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THE VALUATION OF FISHERIES RIGHTS:
A REAL OPTIONS APPROACH

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ABSTRACT

This article develops and implements a Real Option approach to value renewable natural resources in the case of Marine Fisheries. The model includes two sources of uncertainty: the resource biomass and the price of fish, and it can be used by fisheries to optimally adapt their harvesting strategy to changing conditions in these stochastic variables. The model also features realistic operational cash flows and fisheries can shutdown and reopen operations. Using publicly available data on the British Columbia halibut fishery, the required parameters are estimated and the model solved. The results indicate that the conservation of the biomass is both optimal from a financial and a social perspective. The approach could be extended to other fish species and natural resources if the appropriate data were available.

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I. Introduction

The economic sustainability of fisheries is an ongoing concern for consumers, fishers, governments, intergovernmental organizations, and academics. Overfishing occurs when more fish are caught than the natural population growth, and as Ye and Gutierrez (2017) indicate, during the last decade the worldwide percentage of stocks classified as overfished remained stable at 30%, pointing to a failure of self-regulation and a misalignment between economic incentives and conservation. This is the starting point of several efforts from governments and institutions around the world to regulate these markets and achieve a sustainable equilibrium.

The Food and Agriculture Organization of the United Nations (FAO (2008)) indicates that an important part of solving the overfishing problem is to *"adjust fishing capacity to sustainable levels through policy and regulations, including judicious use of subsidies and eradication of illegal, unreported and unregulated fishing."* Nowadays one of the most used policy device is the Individual Vessel Quota (IVQ) system, an allocation of extraction rights of the total annual fish catch (TAC) in the form of transferable quota shares which limits not only the total catch, but also controls the individual fisher's landings.

Although the IVQ policy has been successful on limiting overexploitation, there is still an ongoing discussion on the optimal economic level of the quota. This paper develops a methodology in a dynamic setting to determine the total annual fish catch which maximizes the value of the natural resource. This optimal TAC not only maximizes the value of the resource, but also assures the sustainability of the resource.

The valuation of natural resources under uncertainty is a problem in which the Real Option approach has proven to be appropriate in other contexts, as the work of Brennan and Schwartz (1985) and the significant body of work that followed indicate, but until now it has not been fully applied to marine fisheries. This article develops and implements such approach by modeling fisheries as a complex option on the variables underlying the value of the industry, in this case, the resource stock (biomass) and the fish price. Uncertainty is introduced in the analysis by allowing these variables to follow dynamic stochastic processes. The model has some features similar to Morck et al. (1989) for forestry but in this case the resource growth is specific for a fish population, and operational cash flows are modeled as an explicit function of the biomass and the total harvest. To specify the biomass growth uncertainty we follow Pindyck (1984) and use a logarithmic growth function which explicitly captures the possibility of overpopulation and depletion. For the price of fish we use a standard financial log-normal price dynamics.

To make the problem tractable we consider the case where several competitive price taking fisheries can be represented by a single fishery endowed with the total annual fish catch (TAC) whose property rights are well defined. To simplify the model we also assume that the fishery faces no taxes and that production can opened and shut down at no cost; though these features could be easily incorporated in the model.

The model is solved using a value-function iteration algorithm instead of the more traditional partial differential equation approach used in Real Options problems. The solution approach solves for the optimal dynamic harvesting policy of a representative fishery, and then uses this policy to value the marine harvesting rights. The solution allows also to study how the optimal level of harvesting relates to the two state variables in our model, the biomass and the fish price, and how these rights will optimally evolve with stochastic changes in the state variables. Based on the optimal policy it is possible to simulate the dynamics of the biomass subject to stochastic shocks and optimal harvesting, illustrating how the biomass will evolve over a specific time horizon.

Most of the current literature on fisheries assumes that prices are constant or evolve deterministically (Clark and Kirkwood (1986), Sethi et al. (2005)). A significant improvement of our model is that it includes stochastic prices which turns out to be an important issue. Our analysis also expands the literature by including in the cost function not only fixed operational costs, but also variable costs which are related to the biomass through the fisheries efficiency (catchability), and a quadratic component which incorporates an increasing marginal cost.

To examine the model implications, we apply it to the British Columbia halibut fishery. Combining multiple sources of information we constructed time series for the halibut biomass, total harvest (landings), and price, and using this data all required parameters of the model are estimated. Our estimates show that the volatility of the fish price growth is comparable in size to the estimated volatility of the biomass growth, showing that when previous literature assumed that the fish price followed a deterministic path the fishery's valuation problem is significantly underestimating the uncertainty faced by the fishers.

The model results show that it is optimal for the representative fishery to preserve the biomass for future harvesting, and that if the biomass suffers significant negative shocks then it is optimal to drastically reduce exploitation, even fully stopping the harvest in scenarios of low biomass or low resource prices. That is, the optimal harvesting policy exhibits strong financial incentives to avoid the extinction of the natural resource.

This paper also contributes to the research in the valuation of marine resources using Real Options. The closest paper to ours are Murillas (2001) and Poudel (2013), in which this approach is used to value capital investments in fisheries using a model with uncertainty in the growth of the fish and in the capital, a linear production cost function with no fixed cost, but no uncertainty in the resource price.

Finally, this paper contributes to the marine fisheries literature by presenting empirical estimations for all the parameters required to solve the model. Data for the British Columbia halibut fishery is used because of its availability. Data was collected from several sources including the International Pacific Halibut Commission (IPHC)[1] and Fisheries and Oceans Canada (DFO)[2]. Cost data is hard to find, as Clark et al. (2009) already indicated, so we use the two available financial surveys performed for the DFO by Nelson (2009) and Nelson (2011) to identify the parameters of the modeled cost function.

In summary, this paper presents a Real Option approach to valuing fisheries under the optimal harvesting policy, including a full parameter estimation for its implementation to study the optimal policies and value marine fishery rights for the British Columbia halibut. This approach is not only useful to value extraction rights for a current level of our state variables, it also allows us to understand how it evolves over time, and presents evidence for the value of conservation of the natural resource and the possibility of achieving an economic sustainable equilibrium.

The paper proceeds as following. The valuation model is presented in section 2. Section 3 provides a detailed implementation of the approach using data for the British Columbia halibut fishery. Section 4 gives our concluding remarks. Details on the employed data, estimation methods, and the solution algorithm are provided in the Appendix.

II. A Valuation Model of Marine Fisheries Rights

In this section we develop a dynamic stochastic economic model to study how fisheries should optimally harvest the resource. The value of the marine fishery is assumed to depend on two stochastic variables: the biomass and the price of fish. Following Pindyck (1984) the dynamic of the biomass of the resource is assumed to follow:

$$dI = [G(I) - q]\, dt + \sigma_I I dZ_I \tag{1}$$

where I is the biomass, $G(I)$ is the instantaneous expected rate of growth of the biomass, dZ_I is a standard Wiener process, σ_I is the volatility of the unanticipated shocks to the resource stock, and q is the harvesting rate, which is the stochastic control in the model.

