as or even faster than the discount rate, the *effective* discount rate is in fact zero or negative. Economically, the future is weighted *at least* equally, if not greater, than the present, and the notion of trading-off between today and tomorrow becomes meaningless. Rather, in such a situation (when fish are projected to become extremely scarce relative to future demand, for example) it becomes optimal to continue extending the moratorium forever, as the future growth in price dominates the diminishing effect of discounting (or risk-free interest paid by the bank).

Should there be a stock effect, the net dockside price of fish becomes $p(t) = [p_0 e^{gt} - C/x(t)]$, which introduces an additional cost term into post-moratorium harvest profits (2.26):

$$\begin{aligned}\int_t^\infty p(\tau)F(x(\tau))e^{-\delta\tau}\,d\tau &= \int_t^\infty \left[p_0 e^{gt} - \frac{C}{x(t)}\right] F(x(t))e^{-\delta t}\,dt \\ &= \int_t^\infty p_0 F(x(t))e^{-(\delta-g)t}\,dt - \int_t^\infty \left[\frac{C}{x(t)}\right] F(x(t))e^{-\delta t}\,dt.\end{aligned} \tag{2.28}$$

Since we expect harvest costs to *decrease* as the stock recovers, and they are moreover discounted at the original discount rate δ, which exceeds the effective discount rate $\rho = (\delta - g)$ applied to harvest revenues (assuming $\delta > g$), the harvest cost from a stock effect can only dampen the effect of any expected exponential growth in fish price over the short run. In the long run, these costs will too likewise be dominated by exponential price growth.

2.6 The Option Value of an Alternative "Business-as-Usual" Policy

We reiterate that the foundational natural resource economics approach to fisheries management may be more broadly interpreted as the application of capital theory to a dynamic bioeconomic resource. Indeed, in a recent review of their seminal "Golden Rule" for the optimal steady-state fish biomass x^*, which is of course applicable to other natural capital investment decisions, Clark and Munro (2017) relate:

> The American macro-economist Gardner Ackley argues that a clear distinction must be made between the theory of capital and the theory of investment, although they are obviously very closely related. The theory of capital is about stocks, addressing the question of what is the optimal stock of a particular type of capital. The theory of investment is about flows, addressing the question of what the optimal rate is at which a stock

> of capital should be increased, or depleted, if current stock of the capital is below or above the optimal stock level (Ackley 1978).
>
> We modestly lay claim to having been the first to achieve a tractable solution to the Gordon two-part problem, in that we were able to bring forth reasonable fisheries natural capital investment decision rules...

If the choice of whether (or not) to impose a moratorium on an overharvested fishery is to be interpreted as an investment decision, however, its optimality must be evaluated correspondingly *on the basis of its nature as an investment.* Most intuitively, investments are often judged solely on whether they offer a positive return to investment; that is, whether the expected net present value of discounted benefit flows from undertaking the investment project exceed that of costs. This *orthodox theory of investment* results in a "positive net present value" decision rule.

In contrast, Dixit and Pindyck (1994) identify three potential characteristics of investment that cause *option considerations* to become relevant. Firstly, investments may be partially or completely *irreversible*, so that at least some portion of initial expenditures are *sunk* and cannot be recovered even if the investment were able to be undone. Secondly, *uncertainty over future rewards* arises if payoffs (and/or costs) to investment depend at least in part on future economic (and, in the case of biological resources, potentially biological or ecological) circumstances. Thirdly, investment timing is often flexible and affords the potential *opportunity to delay.* In the *real options* approach to investment, this triumvirate is accounted for by considering a firm with the opportunity to invest to be holding an "option": the *right, but not the obligation* to engage in investment. Exercising the right to make said investment ("killing" the option) foregos the associated "option value", which is an opportunity cost that must therefore be included in the benefit-cost analysis.

In our deterministic model of a fishery moratorium, there is naturally no uncertainty as to future rewards. On the other hand, the decision to cease harvest is most definitely irreversible in the sense that on re-opening the fishery, moratorium costs cannot be recovered; and there is, of course, always the opportunity to delay or even refrain from imposing a moratorium altogether. Thus, whereas real options analysis has rarely been applied to the optimal management of fisheries, and more broadly, renewable resources in general (Mezey and Conrad, 2010), we assert it is the appropriate framework within which to evaluate the optimality of resource closure.

Moreover, while accounting for option value typically implies a higher threshold for investment, we argue that the option value of the alternative "business-as-usual" policy to refrain from imposing a moratorium on an overharvested fishery may in fact be severely negative, especially if the stock is at imminent risk of potential collapse or extinction. Again, in a deterministic world, certainly even a miniscule stock can be harvested sustainably over an infinite time horizon. As a starting point for policy, however, we must acknowledge that severely overharvested fisheries are, in the real world, at much greater risk to collapse, whether due to decreased resilience to averse stochastic population shocks, or if there exists a *minimum viable population* required to sustain the stock.

In our stylized formulation, therefore, a lower bound to the social cost of stock collapse can simply be computed as the cost incurred from an immediate stock collapse followed by a compensated moratorium of infinite duration. Assuming that the entire cost of now unemployed capital is paid upfront:

$$\begin{aligned} NPV(\text{collapse, lower bound}) &= -\left[\int_0^\infty ue^{-\delta t}\,dt + cA^*\right] \\ &= -u\lim_{T\to\infty}\left[\frac{-e^{-\delta T}+e^{-\delta 0}}{\delta}\right] - cA^* \\ &= -\frac{u}{\delta} - cA^*. \end{aligned} \tag{2.29}$$

Additionally, although we do not consider these in our numerical case study, there could potentially be further ecosystem goods and services, as well as intrinsic existence or other non-use values, that will be lost if the stock collapses.

CHAPTER 3

NUMERICAL ANALYSIS AND APPLICATION

Beyond the simplest cases, analytical methods can only progress our understanding of the underlying economics in a problem just so far. Even for our basic moratorium model with *ex gratia* relief payments (2.15), the first-order condition for optimality is an implicit differential equation (2.17), and there is no obvious algebraic way to solve for t^*. Analytic solutions are even less tractable when a stock effect is included. Hence, as an illustrative example, we apply our model to a numerical case study of the moratorium instituted on the Northern Atlantic cod fishery off the Canadian province of Newfoundland and Labrador in 1992.

3.1 The Northern Cod Fishery

Prior to its ultimate collapse to commercial extinction in the late 1980s and early 1990s, the cod population in the Northwest Atlantic was the foundation of one of the world's richest fisheries for half a millennium. A contemporary observer reported that the crew of John Cabot's exploratory 1497 voyage through Newfoundland waters had discovered "[t]he Sea there is swarming with fish which can be taken not only with the net but with baskets" (see, e.g., Kurlansky, 1997), a quote well-repeated ironically by environmentalists in the present day.

Throughout the centuries since, the Northern cod fishery drew both migratory fishermen and outright settlers from Europe, sustaining an annual catch that gradually rose from 100,000 to 300,000 metric tons from the eighteenth to late nineteenth centuries, and the development of a provincial economy almost solely based on the harvesting and processing of cod (Haedrich and Hamilton, 2000; Lear and Parsons, 1993).

As the passenger pigeon of fishery mismanagement, the history of the Northern cod collapse has been extensively recounted elsewhere, both in academic and popular literature. To briefly summarize, in the post-WWII years, the fishery suffered two periods of extreme overexploitation. Firstly, initial pressure arrived from overseas in foreign fishing fleets equipped with "factory trawler" technology that expedited, for the first time, fishing on an industrial scale, with foreign harvests peaking in the late 1960s at an obviously unsustainable 700,000 metric tons, *on top of* domestic landings of 120,000 metric tons.

Secondly, when Canada officially declared its sole exploitation rights over all natural resources in the 200-nautical mile Exclusive Economic Zone, as negotiated at the 1977 3rd United Nations Conference on the Law of the Sea (UNCLOS III), the domestic response was not to relax fishing pressure, but rather indulge in a further expansion of harvesting and processing capacity in an already over-saturated industry, driven by nationalistic enthusiasm and overly optimistic assessments of the cod stock.

Unsurprisingly, these eventually precipitated a tremendous decline in harvests that, coupled with increasingly pessimistic estimates of the cod population, paved way for the then-Minister of Fisheries and Oceans to announce a commercial moratorium on the northern cod fishery (the Northwest Atlantic Fisheries Organization (NAFO)/International Council for the Exploration of the Sea (ICES) management unit 2J3KL) in July 1992. For our case study, we use our model to conduct a demonstrative numerical dynamic benefit-cost analysis of the optimality of this moratorium policy.

3.2 Baseline Bioeconomic Parameters

We calibrate our numerical model of the optimization problem (2.16) using official statistics or primary research sources where possible, and use these statistics and sources to justify our construction of supplementary parameters if specific data is not readily available.

For simplicity, we adopt the logistic growth function (2.23) to describe the dynamics of the cod population. The intrinsic growth rate of the cod stock is taken from a report by Myers, Mertz, and Fowlow (1997), who estimate the parameter r for 20 populations of Atlantic cod from various locations. For the 2J3KL stock (Labrador and Northeastern Newfoundland Shelf), they find an approximate intrinsic growth rate of $r = 0.17$. While we use this value of r as a baseline in our model, we additionally conduct a sensitivity analysis of our results across the range $r \in [0.13, 0.35]$. These are the lower and upper bounds for r reported by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) for the Newfoundland and Labrador Atlantic cod population as a whole, encompassing not only 2J3KL but also NAFO/ICES management units 2GH, Northern Labrador; and 3NO, Southern Grand Bank, the latter of which was later placed under moratorium in 1994 (COSEWIC, 2010).

Haedrich and Hamilton (2000) assume the carrying capacity of the cod fishery to be the biomass $K = 3,000,000$ metric tons calculated in 1962, immediately before foreign fleets began intensive harvesting in Newfoundland waters. By the 1992 closure, fishery biomass X was assessed as having declined to just over 20,000 metric tons and continued falling even after that, reaching only 13,000 tons in 1995. For our baseline, we follow Haedrich and Hamiliton (2000) in setting the same parameters K and a "possibly optimistic" initial stock size of $X(1992 :: t = 0) = 50,000$ metric tons, with sensitivity analysis over the interval $X(0) \in [20,000 \text{ m.t.}, 80,000 \text{ m.t.}]$, chosen to include the lower measurement of $X(0)$ and be symmetrical about our baseline $X(0)$.

We find the dockside price of cod p by dividing the 1992 value of Atlantic coast commercial landings of cod in Newfoundland (NFL Total; \$32,145,000) by the volume

(52,323 metric tons) as recorded by Fisheries and Oceans Canada (DFO, 2016a; DFO 2016b), which implies a price of $p = \$614.36$/metric ton (2 d.p.).[1]

Our source for the harvest cost c^h is Grafton, Sandal, and Steinshamn (2000), who used Fisheries and Oceans Canada (DFO) economic and commercial analysis data on a sample of cod fishers in NAFO regions 3K and 3L to determine an average landings-weighted operational cost of $c^h(x(t)) = C/x(t) = \$353$/metric ton in 1989. Given an estimated exploitable biomass of approximately $x(1989) = 569,000$ metric tons, they thus derived the Atlantic cod fishery-specific cost parameter $C = (\$353/\text{metric ton})(569,000 \text{ metric tons}) = \$200,857,000$.

We will first compute our baseline model fixing the harvest cost (i.e., excluding any potential stock effect), before allowing the harvest cost to be subject to a stock effect, as is more likely appropriate to the cod fishery, in order to allow comparison between the two scenarios. Applying the cost function $c_h(x) = C/x$ to the assumed 1992 biomass of 50,000 m.t., however, gives a harvest cost of just over $\$4,000$, more than 6 times the dockside price p calculated by the DFO landings records; fixing c_h at this value would imply harvesting the fishery would *never* be worthwhile. As Grafton, Sandal, and Steinshamn (2000) note, this reflects the fact that the cod stock completely collapsed in 1992, when fishing would have presumably indeed become economically nonviable. Instead, we adopt the fixed harvest cost for the 1990 biomass of 405,000 m.t. reported by Grafton *et al.*, the last year fishing would have been profitable under the 1992 dockside price: $\overline{c_h} = \$200,857,000/405,000 \text{ m.t.} = \$495.94/\text{m.t.}$. Finally, we examine the sensitivity of the stock effect to variation in the 1989 harvest cost across $c^h(h(x(1989)) \in [\$100, \$500]$, corresponding to a range for the cost parameter of $C \in [\$56,900,000, \$284,500,000]$.

[1]We note this and all other prices and costs through the remainder of the Northern cod moratorium case study are denominated in Canadian dollars.

3.3 Moratorium Costs to Labor and Capital

The initial Northern Cod Adjustment and Recovery Program (NCARP) established by the Canadian government in the wake of the cod moratorium incorporated a broad package of economic measures. Beyond ameliorating the direct socioeconomic impact of the moratorium with unemployment insurance for fishermen and financial support for maintenance and upkeep of idle vessels, NCARP also attempted to facilitate ongoing efforts to restructure the fishery for longer-term sustainability by providing incentives for voluntary early retirement, license relinquishment, and skill retraining (Emery, 1992).

We restrict our attention to the direct economic impact of the moratorium on the primary harvesting sector in order to constrain our benefit-cost analysis within a realistic scope. Then the relevant rate of *ex gratia* unemployment relief payments u is the unemployment insurance paid in 1992 to 13,905 *fishermen only*, and excluding workers employed in fish processing (Newfoundland and Labrador Statistics Agency (NLSA), 2017). Income replacement payments ranged from a minimum weekly payment $w = \$225$ to a somewhat more generous maximum $w = \$406$, for those fishermen willing to engage in skill or non-fishery-related job training (Emery, 1992). To obtain the shortest possible optimal moratorium length, we use the upper bound estimate of $u = \$406/\text{fisherman/week} \times 52\ \text{weeks/year} \times 13,905\ \text{workers} = \$293,562,360/\text{year}$; in our sensitivity analysis, we will allow w (and by extension u) to vary over $w \in [\$225, \$360.75]$, and compare these cases to an ideal "frictionless labor adjustment" scenario under which no unemployment benefits are paid out at all ($w = \$0$).

Although direct measurements of fleet capacity such as gross tonnage or horsepower are unfortunately unavailable in the Fisheries and Oceans Canada (DFO) archival statistics, they do tabulate the number of vessels registered by length (in feet) by province and region. We condense this into a single measure A^* by taking a weighted average of all vessels enumerated in the Newfoundland fishery in 1992 (DFO, 2016c). Since the majority of vessels fishing from Newfoundland were in the <35' length category, we define a theoretical "standardized vessel" of 35' and weight all other vessels proportionally to this 35' standard, with the weight being the midpoint of the length category divided by 35'.[2] By this computation, $A^* = 15,280$ "standardized 35' vessels".

Likewise, there is no ready data on the rate or marginal cost of capital (vessel) depreciation, the parameters γ and c. As a rough proxy for the capital depreciation rate γ, we use the maximum tax deductible rate of depreciation,[3] which for the majority of fishing vessels is $\gamma = 0.15$ (Canada Revenue Agency (CRA), 2017). For the marginal cost of capital (vessel) depreciation c, the closest relevant measure we can find is cited in a descriptive analysis of the cod fishery (Roy, 1997), which gives the average investment (after grants) in full-time small boat enterprises to be $c = \$14,429$. As this value is extremely speculative, we add the variation of c over $c \in [\$7,500, \$20,000]$ to our sensitivity analysis and, as with our sensitivity analysis for the weekly individual unemployment benefit w, juxtapose this against an ideal "frictionless capital adjustment" scenario where capital depreciation need not be compensated ($c = 0$).

Finally, we assume a baseline discount rate δ of 2%. As with climate change policy, the choice of discount rate δ in dynamic benefit-cost analysis can be a source of great political contention, as it has perhaps the most far-reaching repercussions of all model parameters on the benefit-cost outcome. Whilst we have heretofore taken the perspective of a net revenue-maximizing sole fishery manager, we elect not to use

[2]For example, a vessel falling in the 50'-54'11" length category would have weight 52.5'/35' = 1.5, and thus be considered equivalent to 1.5 "standardized 35' vessels". We set the "midpoints" of the <35' and >100' length categories to be 35' and 100', respectively.

[3]In Canada, this is termed the *Capital Cost Allowance*.

a discount rate appropriate for private industry reflective of the market competitive opportunity costs of capital, which the Intergovernmental Panel on Climate Change (2007) considers to be on the order of 4-6% in developed countries. Rather, we choose a lower discount rate that is more representative of the *social rate of time preference*. More recent studies argue that uncertainty in risk-free returns over the long time horizons relevant to environmental policy should dictate a decreasing discount rate over time. The 2% discount rate we adopt corresponds to approximately a "*medium* future" period of consideration, "within 26 to 75 years hence", as recommended by Weitzman (2001). We examine moratorium optimality under discount rates closer to market values ranging upward to $\delta = 0.1$ in our comparative statics analysis.

3.4 Results

Using the baseline parameter values for the Northern cod fishery discussed above and summarized in Table 3.1, we numerically compute the present discounted valued $NPV(t)$ of the entire stream of net benefits from a moratorium as a function of the moratorium length t. As seen in Figure 3.1, our results show that the optimal moratorium length for the Northern cod fishery using the baseline parameter values is $t^* = 0$ years. Thus, under our model and baseline parameter assumptions calibrated to fishery conditions in 1992, and the further assumption that the value of the alternative "business-as-usual" policy to refrain from imposing a moratorium is zero, the cod moratorium is economically inefficient.

In its initially overexploited state ($t = 0$), the minuscule sustainable annual harvest ($F(x(t))$, the dotted green curve) that can be supported by the meager surviving fish stock ($F(X_0 = 50,000$ metric tons$) \approx 8,360$ metric tons) is naturally very low. If the net dockside price is fixed at the mean recorded 1992 price per metric ton of landed cod less the 1990 harvest cost $p - \overline{c_h} = \$118.42$, the present discounted value of the

Par.	*Description*	*Baseline Value*	*Source*
r	intrinsic growth rate of cod population	0.17	Myers, Mertz, and Fowlow (1997)
K	environmental carrying capacity (metric tons, m.t.)	3,000,000 m.t.	Haedrich and Hamilton (2000)
$x(0)$	initial (1992) stock biomass	50,000 m.t.	Haedrich and Hamilton (2000)
p	dockside price/m.t. cod	\$614.36	DFO (2016a, 2016b)
$\overline{c_h}$	fixed harvest cost/m.t. cod *(no stock effect scenario)*	\$495.94	Grafton, Sandal, and Steirshamn (2000)
C	fishery-specific harvest cost parameter *(stock effect)*	\$200,857,000	Grafton, Sandal, and Steirshamn (2000)
w	weekly individual unemployment benefit	\$406	Emery (1992)
u	aggregate yearly unemployment benefits	\$293,562,360	NLSA (2017); Emery (1992)
A^*	fleet req. to safely fish (standard. 35' vessel equiv.)	15,280 boats	DFO (2016c)
γ	capital depreciation rate	0.15	CRA (2017)
c	marginal cost of capital depreciation	\$14,429	Roy (1997)
δ	social discount rate	0.02	Weitzman (2001)
$\boldsymbol{t^*}$	**optimal moratorium length**		**0 years**

Table 3.1: *Baseline bioeconomic parameters used in numerical model and resulting optimal moratorium length* t^*.