Consistent with the literature (Clark (2010)), the instantaneous growth rate of the biomass is assumed to follow a logistic function. This function explicitly captures the fact that if the biomass approaches its carrying capacity I^{max}, resources in the environment become scarce reducing the natural growth to zero. On the other hand, when the biomass is bellow its

[1] https://www.iphc.int/
[2] http://www.dfo-mpo.gc.ca/index-eng.htm

depensation level I^{min}, reproduction falls as matching is less frequent and the resource is in danger of extinction. Considering these characteristics the logistic function is presented Equation 2:

$$G(I) = \gamma \left(I - I^{min}\right) \left(1 - \frac{(I - I^{min})}{(I^{max} - I^{min})}\right) \tag{2}$$

Figure 1 shows the previously mentioned logistic function features for the parameters $\gamma = 0.8$, $I^{min} = 10$, $I^{max} = 150$:

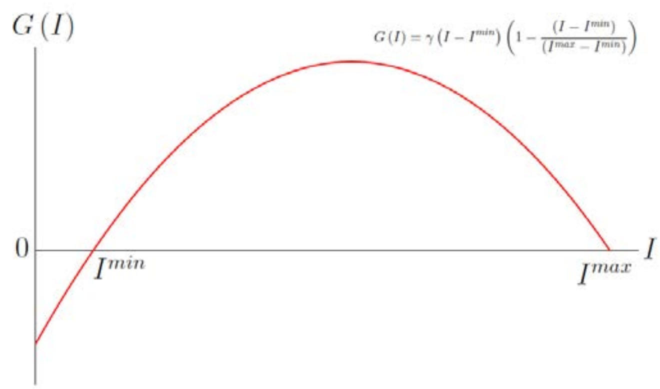

Figure 1: Logistic Natural Growth Function for for the parameters $\gamma = 0.8$, $I^{min} = 10$, $I^{max} = 150$

To illustrate the dynamic behaviour of a biomass with logistic natural growth, we simulate the evolution of a population subject to a constant annual harvest of q. 10,0000 different paths are simulated over a 100 years time horizon. For this exercise we assume that the initial biomass is $I_0 = 100$ and the growth parameters are $\{I^{min} = 10, I^{max} = 150, \gamma = 0.8, \sigma_I = 5\%\}$ for $G(I)$. Figure 2 presents the median of the simulated biomass path for three different levels of constant annual extraction rates, $q = 2$, $q = 7$, and $q = 10$.

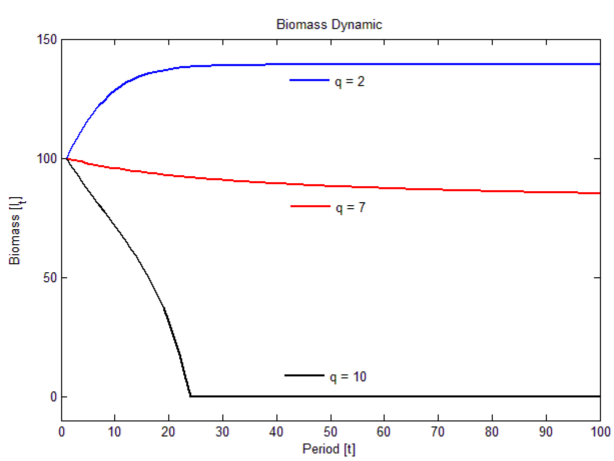

Figure 2: Median of the Simulations of the Biomass, for Different Extraction Policies and Natural Growth Function Parameters $\{I_0 = 100, I^{min} = 10, I^{max} = 150, \gamma = 0.8, \sigma_I = 5\%\}$.

This exercise illustrates how variable the long-term biomass can be. For the harvesting policy $q = 2$ the fishery is sustainable with a long term biomass higher than its initial size, for $q = 7$ a scenario in which the biomass slowly decreases but is sustainable, and for $q = 10$ a scenario in which the biomass decreases in every period finally reaching extinction by year 24. Naturally, in our model the optimal harvesting policy q will not be constant and it will evolve with the state variables.

The second source of uncertainty is the resource price. As is traditional in the finance literature, we assume that the logarithm of the resource price follows an arithmetic Brownian motion:

$$d \ln P = \nu_P dt + \sigma_P dZ_p \tag{3}$$

where P is the unit fish price, ν_P is the expected instantaneous rate of change in the logarithm of price, σ_P is the diffusion coefficient and dZ_P is a Wiener process. We assume that the price and biomass shocks are uncorrelated, that is $\mathbb{E}\left[dZ_I \times dZ_P\right] = 0$. [3]

Consider an infinitely-lived value maximizing fishery, with the equiptment in place and the right to harvest a particular fish specie. The company's cash flow per unit of time from fish harvesting is equal to the revenues minus he costs:

$$\pi(I, P, q) = P \times q - c\left(I, q\right) \tag{4}$$

$c\left(I, q\right)$ is the operating cost function of harvesting q given by the quadratic equation:

$$c(I, q) = \begin{cases} c_0 + \frac{c_1}{\phi I} \times q + c_2 \times q^2 & if\ q > 0 \\ 0 & if\ q = 0 \end{cases} \tag{5}$$

where c_0 is the fixed cost, c_1 is the variable cost, c_2 is the quadratic cost reflecting an increasing marginal cost, and ϕ is the fishing power parameter, or catchability, which captures the efficiency of the extraction technology, that is, when fish is abundant variable costs are lower.

As indicated at the case $q = 0$, the cost function reflects an assumption that production can be costlessly shut down and reopened. This assumption is not critical for the presented results, and a solution for a model on which the fishery pays the fixed cost if not producing is included on the Appendix.

With respect to the increasing marginal cost, it is included to capture potential costs required to achieve harvesting beyond the current levels. Examples of these costs may be

[3] This assumption was initially made for computational convenience and can be easily relaxed, although we tested the independence of the historical realizations of both stochastic processes finding that the correlation between them is 0.01, and not statistically different from zero.

finding new personal, increasing the fleet capacity, or investing in new technology. The presented function is a simple way to include this realistic feature of the costs faced by fisheries.

The present value of the fishery's future expected cash flows for a given harvesting policy $q\,(I, P)$ is defined as:

$$H\Big(I, P, q(I, P)\Big) = \mathbb{E}\left\{\int_{0}^{\infty} \pi(I, P, q(I, P))e^{-rt}dt\right\} \tag{6}$$

where r is the fishery's risk-adjusted cost of capital. Equation 6 can be re-written as:

$$\begin{gathered} H\Big(I, P, q(I, P)\Big) = \\ \mathbb{E}\left\{\pi\Big(I, P, q(I, P)\Big)dt + e^{-rdt}\int_{dt}^{\infty} \pi\left(I + dI, P + dP, q\left(I + dI, P + dP\right)\right)e^{-rs}ds\right\} \end{gathered} \tag{7}$$

Therefore,

$$\begin{gathered} H\Big(I, P, q(I, P)\Big) = \\ \pi\Big(I, P, q(I, P)\Big)dt + e^{-rdt}\mathbb{E}\Big\{H\left(I + dI, P + dP, q\left(I + dI, P + dP\right)\right)\Big\} \end{gathered} \tag{8}$$

A value maximizing fishery will choose the optimal harvesting policy $q^*(I, P)$, that is, the harvesting policy that maximizes the value of the fishery, by solving the following Hamilton–Jacobi–Bellman (HJB) equation:

$$V\left(I, P\right) = \max_{q^*(I,P)\geq 0} \Big\{\pi\left(I, P, q^*(I, P)\right)dt + e^{-rdt}\mathbb{E}\big[V\left(I + dI, P + dP\right)\big]\Big\} \tag{9}$$

were $V(I, P)$ is the value of the fishery under the optimal policy $q^*(I, P)$. As the present value of the cash flows is maximized over the set of feasible harvesting policies it is not dependent of this function anymore.