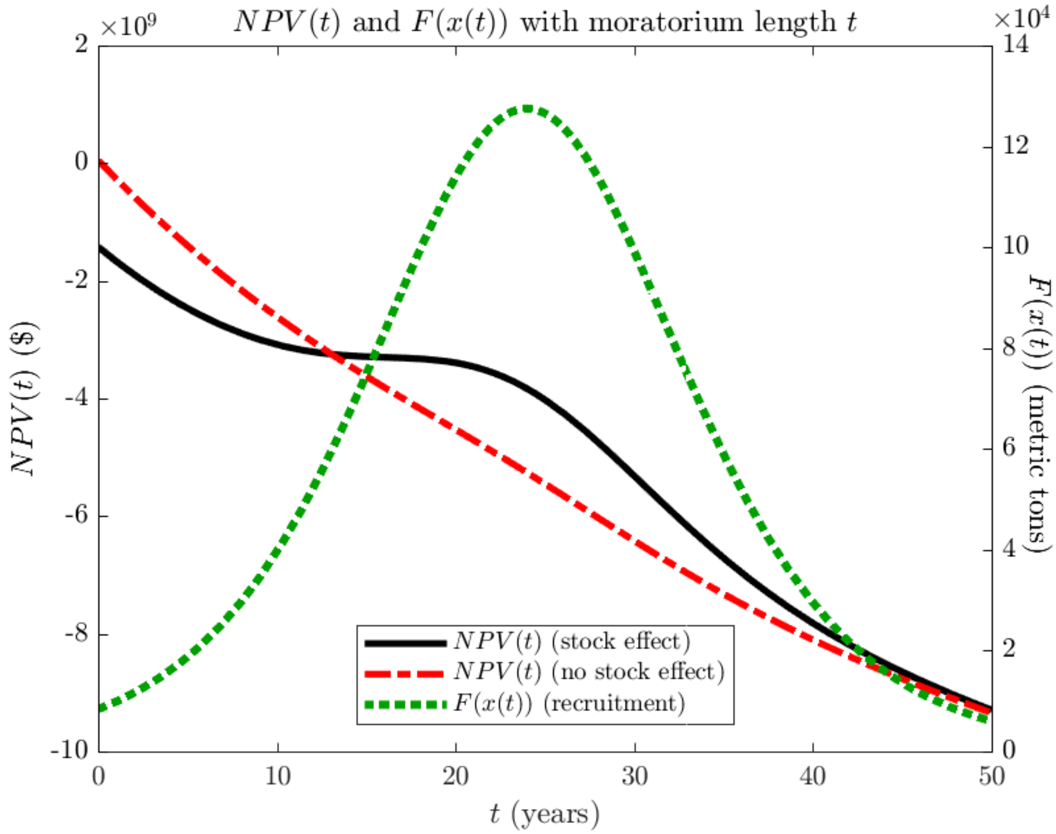

Figure 3.1: *Net present value $NPV(t)$ of a moratorium with (solid black) and without (dot-dashed red) a stock effect on harvest cost; and post-moratorium stock recruitment $F(x(t))$ (dotted green) in the deterministic Northern cod fishery model as a function of moratorium length t.*

revenues that would be earned without a moratorium if the fishery were maintained at its initial state in perpetuity (by restricting harvest to the annual sustainable maximum of 8,360 metric tons) is merely \$49.5 million. As this is vastly exceeded by the assumed total yearly unemployment benefits of approximately $u \approx \$293.6$ million, the net present value curve $NPV(t)$ for the fishery with no stock effect (the dot-dashed red curve) in Figure 3.1 falls below \$0 extremely quickly, and remains negative over the entire simulated half-century. In fact, unemployment costs dominate post-moratorium harvest revenues to such an extent that in the *no stock effect* scenario, the $NPV(t)$ curve is essentially negative and linear: extending the moratorium only serves to incur additional unemployment costs that increased harvests are nowhere near sufficient to cover.

Conversely, accounting for a stock effect has a major effect on the shape of the $NPV(t)$ (solid black) curve. For short moratorium lengths of about a decade or less, the stock effect causes the net present value to be even *lower* than when any stock effect is ignored. This is because at such low stock levels, harvest costs are extremely high and exceed the received dockside price, and fishermen would consequently incur losses on their harvest. With enough time, however, the stock recovers (and harvest costs fall) to the point that fishing becomes more profitable than in the no stock effect case, and the solid black $NPV(t)$ curve (for the cod fishery with stock effect) rises above the dashed red $NPV(t)$ curve (no stock effect), and remains there for the duration of the time interval of interest. This demonstrates that, at least for the northern cod fishery, the stock effect is important and should be taken into consideration when studying moratorium optimality. Nevertheless, even after additionally accounting for a stock effect in our baseline mode, the cod moratorium remains economically inefficient.

The curvature of the $NPV(t)$ (with stock effect) curve is also affected by the cost of continuing the moratorium slowly decreasing in present value terms with t, due to the future being more heavily discounted and the lessening magnitude of capital depreciation (since at a constant rate of depreciation, an increasingly smaller amount of capital remains to be depreciated over time, and $A^*(t)$ decreases exponentially). Simultaneously, as the moratorium increases in length, the density-dependence of the natural growth function $F(x(t))$ begins to assert itself, with its rate of change $F'(x(t))$ (the slope of $F(x(t))$) incrementally accelerating from $t = 0$ until it reaches a roughly constant rate some time more than a decade afterward.

Taken together, these two complementary trends gradually flatten the $NPV(t)$ curve from its immediate decline to about $t = 20$ years, when the fishery approaches its most productive (i.e., the maximum sustainable yield (MSY), which occurs when the biological production $F(x(t))$ is at its peak). When the stock exceeds the point of maximum sustainable yield, additional population growth becomes constrained by the environmental carrying capacity and decreases, limiting the sustainable harvest, and causing $NPV(t)$ to decline once more.

Our sensitivity analysis of the effect of the fishery-specific harvest cost stock effect parameter C on the net present value curve $NPV(t)$ (Figure 3.2) likewise illustrates that the effect of variation in C lessens as the moratorium lengthens and cost and revenue flows become more discounted. Although there is a difference of about \$150 in per-unit harvest costs at MSY (which occurs at $X_{MSY} = K/2 = 1,500,000$ m.t. under logistic growth) between the smallest (red) and largest (blue) values of C, by the time the stock has recovered to this extent, the discount factor has reduced the distance between the red and blue $NPV(t)$ curves substantially. Nevertheless, across all values of the fishery-specific harvest cost stock effect parameter C we analyze, the cod moratorium is economically inefficient.

3.5 Sensitivity Analysis

We additionally conduct sensitivity analyses of our results to the intrinsic growth rate r; the initial (1992) stock size X_0; the weekly individual unemployment benefit w; the marginal cost of capital depreciation c; the net dockside price per unit fish p; and the social discount rate δ, by simulating $NPV(t)$ for the different potential values of these parameters previously discussed in Sections 3.2 and 3.3, *ceteris parabus*.

Figure 3.3 plots the sensitivity analysis of variation in the *biological* parameters r (upper panel) and X_0 (lower panel), with the curves colored as a rainbow spectrum

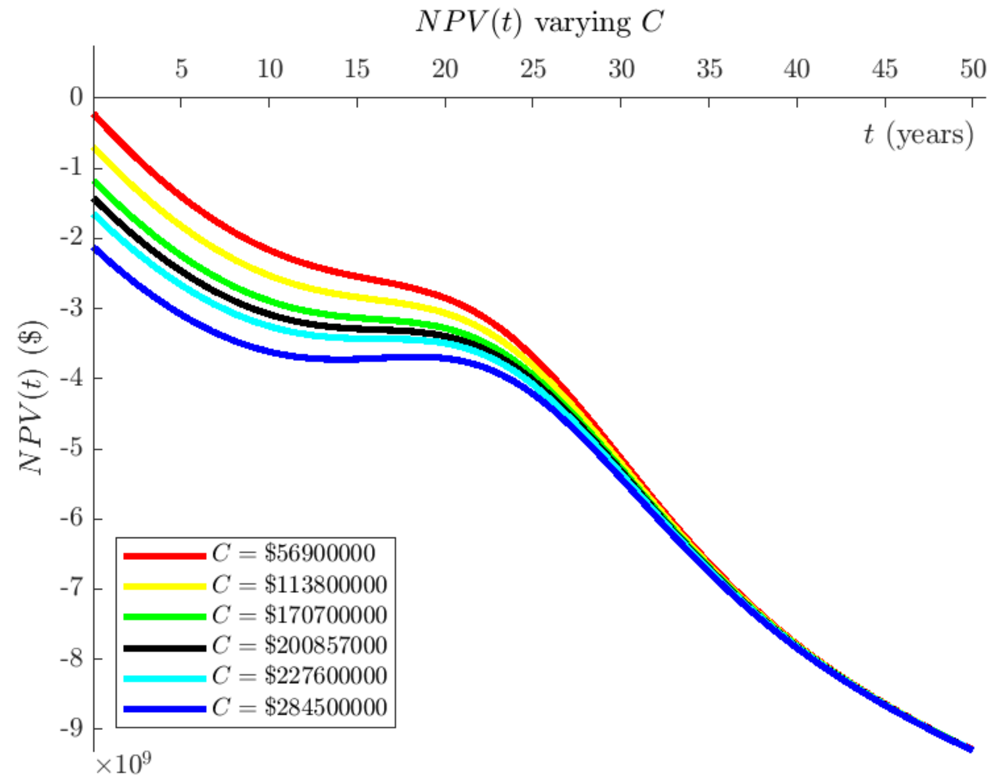

Figure 3.2: *Sensitivity analysis of $NPV(t)$ for the fishery-specific harvest cost stock effect parameter $C \in [\$56.9\ mil., \$284.5\ mil.]$. Curves colored according to a rainbow spectrum with red corresponding to the lowest value of the respective parameter, and blue to the highest. The baseline curve is plotted for reference in black.*

such that red indicates the lowest parameter value; and blue, the highest, and the baseline curve included for reference in black. We see that a relatively small increase in the intrinsic growth rate r significantly affects the shape of the $NPV(t)$ curve. A rise in r and therefore the stock productivity both shortens the time required for the stock to reach maximum sustainable yield, as well as raising the maximum sustainable yield itself. This is shown by the $NPV(t)$ peak moving leftwards (in the direction of decreasing optimal moratorium length) and upwards (higher $NPV(t^*)$), as r ranges from low (red) to high (blue). Indeed, for $r = 0.30$ and $r = 0.35$, the $NPV(t)$ curve peaks at some positive $NPV(t^*) > 0$, implying a non-zero optimal moratorium length $t^* > 0$.

Conversely, the results of our deterministic model are rather less sensitive to variation in the initial stock X_0 (Figure 3.3, lower panel). At the very low initial stock levels of the cod fishery ($X_0 \approx 1.67\%$ of K), changes in X_0 elicit a small, albeit discernible response from $NPV(t)$. As with r, starting at a slightly larger X_0 means the stock will reach maximum sustainable yield a little more quickly, and the $NPV(t)$ peak moves leftwards from low (red) to high (blue) values of X_0. On the other hand, the maximum sustainable yield remains the same in all scenarios, so that the only effect of increasing X_0 on fishery value (the *height* of $NPV(t)$) is that it is marginally less costly to reach t^* earlier. As such, the $NPV(t)$ curves also shift upwards as X_0 ranges from low (red) to high (blue), although with much less distance between them than for r.

Figure 3.4 plots the sensitivity analysis of variation in the *economic cost* parameters w (upper panel) and c (lower panel). It is immediately clear that lowering the weekly individual unemployment benefit w (moving in the opposite direction, from *blue* to *red*), noticeably increases the net present value of a moratorium. However, the $NPV(t)$ curve still does not have a positive maximum at a non-zero $t > 0$ under the actual lower bound $w = \$225$; even if the Newfoundland government had limited weekly individual unemployment payments to the bare minimum, a moratorium would continue to remain economically inefficient in our model. On the other hand, $NPV(t)$ is strongly positive for a moratorium length $t \in [12.5, 45]$ years in the ideal scenario of frictionless labor adjustment (the highest, red curve); implying that within the interval $w \in [\$0, \$225]$, there exists some positive interval of w for which both $NPV(t^*) > 0$ and $t^* > 0$. In fact, varying w further below the minimum weekly *ex-gratia* unemployment relief payment made under the Northern Cod Adjustment

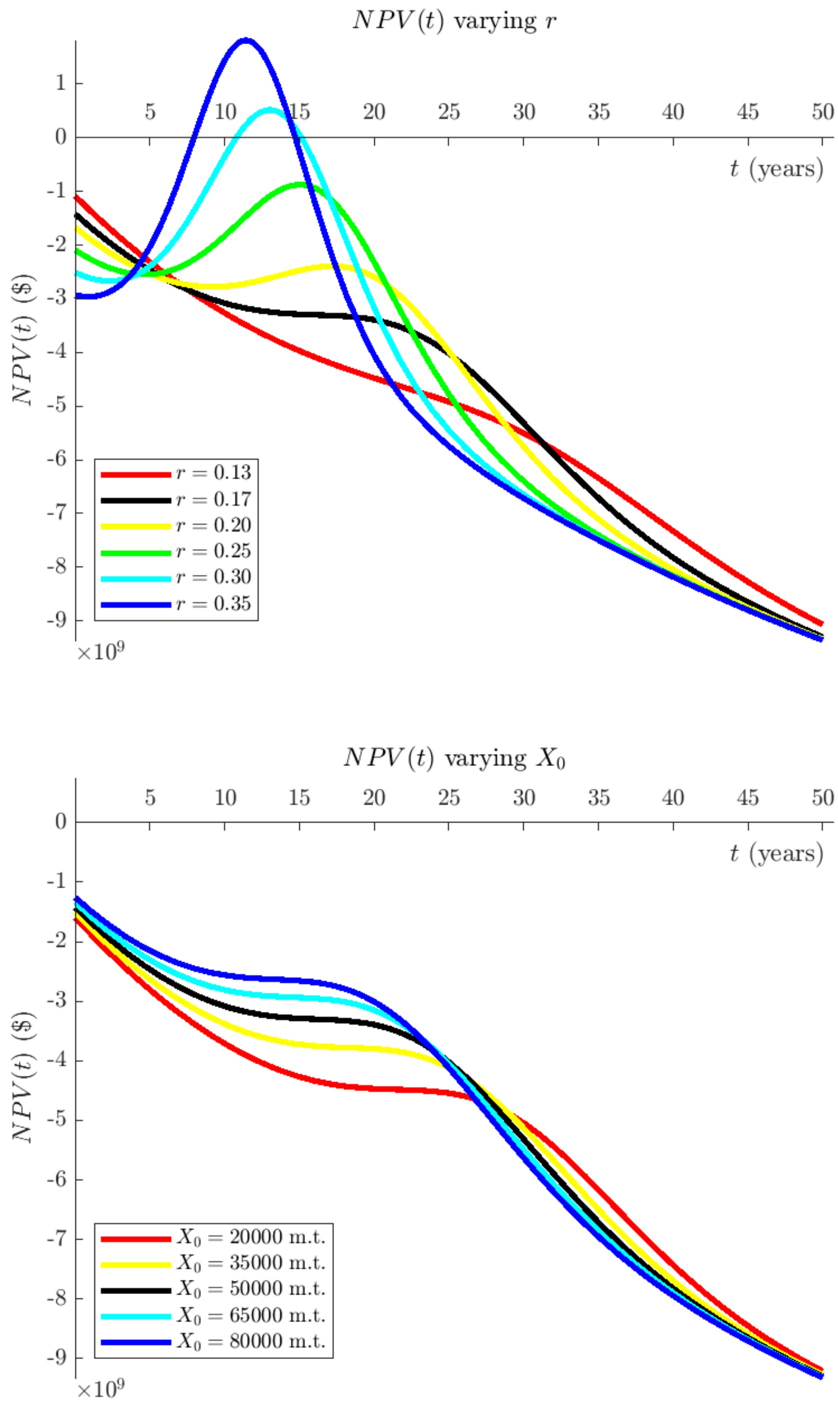

Figure 3.3: *Sensitivity analysis of $NPV(t)$ for intrinsic growth rate $r \in [0.13, 0.35]$ (upper panel), and initial biomass $X_0 \in [20,000$ m.t.$, 80,000$ m.t.$]$ (lower panel). Curves colored according to a rainbow spectrum with red corresponding to the lowest value of the respective parameter, and blue to the highest. The baseline curve is included for reference in black.*

and Recovery Program (NCARP), we see that $NPV(t^*)$ has a slightly positive peak at $w = \$112.50$: the cod moratorium would have had a positive net present value and an optimal moratorium length of $t^* \approx 23$ years with weekly *ex-gratia* unemployment relief payments of this amount or less.

In comparison to w, the marginal cost of capital depreciation c has little or no apparent bearing on $NPV(t)$ whatsoever; even the (red) $NPV(t)$ curve for frictionless capital adjustment ($c = \$0$) is barely distinguishable from its other rainbow-colored counterparts. To understand this, we recall that fishing capital is assumed to depreciate exponentially, and the associated costs are further discounted when expressed in net present value terms. Consequently, after the marginal cost of depreciation is multiplied by the exponential rate and discount factors, its ensuing impact on $NPV(t)$ is ultimately negligible compared to unemployment costs.

Figure 3.5 plots the sensitivity analysis of variation in the net dockside price per unit fish p (upper panel) and the discount rate δ (lower panel); these results are also summarized in Table 3.2. The behavior of $NPV(t)$ as the net dockside price per unit fish p increases is very straightforward. Revenues are greater and the $NPV(t)$ peak clearly becomes proportionately more prominent. It is difficult to distinguish visually, but the exhaustive numerical computation of t^* varying p in Table 3.2 demonstrates that $\partial t^*/\partial p > 0$ also, confirming our prior analytic result (see the discussion of equation 2.18).

In contrast, a higher discount rate signifies that present cash flows are weighted even more heavily with respect to future net benefits, flattening the $NPV(t)$ curve. At competitive market rates, the $NPV(t)$ peak associated with the maximum sustainable yield disappears entirely. Analytically, increasing the social rate of discount δ on the right-hand side of (2.18) must be accompanied by an increase on the left-hand side in $F'(x(t^*))x'(t^*)$. From the concavity of the logistic growth function $F(X)$ ($F''(X) < 0$),