A. Boundary Conditions and Constraints

The value of the fishery must satisfy the HJB equation presented in Equation 9 subject to the following boundary conditions:

1. If the price of the fish drops to zero, the value of the fishery must also go to zero[4]:

$$V(I, 0) = 0 \tag{10}$$

2. If the resource biomass is lower than the depensation level I^{min}, fisheries will face resource extinction, thus the value of the fishery must fall to zero:

$$V(\hat{I}, P) = 0 \quad for\ \hat{I} \leq I^{min} \tag{11}$$

3. If the resource biomass is lower than the depensation level I^{min}, all fishing must stop. This impose the following constraint on the stochastic control:

$$q(\hat{I}, P) = 0 \quad for\ \hat{I} \leq I^{min} \tag{12}$$

The listed boundary conditions are chosen primarily to reflect financial or technological restrictions. The complete valuation of marine fisheries rights is the solution to Equation 9, with respect to the optimal harvesting policy and the boundary conditions 10, 11 and 12. Together, these equations determine the optimal harvesting policy $q^*(I, P)$ and the value of the fishery $V(I, P)$ under this policy. A value-function iteration algorithm is implemented to numerically solve the model. Details of this approach are provided in the Appendix.

In Section III we present the model solution using data of the British Columbia halibut fishery, including estimation of the relevant parameters, the harvesting policy, and the fishery's value.

III. The British Columbia Halibut Fishery Case

To illustrate the implementation of the methodology proposed in this article we calibrate and solve the model for the case of the British Columbia halibut. We use data from the International Pacific Halibut Commission (IPHC), established in 1923 by a convention between Canada and the U.S. for the preservation of the Pacific halibut fishery. The IPHC provides recommendations to these governments on the total catch limit and monitors the resource over the regulatory areas presented in Figure 3. We focus on the area 2B corresponding to British Columbia.

[4] Altough this is true, note however that given the stochastic process in Equation 3 the price will never reach zero

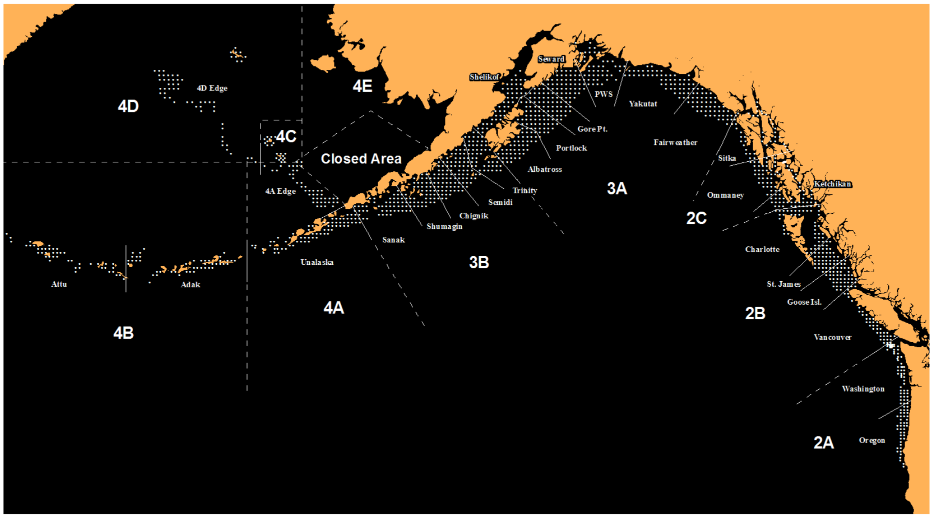

Figure 3: International Pacific Halibut Commission Regulatory Regions. Source: IPHC.

Our second source of data is the Department of Fisheries and Oceans of Canada (DFO), agency responsible for *"...sustainably manage fisheries and aquaculture and work with fishers, coastal and Indigenous communities to enable their continued prosperity from fish and seafood."*[5] Specifically, we use the British Columbia halibut landing price data and financial reports published on their site.

In the following subsections we present the estimations for the parameters of the BC halibut biomass dynamic, price dynamic, cost function, and risk adjusted discount rate. With all the estimated parameters we end this section by presenting and discussing the model results.

A. Parameter Estimation

A.1. British Columbia Halibut Biomass Dynamic Parameters

Although the biomass is not perfectly known, the stock assessment provided by Stewart and Hicks (2017) and Stewart and Webster (2017) is the closest proxy to its true magnitude. As detailed in the cited documents the biomass estimation is the result of a combination of several models which use short and long term data. Figure 4 shows the time series for the biomass and the landings of halibut for the British Columbia region, for the period 1996-2017.

[5] `http://www.dfo-mpo.gc.ca/about-notre-sujet/org/mandate-mandat-eng.htm`

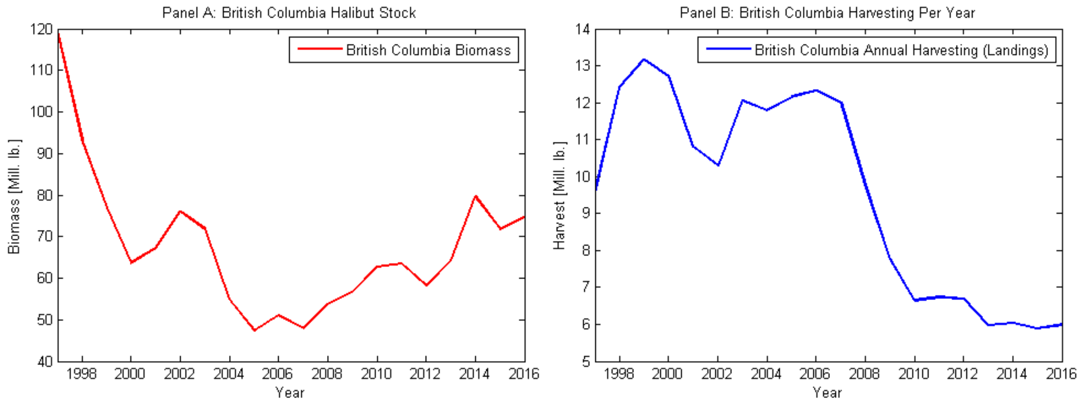

Figure 4: British Columbia halibut stock assessment and landings, 1996-2017. Source: IPHC.

Panel A of Figure 4 shows that the biomass exhibited a strong decline between 1996 and 2000, period also characterized by high harvesting as Panel B of Figure 4 exhibits. By 2010 the biomass was almost half of the 1996 level and harvesting was reduced to levels that remain controlled.

Using this data we estimate the parameters of the biomass logistic growth function, and the volatility of the random shocks. Combining a discrete version of Equations (1) and (2) we obtain the non-linear regression:

$$\frac{I_{t+1} - I_t}{I_t} + \frac{q_t}{I_t} = \gamma \frac{(I_t - I^{min})}{I_t} \left(1 - \frac{(I_t - I^{min})}{(I^{max} - I^{min})}\right) + \epsilon_t \tag{13}$$

Equation 13 is a non-linear function of the required parameters, so the estimation is done using the Damped Least Squares technique[6], the results of this approach are presented in Table I.

Table I: Estimated Parameters for the Biomass Dynamic, 1996-2017

The parameters are estimated using Damped Least Squares (Levenberg-Marquardt algorithm). The data covers from 1996 to 2017 and is provided by the IPHC. All coefficients are estimated simultaneously. The volatility of the residuals of the estimated regression corresponds to the parameter σ_I presented in the model.

γ	0.61
I^{min}	10.01
I^{max}	85.52
σ_I	0.11

Figure 5 illustrates the goodness of fit of the estimation by comparing the biomass natural historical growth rate (LHS of Equation (13)) versus the growth (Expected value of the RHS of Equation (13) calculated using the estimated parameters.