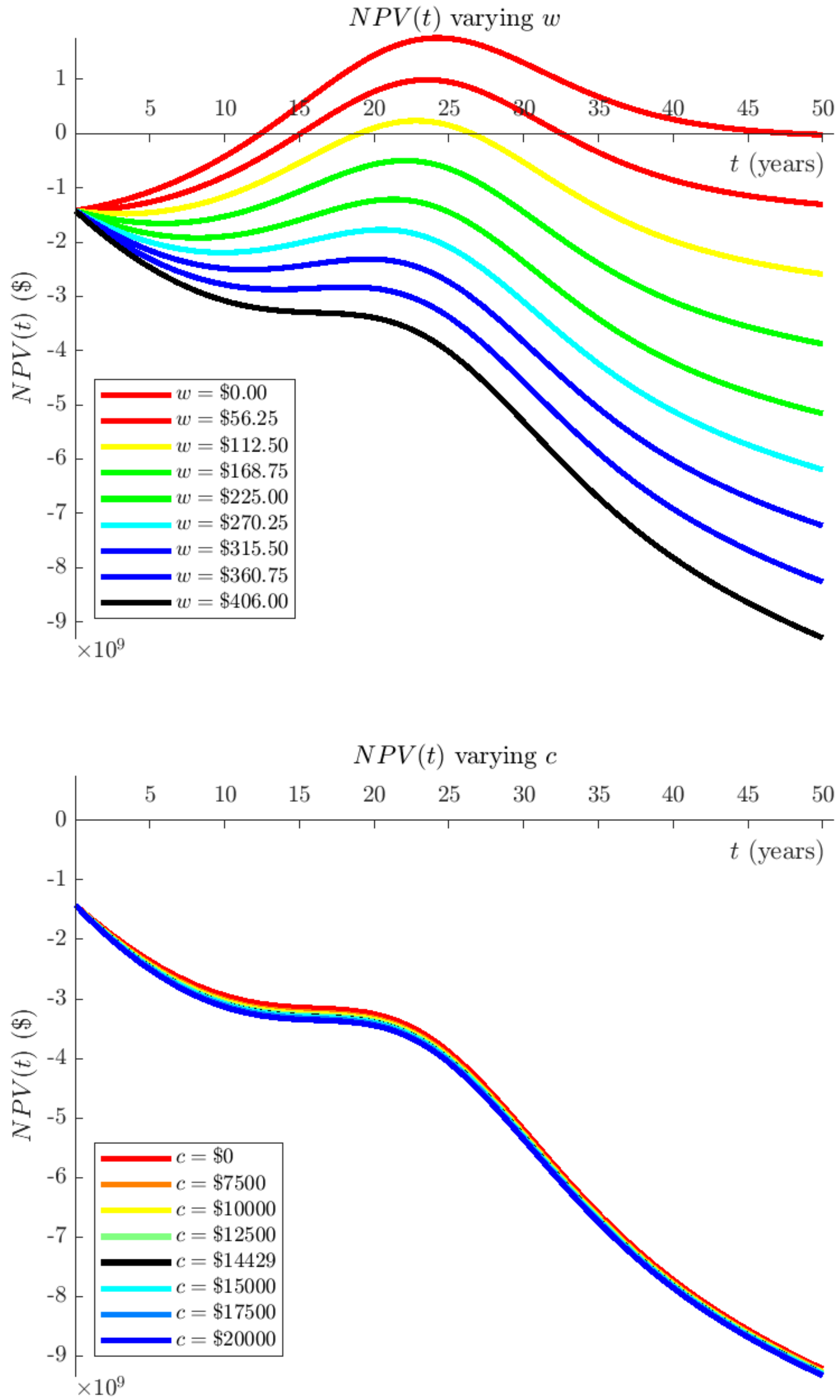

Figure 3.4: *Sensitivity analysis of $NPV(t)$ for the weekly individual unemployment benefit $w \in \{[\$0, \$360.75]\}$ (upper panel), and marginal cost of capital depreciation $c \in \{\$0; [\$7,500, \$20,000]\}$ (lower panel). Curves colored according to a rainbow spectrum with red corresponding to the lowest value of the respective parameter, and blue to the highest. The baseline curve is included for reference in black.*

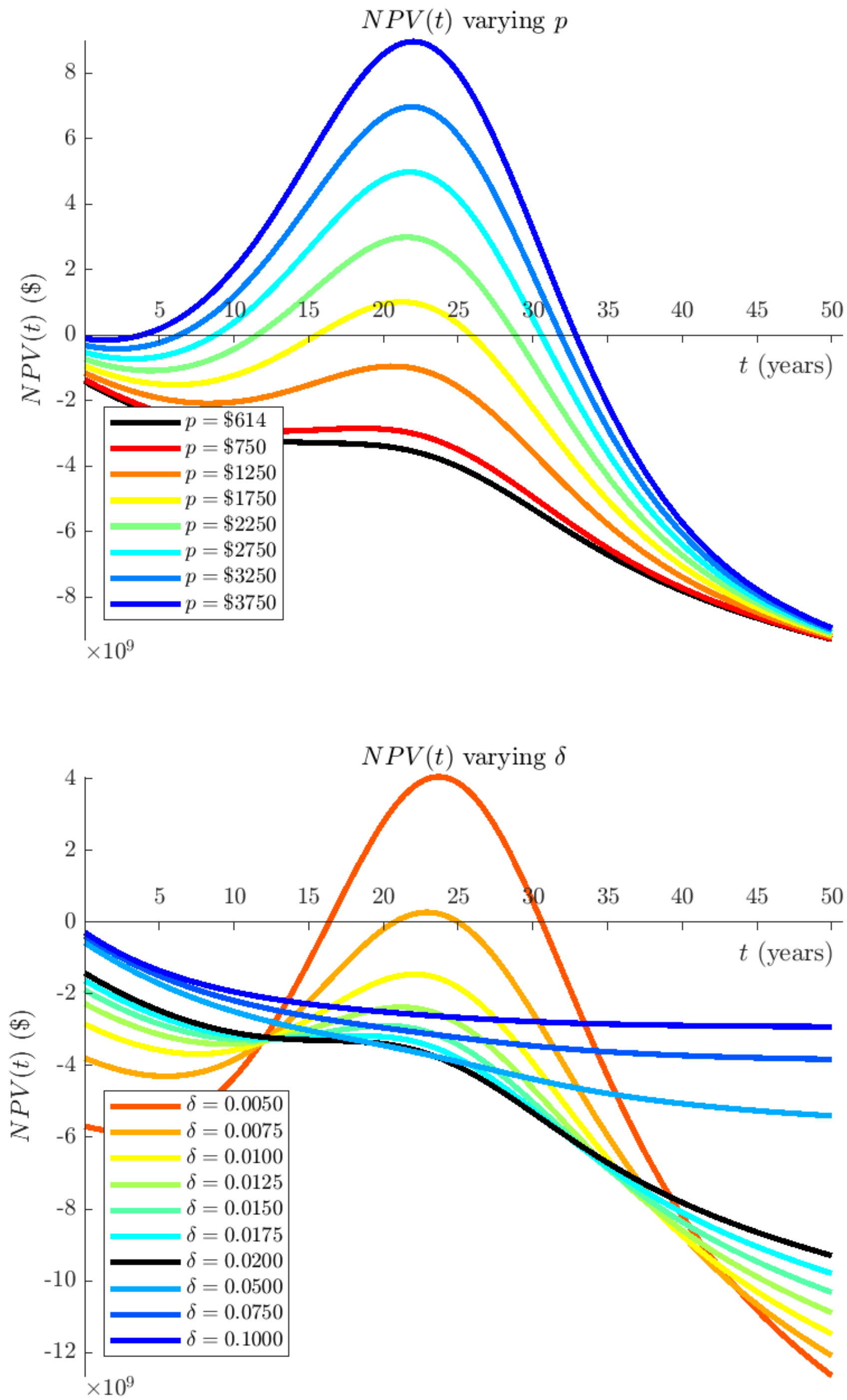

Figure 3.5: *Sensitivity analysis of $NPV(t)$ for the net dockside price per unit fish p (upper panel), and discount rate δ (lower panel). Curves colored according to a rainbow spectrum with red corresponding to the lowest value of the respective parameter, and blue to the highest. The baseline curve is included for reference in black.*

p	t^* (years)
\$750	0
\$1,250	20.6075
\$1,750	21.2365
\$2,250	21.5583
\$2,750	21.7557
\$3,250	21.8895
\$3,750	21.9863

δ	t^* (years)
0.0050	23.7019
0.0075	22.9122
0.0100	22.0853
0.0200	0
0.0500	0
0.0750	0
0.1000	0

Table 3.2: *Selected comparative statics of optimal moratorium length t^* across variation in net dockside price per unit fish p and discount rate δ.*

this results in a shortening of the optimum moratorium length t^*. At a sufficiently high discount rate, $NPV(t)$ becomes entirely negative, and we should not impose a moratorium of any length at all.

3.6 Varying the Real Price of Cod

To examine whether and how the price of cod varied over the time period of our analysis, we use the entire on-line archive of Seafisheries Landings data for the Atlantic Regions from Fisheries and Oceans Canada (DFO, 2016d) to construct a time series of the average price of Atlantic cod recorded in Newfoundland from 1990 to 2016, for which annual landed commercial value and quantity data is available. Figure 3.6 plots annual landings and both nominal and real price (in 1992 dollars) of cod over these years. The real cod price is calculated by deflating the computed nominal cod price using the Newfoundland and Labrador CPI for the basket of all items recorded by Statistics Canada (2017), with the CPI re-indexed to a 1992 base.