[6]The technique is also known as the Levenberg-Marquardt algorithm. For technical details check Heer and Maussner (2009)

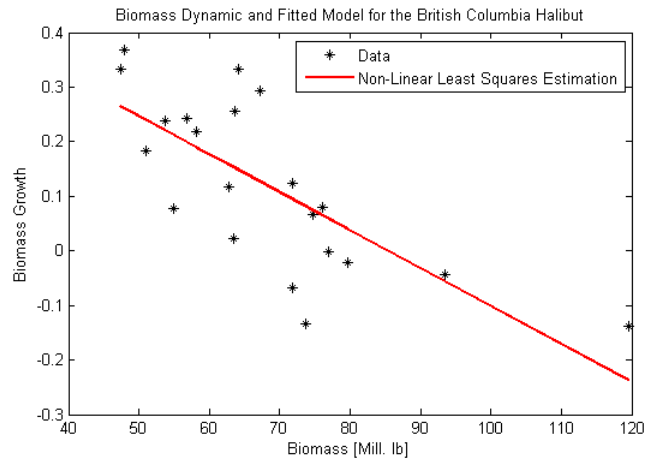

Figure 5: British Columbia Halibut Biomass Growth and the Non-Linear Least Squared Model Estimation

Figure 5 shows that the estimated parameters are effective in capturing the relation between the biomass level and its growth, although there is a significant level of biological uncertainty captured by σ_I, which explains the overall difference between the fitted model and the data.

A.2. British Columbia Halibut Price Dynamic Parameters

From the Department of Fisheries and Oceans of Canada (DFO) website[7], we gather the halibut ex-vessel historical prices for British Columbia. The time series covers from 1990 to 2016 and is used to compute the annual logarithmic return of the halibut price. These returns are deflated using the CPI for the British Columbia province. Figure 6 presents the time series of halibut prices (Panel A) and the distribution of the real logarithmic price returns (Panel B).

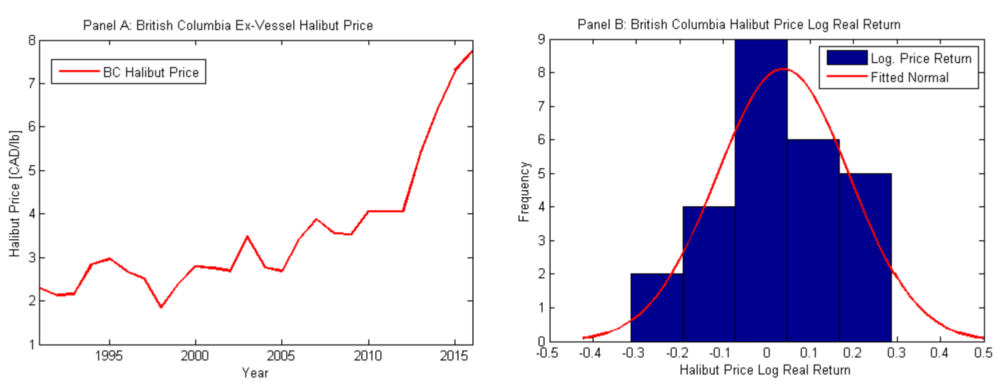

Figure 6: British Columbia Halibut Ex-Vessel Price and Real Logarithmic Returns, 1990-2016. Source: Fisheries and Oceans of Canada - Quantities and Values

[7] http://www.dfo-mpo.gc.ca

To estimate the price dynamic parameters presented in Equation 3, a normal distribution is fitted to the real logarithmic return, the estimated drift and volatility are presented in Table II:

Table II: Ex-Vessel Year Price Dynamic Parameters, 1992-2016

The parameters are the mean and standard deviation obtained for the Real Logarithmic Returns of the British Columbia Halibut Ex-Vessel Price. The data covers from 1990 to 2016 provided by the DFO.

ν_P	0.038
σ_P	0.15

A.3. British Columbia Halibut Fishery Costs Parameters

The model's cost function is presented in Equation 5 and includes a fixed operating cost, a linear harvesting cost which is related to the biomass through the fishery's efficiency (catchability), and an increasing marginal cost captured by the quadratic component. The parameters of this function are estimated using two surveys performed by Nelson Bros Fisheries Ltd. for the DFO (Nelson (2009) and Nelson (2011)), these surveys are summarized in Table III:

Table III: British Columbia Halibut Fishery Revenues, 2007 and 2009

The values are obtained from the reports prepared for the DFO-Pacific Region by Stuart Nelson of Nelson Bros Fisheries Ltd. (Nelson (2009) and Nelson (2011)), and provide estimates of the financial performance for vessels operating in British Columbia for the years 2009 and 2007. These reports are done with a combination of data from the DFO and consultant collected information through interviews/correspondence with fishermen and experts. Group 1 is the group of vessels with the highest third individual landings, Group 2 is the group of vessels with the middle third individual landings, and Group 3 is the group of vessels with the lowest third individual landings. All values are expressed in 2017 CAD using the CPI for British Columbia.

	2007 (Expressed in 2017 CAD)			**2009** (Expressed in 2017 CAD)		
	Group 1	Group 2	Group 3	Group 1	Group 2	Group 3
Total Biomass [Mill. lb.]	53.69	53.69	53.69	62.78	62.78	62.78
Landings [Mill. lb.]	5.51	2.88	0.95	3.33	2.14	0.72
Vessel Price [CAD/lb.]	$5.56	$5.56	$5.56	$5.99	$5.99	$5.99
Gross Revenue [Mill. CAD]	$30.68	$16.03	$5.29	$19.98	$12.85	$4.30
Total fishery specific expenses	$8.43	$4.75	$1.67	$5.63	$3.77	$1.46
Crew and captain shares	$8.65	$4.78	$1.37	$5.99	$3.85	$0.86
Total Vessel Expenses	$1.28	$1.28	$1.30	$1.23	$0.99	$0.69
Total Cost [Mill. CAD]	**$18.36**	**$10.81**	**$4.34**	**$12.85**	**$8.62**	**$3.02**
EBITDA [Mill. CAD]	**$12.32**	**$5.23**	**$0.95**	**$7.13**	**$4.22**	**$1.28**

Table III presents two years of costs and revenues for the British Columbia halibut fisheries. During 2007 the fisheries registered higher harvest and lower costs in comparison to 2009. All dollar values are inflated using the British Columbia CPI and expressed in 2017 Canadian Dollars (CAD), making all future costs estimations and values comparable.

The parameters of the cost function are determined solving an over-identified system of equations for the daily cost[8], that is, we solve Equation 5 by leaving one parameter free, in this case c_2, and then solve for the remaining two c_0, c_1, subject to $c_0 > 0$, $c_1 > 0$ and $c_2 > 0$.

Using the different groups of fishers presented in Table III several combinations of them can be used to identify the required parameters. Over all these combinations, the highest cost-efficient production[9] is achieved using the data of {Group 1(2007), Group 1(2009)}, and the lowest cost-efficient production is obtained when using data of {Group 3(2007), Group 3(2009)}. To implement our model, we use the set {Group 2(2007), Group 2(2009)}, as it represent the intermediate efficiency case.

For {Group 2(2007), Group 2(2009)}, the set of feasible values for the parameter c_2 is $[1, 110]$, that is, if $c_2 > 110 \implies c_1 < 0$. For the quadratic cost parameter we choose a value at the percentile 30% of the feasible values, that is $c_2 = 35$. This value gives a balanced combination between the increasing marginal cost and the linear component of the harvesting cost.

As mentioned, the parameters are the solution of an over-identified system for the same pair of costs, so all combinations of parameters trade off weight between the quadratic and liner component of the cost to generate the same total cost. Selecting the percentile 30% gives a positive weight to the quadratic component but still keeps more weight on the linear cost component, which has been the standard cost model in the fisheries valuation literature. To check for the sensitivity of this assumption, we also estimate the parameters for $c_2 = 55$.