Surprisingly, we see in Figure 3.6 that the real cod price only increased for a few years after the moratorium, peaking in 1998 at just under \$1,500/metric ton. This possibly suggests that after a few years of adjustment to moratorium conditions, landings of Icelandic or Norwegian cod had become adequate to close the shortfall in

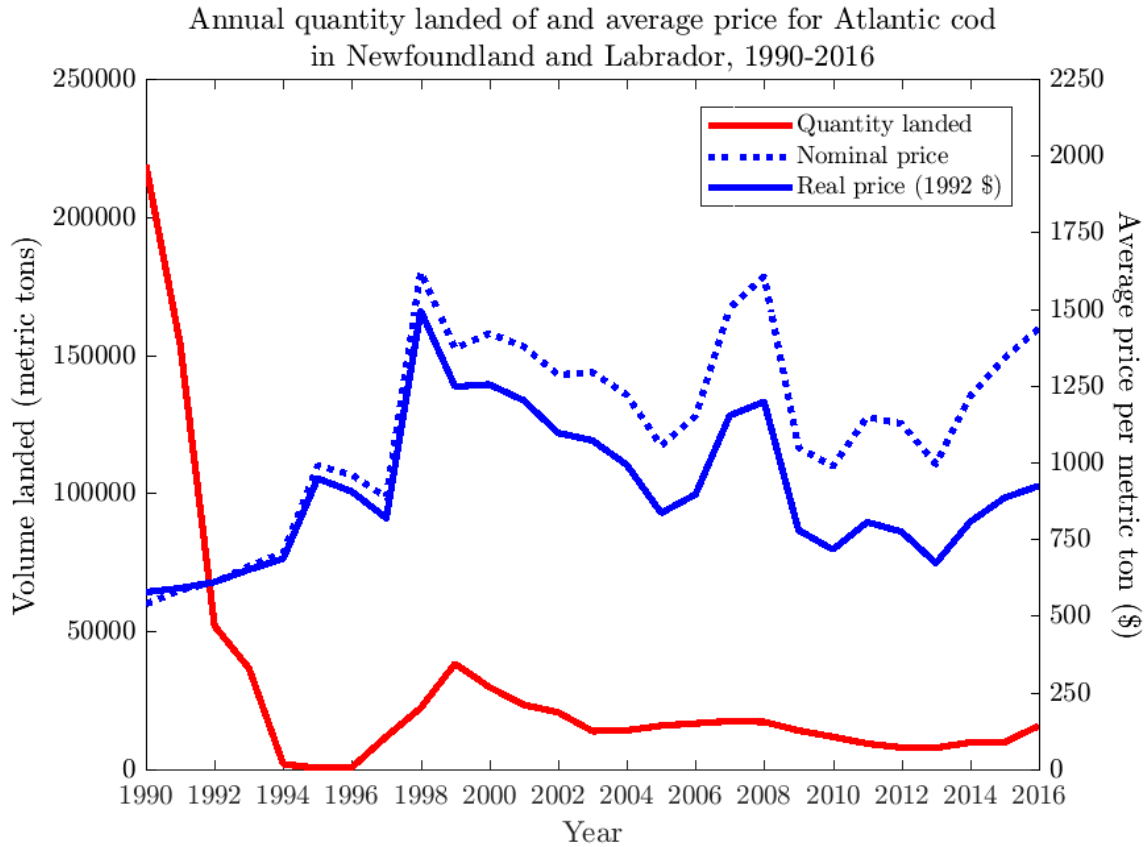

Figure 3.6: *Annual landings (solid red); and average nominal (dotted blue) and real price (in 1992 dollars, solid blue) of Atlantic cod in Newfoundland and Labrador, 1990-2016. Landed quantity and commercial value data from Fisheries and Oceans Canada (DFO, 2016d); CPI data from Statistics Canada (2017).*

cod supply; or that other groundfish species gained acceptance as suitable substitutes in fish markets in North America.

To assess if *anticipating* a higher price for cod may have affected the optimality of the cod moratorium policy, we recompute the net present value curve $NPV_{2016}(t)$ as a function of the cod moratorium length, but now evaluated at the most recent available real price of cod (for the year 2016, in 1992 dollars), p_{2016} = \$927.97/metric ton. As an upper bound, we also compute the net present value curve $NPV_{p_{max}}(t)$ using the maximum observed real cod price over the period 1990-2016, \$1,498.50/metric ton, recorded in 1998. In Figure 3.7, we compare these two new $NPV(t)$ curves against the original baseline, $NPV_{1992}(t)$, including again a background plot $F(x(t))$ as reference.

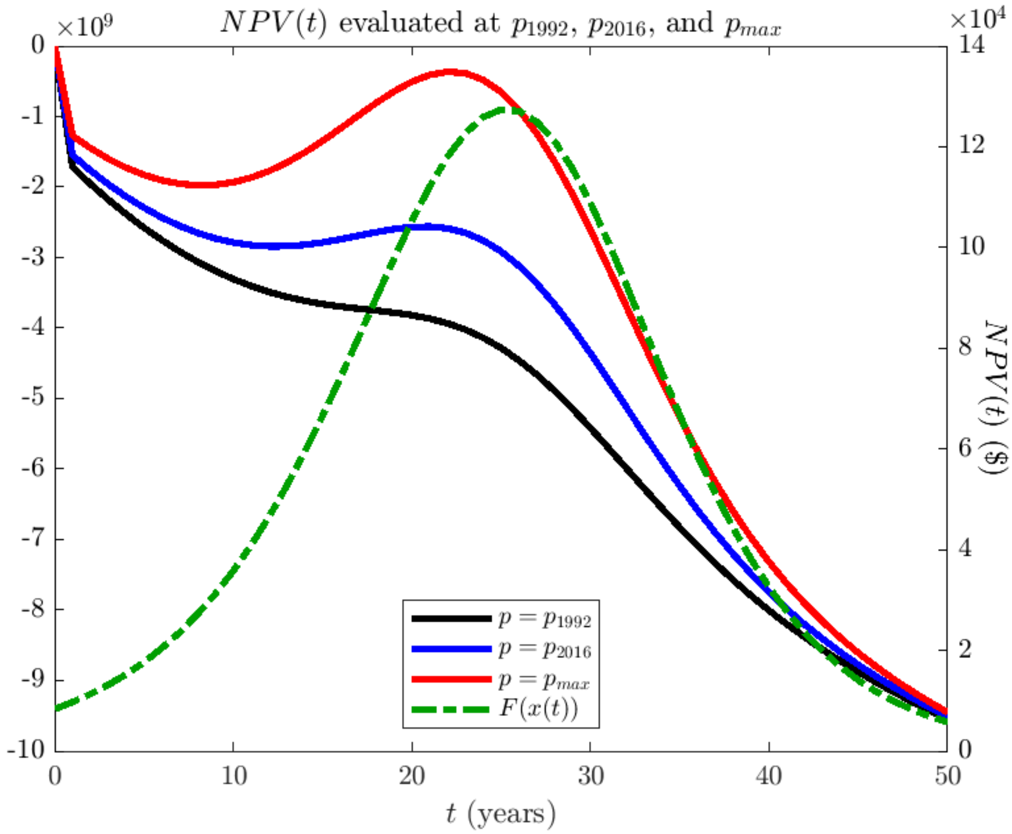

Figure 3.7: *$NPV_{1992}(t)$ (solid black), $NPV_{2016}(t)$ (solid blue), and $NPV_{p_{max}}(t)$ (solid red) are the net present value at the 1992, 2016, and highest observed real cod prices, respectively. $F(x(t))$ (dashed green) is the post-moratorium stock recruitment of the deterministic Northern cod fishery model as a function of moratorium length t.*

Although the real price of cod in 2016 represents an increase of 51% from 1992, we already saw from our comparative statics for p (Table 3.2) that it would be insufficient to raise the net present value of the moratorium above zero. The cod price must therefore be higher in order for a moratorium to be efficient against an alternative "business-as-usual" policy of no moratorium with no option value. However, even assuming cod price to be constant at the observed maximum, the net present value curve $NPV_{p_{\max}}(t)$ does not have a positive peak.

3.6.1 Moratorium Net Present Value Under Rational Expectations

Our computations of the net present value curve $NPV(t)$ as a function of prospective moratorium length t have thus far held the dockside net price of cod, p, at a constant value. In reality (as might be expected), Figure 3.6 shows that the price of cod in Newfoundland indeed fluctuated over time. Following our analytic extension of the model to incorporate time-varying prices (Section 2.5), we proceed here to allow for a variable price in our numerical analysis.

As we only have data on prices p_t on an annual basis over 1990-2016, we transform our continuous-time model to a discrete time model where each period t represents one year, with the variables subscripted with a time index rather than being functions of time, and where $t = 0$ corresponds to the year 1992 and $t = 24$ corresponds to the year 2016. In particular, we specifically treat stock variables (e.g., fish biomass) as measured *at the beginning* of each time period, and any flows (e.g., fish population recruitment) to occur *during* the period, between such measurements. Lastly, we recall that in a discrete-time framework, the appropriate discounting multiplier is the discrete-time discount factor $\rho \equiv 1/(1 + \delta)$.

Let X represent the fish biomass as before. From $t = 0$ through the length of the moratorium, the equation of motion in difference form is given by:

$$X_t - X_{t-1} = F(X_{t-1}) \quad \Leftrightarrow \quad X_t = X_{t-1} + F(X_{t-1}).$$

We use U to denote the cumulative net present value of unemployment insurance relative to $t = 0$, likewise paid out up until the beginning of period t. One might interpret U_t as accounting for last year's discounted unemployment payment, $\rho^{t-1}u$, added to cumulative unemployment costs in the previous period, U_{t-1}:

$$U_t - U_{t-1} = \rho^{t-1}u \quad \Leftrightarrow \quad U_t = U_{t-1} + \rho^{t-1}u.$$

The cumulative cost of capital depreciation, D, is slightly more complicated. We assumed that in each period, the initial capital stock A^* depreciated at a constant rate γ, at a unit capital cost $c > 0$. Thus the capital stock, A, evolves as:

$$A_t - A_{t-1} = -\gamma A_{t-1} = \quad \Leftrightarrow \quad A_t = (1-\gamma)A_{t-1} = (1-\gamma)^t A^*.$$

The additional depreciation cost incurred each year is then:

$$D_t - D_{t-1} = \rho^{t-1}c\gamma A_{t-1} = \rho^{t-1}c\gamma(1-\gamma)^{t-1}A^* \quad \Leftrightarrow \quad D_t = D_{t-1} + \rho^{t-1}c\gamma(1-\gamma)^{t-1}A^*.$$

We use our discretized model to simulate a social planner computing the *expected* post-moratorium revenue from sustainable harvest, R, after the moratorium is lifted at the beginning of period t, under three different scenarios.