[8] We consider a 150 days season

[9] By cost-efficiency we refer to the highest production for the lowest cots

Table IV: British Columbia Halibut Fishery Cost Parameters

The parameters are calculated using the productions costs of Group 2 for 2007 and 2009, expressed in 2017 CAD. The data is obtained from the reports prepared for DFO-Pacific Region by Stuart Nelson of Nelson Bros Fisheries Ltd. The over-identified equation $C_t = c_0 + c_1 \frac{q_t}{I_t \times \phi} + c_2 q_t^2$ is solved considering a 150 days season, for $c_2 = 35$ and $c_2 = 55$. Panel A presents the parameters for each value of $c2$. Panel B presents the costs reconstructed from the parameters and landings to show that they generate the same costs as those used to solve the system.

Panel A: Estimated Cost Parameters

$$\text{Parametrization 1 } C_1 : \{c_0 = 0.02, c_1 = 103.95, c_2 = 35\}$$
$$\text{Parametrization 2 } C_2 : \{c_0 = 0.02, c_1 = \ 78.62, c_2 = 55\}$$

Panel B: Production Costs [2017 CAD] for $I_{2007} = 53.69$ [Mill. lb.] and $I_{2009} = 62.78$ [Mill. lb.]

q_t [Mill. lb.]	C_1 (I_{2007})	C_1 (I_{2009})	C_2 (I_{2007})	C_2 (I_{2009})	Reported Harvesting Cost
0.50	$4.32	$4.18	$4.37	$4.26	-
1.50	$6.72	$6.30	$6.56	$6.25	-
2.14	*$8.51*	***$7.91***	*$8.36*	***$7.91***	***$7.91***
2.88	***$10.81***	*$10.00*	***$10.81***	*$10.20*	***$10.81***
5.00	$18.80	$17.40	$20.03	$18.97	-
7.45	$30.67	$28.58	$34.80	$33.22	-

Figure 7 complements the results presented in Table IV by illustrating how the proposed parametrizations differ over the feasible range of harvesting.

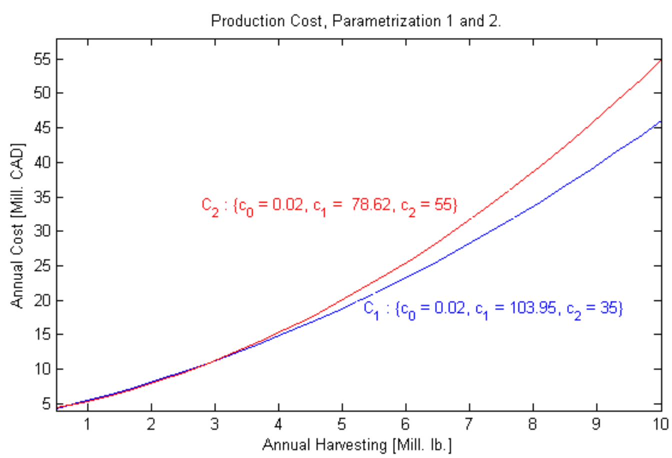

Figure 7: Proposed Parametrization for the Cost Function. British Columbia Halibut Fishery.

The figure shows how both cost parametrizations are similar for observed harvest of each of the studied groups (between 1 and 4 million pounds per year), but when the harvesting increases the costs diverge, showing how the quadratic component of the cost generates a higher total cost when production growths beyond the previously observed levels.

Although we are able to provide a parametrization of the cost function, it is clear that more data will be necessary to achieve a better implementation of the model. Clark et al.

(2009) already pointed out this issue, and unfortunately these surveys are not available for other years. Any effort to fully implement the model will have to deal with the lack of information of the production costs, which will require collecting and standardizing additional information.

A.4. Risk Adjusted Fishery Discount Rate

To estimate the risk adjusted discount rate for fisheries we look at the historical returns for companies classified as Fisheries using the SIC industrial classification, which codes are:

- 0912: Fisheries, Finfish
- 0913: Fisheries, Shellfish
- 0919: Miscellaneous Marine Products
- 0921: Fish Hatcheries and Preserves

Unfortunately not a significant number of firms are recorded on CRSP with the identified SIC codes. In Fama and French (1997) however, these firms are included in the macro-sector portfolio "Agriculture". We use this portfolio definition to obtain a robust estimation of the sector beta and the expected rate of return. The CRISP database is used to obtain the firm's stock returns and the historical risk-premium is obtained from Kenneth R. French site[10].

For the returns of each firm registered in the "Agriculture" portfolio, 60-months rolling betas are computed. The median beta for the Agriculture portfolio during the 1987-2016 period is 0.35. Combining this value with the historical risk premium and risk-free rate the estimated real rate of return for a fishery company is 2.9%. The detailed calculation is presented in Table V

Table V: Fishery's risk adjusted rate of return

The included beta is the annual average of the median 60-months rolling betas of the firms registered in the "Agriculture" portfolio. The risk premium and risk-free rate are obtained from the historical excess of return for the Canadian stock and bond market. The Bank of Canada inflation target of 2% is used to obtain the real rate using the continuous compounding Fisher equation. Data from CRSP and Ken French website. $R_{Fishery} = R_f + (R_m - R_f)\beta_{Fishery}$

β	0.349
$R_m - R_f$	0.055
R_f	0.030
$\mathbf{R^{Nom}_{Fishery}}$	**0.049**

[10] http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/index.html

Using the compounded version of Fisher equation we have: $R^{Real}_{Fishery} = (1 + R^{Nom}_{Fishery})/(1 + \pi) - 1 = 0.029$. As the model is solved in continuous time, we use the continuously compounded rate $r^{Real}_{Fishery} = log(1 + 0.029) = 0.02843$ to discount future cash-flows.

For the few fisheries included on CRSP, Table VI presents the estimated rolling-betas and nominal returns.

Table VI: Fishery Betas, Available Firms

The parameters are the average of the 60-months rolling betas for the firms in CRPS whose SIC code is 0912, 0913, 0919 or 0921. The risk adjusted returns are computed using the included beta and the risk premium presented in Table V

Company	Period	**Beta**	$\mathbf{R_{Fishery}}$
Marine Harvest ASA	Feb. 2014 - Jun. 2016	**0.3503**	**0.0493**
Aquaculture Production Tech Ltd.	Jun. 2007 - Mar. 2011	**0.7470**	**0.0711**
Marine Nutritional Sys Inc.	Nov. 1996 - Jun. 2007	**0.8399**	**0.0762**

The range of nominal rates of returns for fisheries is $[0.049, 0.076]$. Marine Harvest ASA has the most recent data, and its rate of return is consistent with the estimation presented in Table V, therefore, this will be the primary risk adjusted real rate of discount used in the model.

B. Model Solution: The Value-Function Iteration Approach

To solve the Hamilton–Jacobi–Bellman equation for the fishery's value $V(I, P)$, we follow the Value-Function Iteration Approach as presented in Heer and Maussner (2009). We start from Equation 9:

$$V(I, P) = \max_{q \geq 0} \left[\pi \left(I, P, q(I, P) \right) + e^{-r\Delta t} \mathbb{E} \left\{ V(I', P') \, | I, P \right\} \right] \tag{14}$$

where $q(I, P)$ is the extraction policy, and (I', P') is the state in Δt units of time of the two stochastic variables in our model, the price and the biomass.

The problem is re- written using a discretization of the continuous-time formulation. Define the state space for the biomass and the resource price as (I_n, P_m), where $I_n \in \{I_1, I_2, ..., I_N\}$ and $P_m \in \{P_1, P_2, ..., P_M\}$. The optimal control is also discretized to the set $q_j \in \{0, q_1, ..., q_J\}$. Over the state space the function $V = V_{nm}$ is a $N \times M$ matrix representing the value of the fishery for the state (I_n, P_m).

The biomass and the price stochastic shocks are denote by Z^I and Z^P respectively. These shocks are i.i.d. and normally distributed. The shocks discretization is a finite Markov chain $Z^I_k \in \{Z^I_1, Z^I_2, ..., Z^I_K\}$ and $Z^P_l \in \{Z^P_1, Z^P_2, ..., Z^P_L\}$ for the biomass and the resource price respectively. For the biomass growth shocks $\lambda^I = \lambda^I_k$ represents the probability of transition from the current shock of the biomass Z_0^I to a shock Z_k^I in the next period. For the price shocks $\lambda^P = \lambda_l^P$ represents the probability of transition from the current price shock Z_0^P to a shock Z_l^P. Using this discretization of the state space, value function, harvesting policies and stochastic shocks, Equation 14 can then be re-written as:

$$V_{n,m} = \max_{q_j \in \{0, q_2, \ldots, q_J\}} \left\{ \pi(I_n, P_m, q_j) + e^{-r\Delta t} \sum_{k=1}^{K} \sum_{l=1}^{L} \lambda_k^I \times \lambda_l^P \times V\left(I_n + \Delta I_n, P_m + \Delta P_m\right) \right\} \quad (15)$$

where $I_n + \Delta I_n$ and $P_m + \Delta P_m$ are the state of the biomass and price in Δt units of time. These variables are defined using the discrete-time version of Equations 1 and 3 and are formalized for a specific policy q_j and stochastic shocks (Z_k^I, Z_l^P) as:

$$I_n + \Delta I_n = I_n + (G(I_n) - q_j)\Delta t + I_n \sigma_I \sqrt{\Delta t} Z_k^I \quad (16)$$

$$P_m + \Delta P_m = P_m e^{\nu_P \Delta t + \sigma_P \sqrt{\Delta t} Z_l^P} \quad (17)$$

The solution algorithm follows Heer and Maussner (2009). It starts from a guess of the value-function $V_{n,m}^0$ and iterates over the defined state space. In each point of the two-dimensional state (I_n, P_m) the right-hand-side of Equation 15 is maximized using the stochastic optimal control q_j. If the optimized value of the current iteration is greater than the previous iteration value-function for the state, the old value-function is replaced by the current iteration maximized value. The process is repeated until no significant changes are made to the value-function in the latter iteration.

To complement this short description we present a formal scheme of the solution algorithm in the Appendix. The following section presents the results of the application of the value-function iteration approach for the British Columbia halibut fishery.

C. Numerical Results

As previously mentioned the model is solved for the British Columbia halibut fishery. Based on Clark (2010) we consider a 150 days season, therefore the relevant time step for our numerical solution is $\Delta t = 1/150$. The rest of the parameters used to solve the model are summarized in Table VII.

Table VII: Estimated Parameters for the British Columbia Halibut Fishery

This table is a summary of the parameters estimated on the previous subsections. Details on each parameter estimation can be found there.

Panel A: Biomass Growth Parameters

Parameter	Estimated Value	Description
I_0	57.82	2017 Biomass Assessment
I^{min}	10.01	Non-Linear Least Squares Biomass Growth Estimation
I^{max}	85.52	Non-Linear Least Squares Biomass Growth Estimation
γ	0.61	Non-Linear Least Squares Biomass Growth Estimation
σ_I	0.11	Non-Linear Least Squares Biomass Growth Estimation

Panel B: Resource Price Parameters

Parameter	Estimated Value	Description
P_0	7.75	2017 Halibut Price
ν_P	0.04	Real Halibut Log Price Returns Estimation
σ_P	0.15	Real Halibut Log Price Returns Estimation

Panel C: Cost Function Parameters

Parameter	Estimated Value	Description
c_0	0.02	Daily Cost Function Estimation
c_1	83.89	Daily Cost Function Estimation
c_2	35	Daily Cost Function Estimation

The grids for the state space, policies, and random shocks are constructed dividing a specified set in an equally-spaced discrete points. For the biomass grid boundaries are the estimated depensation level I^{min}, and carrying capacity I^{max}. For the price grid the boundaries are the 99% confidence interval, for a 10 year time horizon, constructed using the historical price distribution. For the policy grid we use a boundary of 20 million pounds per year, which is high in comparison to the current 7.45 million pounds limit, avoiding in this way having a binding upper limit on the harvesting. The specific dimensions and boundaries for these sets are presented in Table VIII:

Table VIII: Grid Dimensions and Limits for Numerical Solution

This table presents the limits and density of the discrete grids used in the value-function algorithm. Each grid used to solve the problem is a discrete set of equally spaced points within the specified interval.

Grid	Dimension	Interval	Units
Biomass Grid: I_n	80	$[10.01, 85.52]$	Million Pounds [Mill. lb.]
Price Grid: P_m	80	$[3.65, 35.03]$	CAD per pound [CAD/lb.]
Random Shock: Z_j	15	$[-2.33, 2.33]$	
Policy Grid: q_i	50	$[0, 20]$	Million Pounds per Year [Mill. lb.]

On the following subsections results for two set of parameters are presented. In the first we use the estimated real risk adjusted fishery discount rate of 2.8%. Results for a social rate of 1% are included in the subsequent section.

The model results for an alternative cost function parametrization, and a fishery which has to pay the fixed cost in case of not producing, are included in the Appendix. The main characteristic and main conclusions of the following numerical results do not drastically change on these additional cases.

C.1. Value Function and Harvesting Policies for the British Columbia Halibut Fishery Parametrization and Real Risk Adjusted Discount Rate

The result for the value of the British Columbia halibut fishery under the optimal harvesting policy is reported in Figure 8.

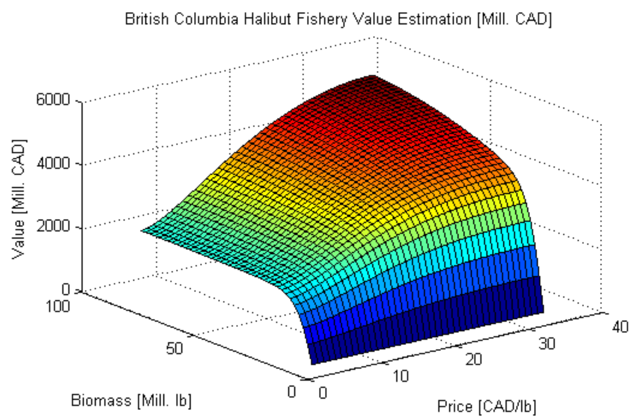

Figure 8: Value of the British Columbia Halibut Fishery Using the Real Risk Adjusted Fishery Discount Rate of 2.8%

As the resource price increases, current revenues and the incentives to increase the harvest also increase. But this will diminish the biomass level, reducing the future resources growth and increasing the future marginal cost trough the catchability of the resource. This represents the main economic trade-off in the model.

This trade-off can be observed in Figure 8. As the marginal increment in the value of the fishery is positive when the price or the biomass grow. The marginal increment in the value over the state space is non-linear, however, an extra unit of biomass becomes more valuable in high price states in comparison to low price states, as in high biomass states an extra unit not only improves the the current and future profits in a high price state, it also reduces the extraction cost.

The value of the fishery is zero in the case that the biomass reaches the lower boundary I^{min}, reflecting that once this level is reached extinction becomes inevitable.