Our original baseline assumption is that the price of cod remains constant at its 1992 value. Equivalently, one could conceptualize this calculation being made by a "static" social planner (in the sense that they are conducting the benefit-cost analysis once, at $t = 0$, i.e., the initial year, 1992), with no foresight and the "naïve" expectation that the cod price will not change over time:

$$\begin{aligned}
[R(\text{static, no foresight, naïve})]_t &= \sum_{\tau=t}^{\infty} \rho^{\tau} \left(p_{1992} - \frac{C}{X_t} \right) F(X_t) \\
&= \left(p_{1992} - \frac{C}{X_t} \right) F(X_t) \sum_{\tau=t}^{\infty} \rho^{\tau} \\
&= \left(p_{1992} - \frac{C}{X_t} \right) \frac{F(X_t)\rho^t}{1-\rho},
\end{aligned}$$

where we once again use the sum to infinity of a geometric series, $S_\infty = a/(1-r)$. We compare this baseline to two alternative rational expectation scenarios.

The first rational expectations scenario is that of a *"dynamic" agent with no foresight, "naïve" expectations, and "updating" prices.* Suppose instead that the social planner institutes the moratorium and, *as each period t commences*, re-evaluates the benefits and costs of ending the moratorium *in that period t* using that the cod price in period t as the steady-state post-moratorium cod price. We call this agent "dynamic" because they are aware that fish prices may change during the moratorium before the moratorium is lifted. However, they still have no foresight and naïve expectations, as they assume that the cod price p_t at the time t the moratorium is lifted will remain constant after the moratorium is lifted, throughout the post-moratorium future:

$$[R(\text{dynamic, no foresight, naïve})]_t = \sum_{\tau=t}^{\infty} \rho^{\tau} \left(p_t - \frac{C}{X_t} \right) F(X_t) = \left(p_t - \frac{C}{X_t} \right) \frac{F(X_t)\rho^t}{1-\rho}.$$

The second rational expectations scenario is that of an *agent with perfect foresight and "naïve" expectations* (which we abbreviate as "perf." and "naï."). If the agent has perfect foresight of the price trajectory $\{p_t\}_{t=0}^{24}$ for the first 25 years, corresponding to the years 1992-2016 for which we have cod data, there is no difference between their computing revenues "statically" or "dynamically". Since the vector of prices is only available up to $t = 24$ (the year 2016), however, they must still make assumptions as to price behavior beyond the horizon of their foreknowledge. Here we assume they maintain "naïve" expectations and consider the price to remain constant at p_{2016} in future years:

$$[R(\text{perf., naï.})]_t = \begin{cases} \displaystyle\sum_{\tau=t}^{24} \rho^{\tau} \left(p_{\tau} - \frac{C}{X_{\tau}} \right) F(X_t) + \sum_{\tau=24}^{\infty} \rho^{\tau} \left(p_{2016} - \frac{C}{X_{\tau}} \right) F(X_t), & t < 24; \\ \displaystyle\sum_{\tau=t}^{\infty} \rho^{\tau} \left(p_{2016} - \frac{C}{X_{\tau}} \right) F(X_t), & t \geq 24. \end{cases}$$

We plot the discrete-time NPV_t curve for these two rational expectations scenarios, along with our baseline scenario that the price of cod remains constant at its 1992 value and the alternative scenario that the price of cod remains constant at its maximum observed value over the period 1990-2016, in Figure 3.8. We see that the NPV_t curve is lowest under baseline conditions (black), because the cod price in all subsequent years exceeded the 1992 price, and they are bounded above by the NPV_t curve that assumes the highest observed cod price (red). The stochastic nature of the cod price trajectory is clearly tracked when the agent acts "dynamically" and updates prices each period along the second (blue) NPV_t curve. The third (green) NPV_t curve, for an agent with perfect foresight, appears to be an average smoothing of the (blue) NPV_t curve, as both the positive and negative fluctuations of the cod price are included in the computation of forecast revenues over the period for which prices are known.

3.6.2 "Sophisticated" Rational Expectations: Forecasting Prices

In contrast to a "naïve" social planner, who takes some price (whether it be the price of cod in 1992, the price in the latest period, the last observed price, or the maximum price) as remaining constant in the unknown future, a social planner with "sophisticated" expectations seeks to *forecast* future prices.

We consider a social planner with "sophisticated" expectations who uses a model to forecast future prices. We first test whether the trajectory of real cod prices can be modeled as increasing exponentially at rate α over time. Assuming that $p_t = p_0 e^{\alpha t}$, taking logarithms on both sides transforms this into the linear log-log relationship:

$$\ln p_t = \ln p_0 + \alpha t \quad \Leftrightarrow \quad (\ln p_t - \ln p_0) = \alpha t.$$

We estimate α using ordinary least squares (OLS) regression with robust standard errors for both specifications on the observed cod price data in Stata, reporting our results in Table 3.3. There is no difference in the estimated coefficient α on t be-

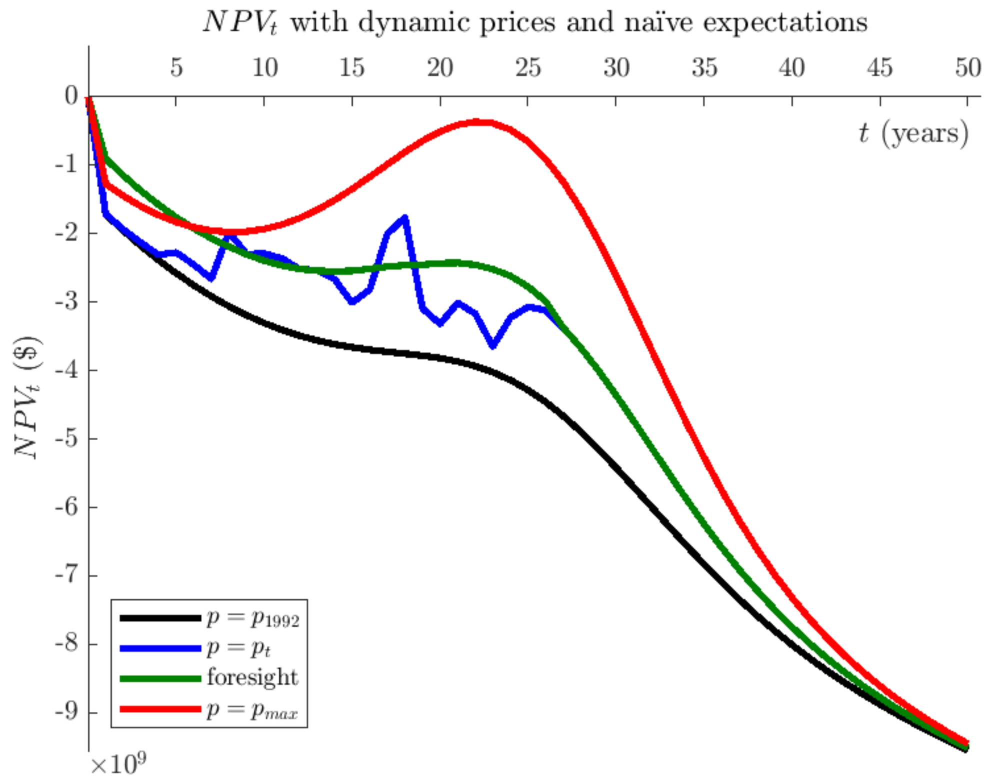

Figure 3.8: *Discrete-time net present value NPV_t with dynamic prices and naïve expectations for four different scenarios: (1) the "static" social planner (baseline, in black), who evaluates the benefit-cost calculation assuming cod price remains constant at its 1992 value; (2) the "dynamic" social planner (in blue), who reevaluates the benefit-cost calculation each period, assuming cod price remains constant at its current value if the moratorium is lifted; (3) the social planner with perfect foresight (in green), who is aware of the known price trajectory, and only assumes the price stays constant at its last available value in the unknown future; and (4) the "static" social planner, using the maximum observed price (in red).*

tween specifications, nor is it statistically significant at any level. Hence we reject exponential price growth as a model for the observed cod price data.

We also regress the real price of cod against its value lagged one; one and two; and one, two, and three periods in order to investigate whether the observed cod price trajectory is better described by an autoregressive (AR) process. We estimate and

	Dependent variables are:	
	$\log p_t$	$(\log p_t - \log p_0)$
	(1)	(2)
t	0.005	0.005
	(0.006)	(0.006)
	[0.878]	[0.878]
Constant	6.728^{***}	0.307^{**}
	(0.098)	(0.098)
	[68.576]	[3.131]
N	27	27
R^2	0.029	0.029

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Robust standard errors in parentheses,
t-statistics in square brackets.

Table 3.3: *Ordinary least squares regression of* $\ln p_t$ *and* $(\ln p_t - \ln p_0)$ *on* t*, testing whether observed cod prices can be modeled by exponential growth.*

compare these AR(1), AR(2), and AR(3) specifications in Table 3.4. We find that an AR model explains the Newfoundland cod price data far better than the exponential growth model in Table 3.3; in all of the AR specifications, the coefficient on p_{t-1} is statistically significant to $p < 0.001$, and the model R^2 ranges from 0.373 (AR(3), column (3)) to 0.444 (AR(1), column (1)). Although the Akaike and Bayesian-Schwarz Information Criteria (AIC and BIC) are minimized by the AR(3) specification, R^2 is significantly higher for AR(1), and the additional lags in the AR(2) and AR(3) models are not jointly significant according to their F-statistics. Therefore, we select the best-fitting and most parsimonious AR(1) specification to use in our simulation of an agent computing moratorium net present value NPV_t with forecasted prices.