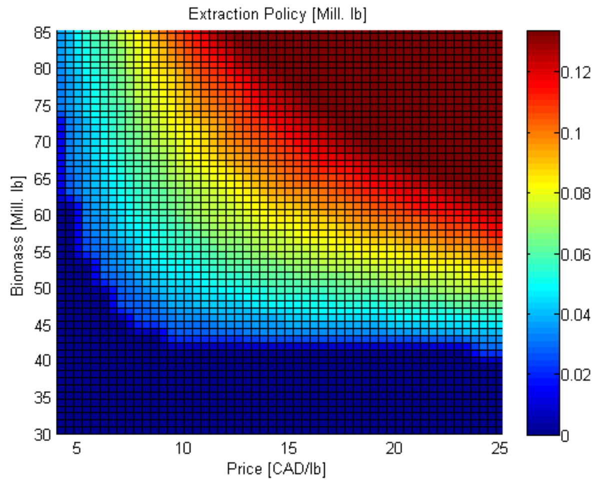

Figure 9: Optimal Harvesting Policy of the British Columbia Halibut Fishery Using The Real Risk Adjusted Fishery Discount Rate 2.8%

The optimal harvesting policy is chosen to maximize the value of the fishery. This value is shown in Figure 8. Now we turn to examine the optimal harvesting policy for different values of the state variables. Figure 9 illustrates the range of daily optimal harvesting, which goes from zero, in states of low biomass and price, to approximately 0.13 million pounds per day (20 million pounds per year) in states of high price and biomass at its carrying capacity (I^{max} = 85 million pounds). The optimal harvesting policy is also a non-linear function of the state variables.

For example, the harvesting policy in a high price state ($20 CAD per pound) goes from zero to 0.13 million pound per day as the biomass increases, but if the price is low ($5 CAD per pound) harvesting goes from zero to just 0.04 million pound per day. Table IX presents results for the value function and optimal harvesting policies for different values of the state space, including the current level of biomass and halibut price.

Figure 9 also indicates that the fishery should optimally close operations temporarily in several states, most of them characterized by low biomass and low fish prices. The periods without harvesting allow the stock to recover, increasing future growth and reducing future harvesting costs.

Table IX: Value Function and Harvesting for the British Columbia Halibut Fishery

Numerical results for selected values of the state space, including the current state I_0 = 57.82 million pounds, P_0 = \$7.75 CAD per pound. Real Risk Adjusted Fishery Discount Rate is 2.8%. Results from the value-function iteration algorithm included in the appendix for the British Columbia Halibut Fishery.

Panel A: Value of Halibut Fishery [CAD Billion]

Biomass/Price	$P = 4.75$ [CAD/lb]	$P_0 = 7.75$ [CAD/lb]	$P = 10.75$ [CAD/lb]
$I = 42.81$ [Mill. lb]	\$2.17	**\$2.47**	\$2.87
$I_0 = 57.81$ [Mill. lb]	**\$2.19**	**\$2.52**	**\$2.98**
$I = 72.81$ [Mill. lb]	\$2.20	**\$2.55**	\$3.02

Panel B: Optimal Harvesting Policy (Million Pounds per Year [Mill. lb])

Biomass/Price	$P = 4.75$ [CAD/lb]	$P_0 = 7.75$ [CAD/lb]	$P = 10.75$ [CAD/lb]
$I = 42.81$ [Mill. lb]	0	**0**	3.91
$I_0 = 57.81$ [Mill. lb]	**1.71**	**7.44**	**10.01**
$I = 72.81$ [Mill. lb]	5.64	**10.44**	13.97

Panel A of Table IX shows that the value of British Columbia halibut fishery at the current state is approximately \$2.52 billion CAD. The optimal harvesting policy will be 7.44 million pounds per year, which is consistent with the current total annual fish catch (TAC) of of 7.45 million pounds per year.

The extraction optimal policy presented in Panel B of Table IX illustrates how it changes for different values of the state space, highlighting the importance of a dynamic harvesting rights system which adjust promptly to changes on the resource price and biomass assessment.

C.2. Simulations of the Biomass and Harvesting Policies for the British Columbia Halibut Parametrization and Risk Adjusted Discount Rate

To illustrate how the halibut biomass will evolve if the optimal harvesting policy is implemented, simulations of the price and biomass are generated combining their respective distribution with the optimal policy. We simulate 10,000 different paths over an horizon of 10 Years for the biomass and the period extraction, all starting from the current state: $I_0 = 57.82$ million pounds and $P_0 = 7.75$ CAD per pound.

Figure 10 presents two different paths for the simulated fish price, biomass, and harvesting policy over a 10 year horizon.

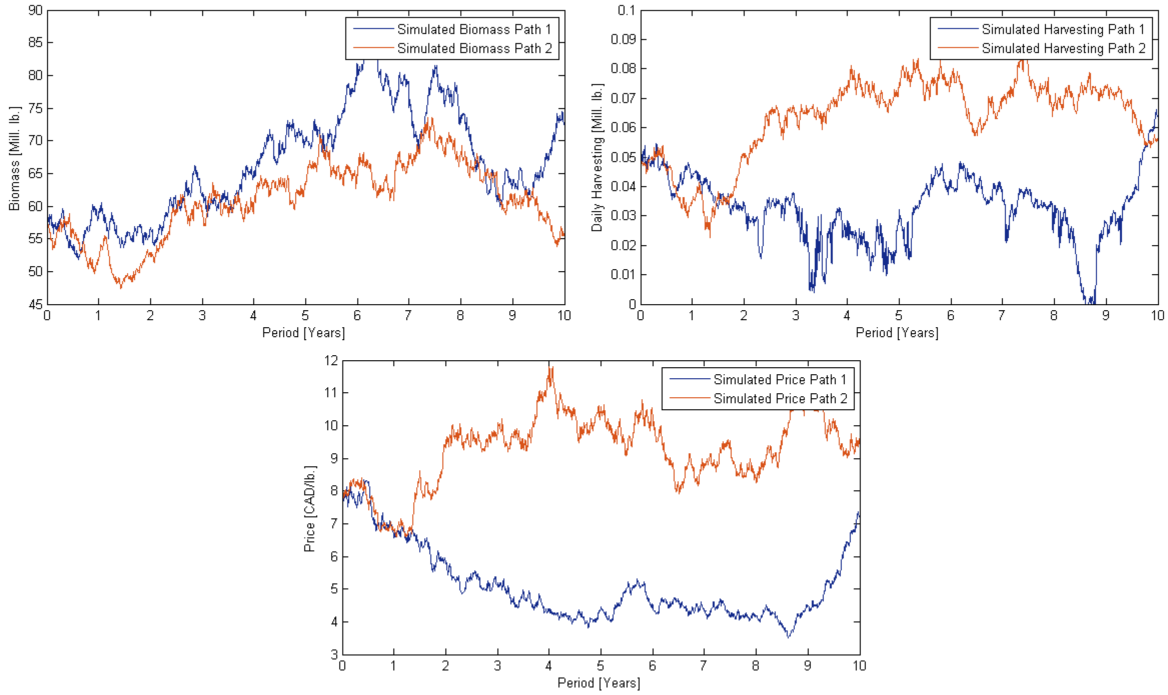

Figure 10: Simulated paths for the Price, Biomass, and Optimal Harvesting Policy for the British Columbia Halibut Fishery Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 10 shows a significant variability of the optimal harvest for the simulated paths. As the two states variables experience random shocks, the uncertainty faced by fisheries is significant, and the optimal harvesting policy adjusts reflecting those changes. "Path 1" is characterized by negative price shocks during the first 5 simulated years, which generates a reduction in the harvesting, even reaching a zero harvest period by the end of year 8. As the price remains low not a significant amount of resource is extracted (approximately 0.03 million pounds per day, 4.5 million pounds per year), allowing the biomass to growth, even reaching its carrying capacity (I^{max}) at year 6. "Path 2" differs by exhibiting a high price level for most of the simulation. As a consequence, the extraction policy remains at high levels (approximately 0.07 million pounds per day, 10.5 million pounds per year), and the biomass remains at a level close to the initial state even after suffering positive shocks by the end of year 5.