In Figure 3.9, we plot the discrete-time NPV_t curve for a "sophisticated" agent forecasting future cod prices with the AR(1) model estimated in Table 3.4. The NPV_t curve is naturally lowest under baseline conditions (black), because the cod price in all subsequent years exceeds the 1992 price, and they are bounded above by the NPV_t

	Dependent variable is cod price p_t		
	(1)	(2)	(3)
p_{t-1}	0.639***	0.588***	0.561**
	(0.106)	(0.140)	(0.152)
	[6.009]	[4.185]	[3.688]
p_{t-2}		0.029	-0.075
		(0.122)	(0.215)
		[0.239]	[-0.349]
p_{t-3}			0.129
			(0.169)
			[0.763]
Constant	343.305**	369.160**	377.667**
	(107.839)	(120.341)	(121.961)
	[3.183]	[3.068]	[3.097]
N	26	25	24
R^2	0.443	0.405	0.373
AIC	344.7	334.0	322.8
BIC	347.2	337.6	327.5
F		F(1,22)=0.06	F(2,20)=0.36

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Robust standard errors in parentheses, t-statistics in square brackets. F-statistic reported for (joint) significance of additional lags not in specification (1).

Table 3.4: *Ordinary least squares regression of p_t against its one, two, and three lags. In addition to R^2, we report the Akaike and Bayesian-Schwarz Information Criteria (AIC and BIC) for each specification; and for the AR(2) and AR(3) models, the F-statistic on joint significance of the additional lags not entered in (1) as well.*

curve that assumes the highest observed cod price as constant (red). The second (blue) curve computes NPV_t when prices vary over time according to the estimated AR(1) model. Lastly, the AR(1) model $p_t = \alpha p_{t-1} + \beta$ with $0 < \alpha < 1$ and constant $\beta > 0$ simply converges to its sum to infinity $p_\infty = \beta/(1-\alpha)$, which, according to our estimated parameters is \$948.424 per metric ton; we use this limiting price as the steady-state price of cod in the third (green) NPV_t curve. The second and third (blue and green) NPV_t curves essentially overlap, because the AR(1) process converges very quickly to p_∞.

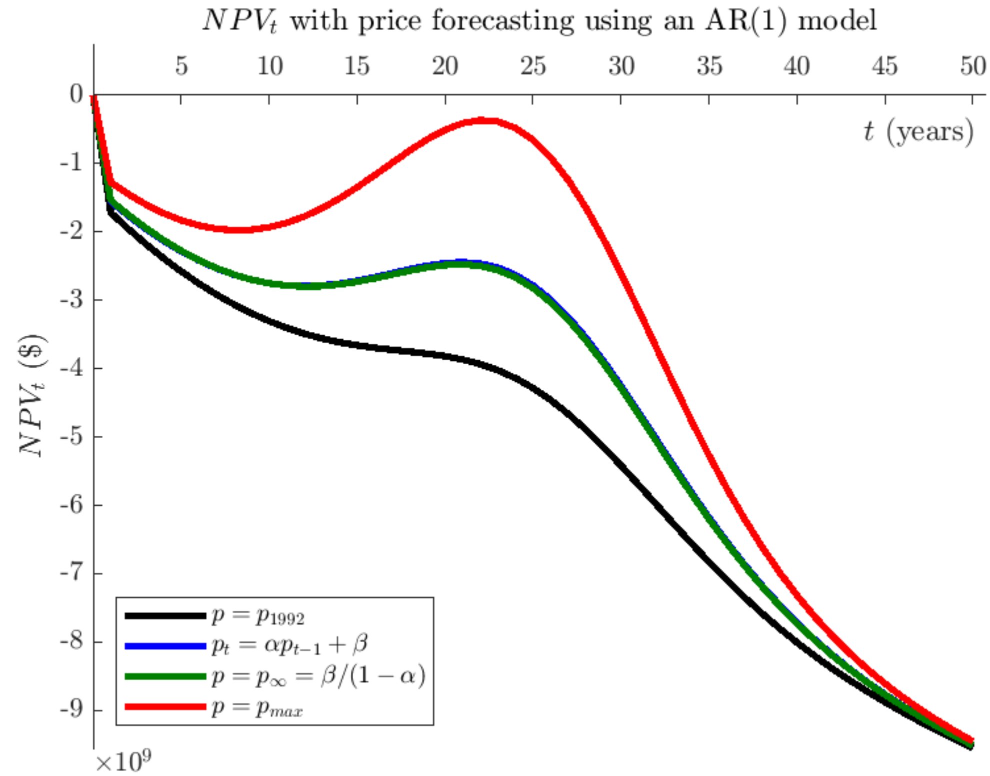

Figure 3.9: *Discrete-time net present value NPV_t curves under four scenarios: (1) the "static" social planner (baseline, in black), who evaluates the benefit-cost calculation assuming cod price remains constant at its 1992 value; (2) the "sophisticated dynamic" social planner (in blue), who forecasts the price throughout the model timespan using the previously-estimated AR(1) model and parameters; (3) the "sophisticated static" social planner (in green), who takes the cod price as constant at the limiting value of the estimated AR(1) process; and (4) the "static" social planner, using the maximum observed price (in red).*

CHAPTER 4

CONCLUSION

While a moratorium that completely closes an overharvested fishery may best facilitate stock recovery, such a policy can be particularly costly for economies dependent on fish consumption for sustenance, or on fishing and fishing-related industries for income and economic well-being. Nevertheless, even if a fishing moratorium is a policy option that should be reserved only for the most dire of circumstances, it is useful to understand the economic consequences both of potentially failing to prevent such a worst-case scenario, and having already mismanaged fisheries to the point of collapse.

In this Master's thesis, we develop a bioeconomic model to evaluate the optimality of a fishing moratorium when costs to labor and capital in the form of *ex gratia* relief payments are taken into consideration. We first present our model analytically, drawing parallels and distinctions between the optimal Faustmann-Wicksell forest rotation and optimal fishery moratorium with *ex-gratia* unemployment relief and vessel depreciation payments, deriving an analytic solution for the case of logistic growth, and extending the model to allow for time-varying prices.

We next apply our model to a numerical case study of the ongoing moratorium instituted on the Northern Atlantic cod fishery off the Canadian province of Newfoundland and Labrador beginning in 1992. Assuming that fishermen are compensated throughout the moratorium at the 1992 baseline of total unemployment insurance claims, fishing vessels depreciate at an exponential rate from their 1992 level, and the option value of the alternative "business-as-usual" policy to refrain from imposing a moratorium is zero, the cod moratorium is economically inefficient, with the fishery value being maximized at a moratorium length $t^* = 0$. This is because the aggregate discounted costs of making annual unemployment relief payments u significantly outweigh the aggregate discounted benefits of greater sustainable post-moratorium harvests.

Sensitivity analyses show that the cod moratorium may become optimal (i.e., $t^* > 0$) if (i) the intrinsic growth rate r of the Northern cod stock is sufficiently high; (ii) the anticipated future net dockside price of cod p is sufficiently high; (iii) the social discount rate δ is sufficiently low; (iv) the weekly unemployment benefit w paid to fishermen during the moratorium is sufficiently low; or (v) the option value of the alternative "business-as-usual" no moratorium policy is severely negative, possibly owing to the risk of potential collapse or even extinction of the stock. Conversely, the initial stock level X_0 and the marginal cost of capital depreciation c have little or no effect on moratorium net present value.

Although the cod moratorium may become optimal (i.e., $t^* > 0$) if the anticipated future net dockside price of cod p is sufficiently high, we find that it remains economically inefficient when the benefit-cost analysis is conducted using cod prices that vary or are forecast using actual price data from Newfoundland over 1990-2016. The cod price never reached nor maintained a sufficiently high level for the moratorium to attain a positive net present value.

Our results therefore demonstrate that if *ex gratia* relief payments made to labor and capital are taken into consideration, a fishery moratorium may not be economically efficient when compared to an alternative "business-as-usual" policy of no moratorium with an option value of zero, since the aggregate discounted costs of making annual unemployment relief payments can substantially outweigh the aggregate discounted benefits of greater sustainable post-moratorium harvests, even when potential future price increases are accounted for. However, we must also recognize that extensively depleted fisheries are likely at increased risk of complete collapse, and the expected option value of not imposing the cod moratorium might have been, in fact, drastically more negative. Under such a scenario, the cod moratorium would become optimal policy even if imposing one incurred a net cost to society, versus the specter of an utter bioeconomic catastrophe.

Our research elucidates a dynamic benefit-cost framework for assessing the economic viability of a fishery moratorium. We find our dynamic benefit-cost analysis of the Northern cod moratorium to be greatly sensitive to the intrinsic growth rate r, the net dockside price p per unit fish, the social discount rate δ, and the weekly individual unemployment benefit w (and, by extension, the yearly aggregate unemployment benefit, u); and, to a somewhat lesser extent, the initial stock size X_0. Scientific assessment of the fishery parameters r and X_0 will always contain some unavoidable level of uncertainty, indicating that bioeconomic modeling should be undertaken over a relevant interval and not merely a single value of any one biological parameter. Similarly, future prices cannot be known *a priori* and forecasts should be done over a range of such. While the choice of discount rate is, on the contrary, in some sense a political question to be determined by society, the analogous variability of outcomes suggests that evaluating optimal behavior for a variety of discount rates should likewise be standard practice as well.

Beyond being in accordance with economic intuition, our results reaffirm the need for fishery management to account for biological uncertainty in stock modeling and assessment, and economic uncertainty in price forecasting. We hope to build upon our dynamic fishery model to analyze the optimality of a harvest moratorium under uncertainty, and also to incorporate nonlinearity in benefits and/or costs. Indeed, although we took the *ex gratia* unemployment relief payments to be constant and modeled capital depreciation costs as evolving predictably in our case study of the Northern cod moratorium, it may very well be the case that, for example, a significant proportion of former Atlantic cod fishermen have in fact been able to easily find alternative work for themselves and their boats fishing for other substitute commercial species. On the other hand, there could be unexpected post-moratorium costs to resuming fishing after the moratorium is lifted, if labor exits the industry in the interim, and specialized human capital is irreversibly lost. We look forward to further exploring these nuances in future work.

CHAPTER 5

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