Panel A of Figure 11 shows the median, and the 1^{th} and 99^{th} percentiles, of the biomass dynamic paths. The median biomass is characterized by a growth period on which the harvesting progressively increases, and by the end of the simulation the biomass median level is higher that the initial state. The 1^{th} percentile of the biomass indicates that the there are several paths on which the biomass decreases, but it always remains away from depletion. The 99^{th} percent percentile illustrates that in paths of positive biomass shocks the biomass will approach its carrying capacity (I^{max}). Panel B of Figure 11 provides the same information for the optimal harvesting policy.

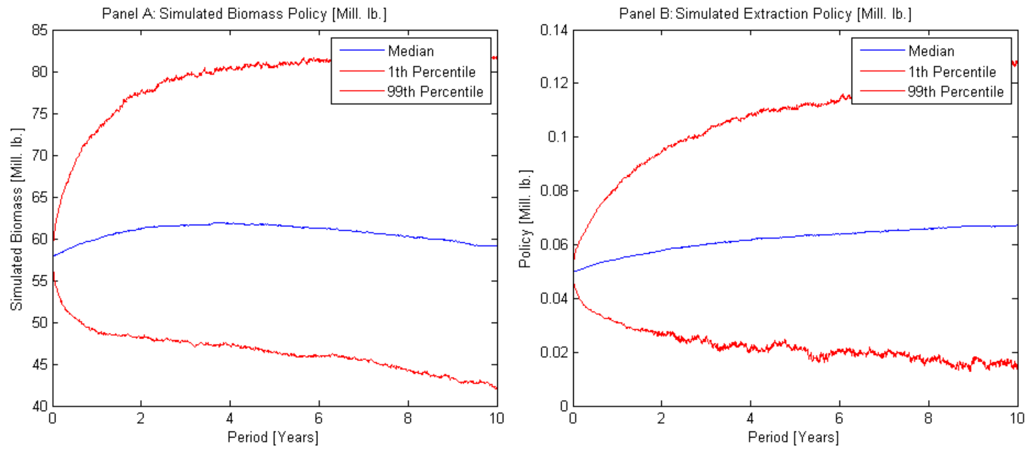

Figure 11: Median, 1^{th} and 99^{th} Percentiles of the Simulated Biomass and Harvesting Policy for the British Columbia Halibut Fishery Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

These simulations exemplify the results of the model. First, we observe a significant amount of uncertainty and a harvesting policy which adjusts promptly. Second, we notice that the biomass will increase in most of the simulated paths and it will not reach levels close to extinction with 99% probability, presenting strong evidence for the intuition that conservation is economically optimal.

C.3. The British Columbia Halibut Fishery Parametrization and a Social Discount Rate

The previous results are computed using a private discount rate. Given that this market is regulated by governmental institutions and resources are publicly owned, its important to understand how these results will change if a social discount rate is used (Clark and Munro (2017)). We set the social real discount rate to 1%, increasing the weight of future cash flows relative to current cash flows and the importance of the conservation of the resource. Figure 12 present the results for the value function and harvesting policies for the model using this new rate.

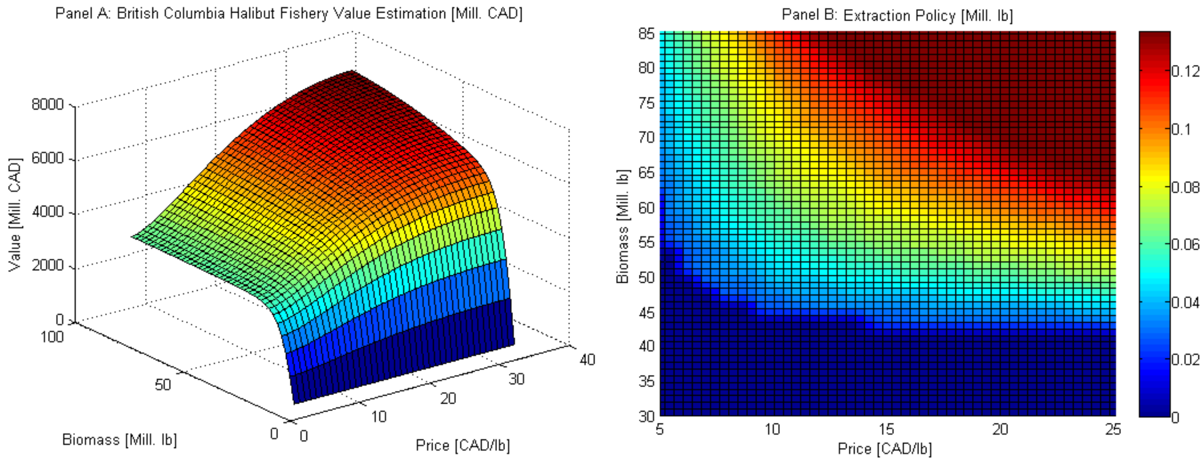

Figure 12: Value and Optimal Harvesting Policy for the British Columbia Halibut Fishery Using the Social Discount Rate of 1%

The value of the fishery increases in comparison to the private discount rate as the future cash flows have a higher present value. With respect to the extraction policy the main difference is that there are more states with a no extraction policy, indicating that the value of future revenues generated by conservation increase as they are discounted at a lower rate.

As in the previous section we simulate 10,000 paths for the biomass and the halibut price, over a 10 Years horizon and calculate the annual percentiles and median for the optimal harvesting and the biomass over the simulations. This allows us to compare the results with the ones obtained using a private discount rate. We present the annual percentiles and harvesting median over the simulated paths.

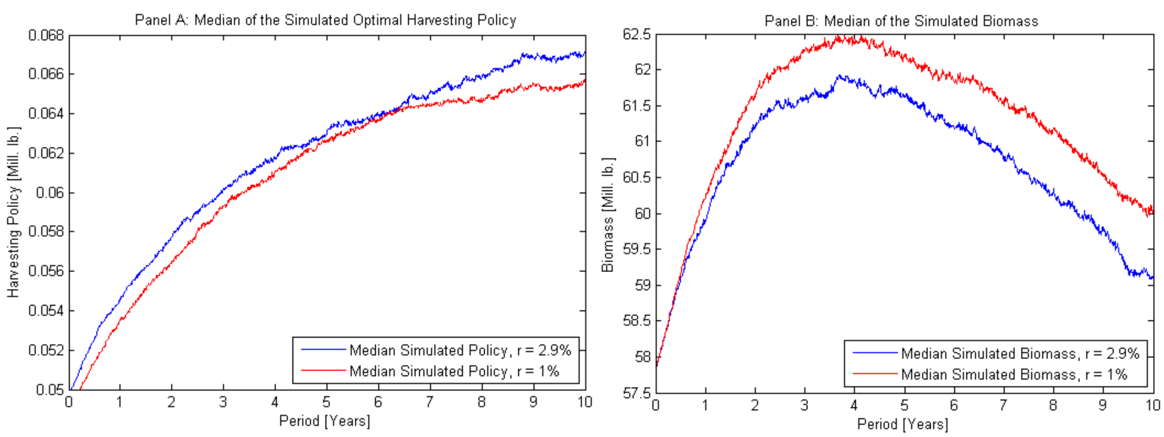

Figure 13: Simulated Biomass and Harvesting Policy for the British Columbia Halibut Fishery Using the Social Discount Rate of 1%, Compared to the Simulations Computed Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 13 shows that when using a social discount rate the model generates a higher median biomass over all the simulated period. This is the result of a harvesting policy which is also smaller than when discounting with the private rate over all the period.

Panel A of Figure 14 reports the volatility of the biomass over all the simulations. Although both simulations are subject to the same sources of uncertainty, the overall variability of the resource stock is lower when we use a social discount rate. This is evidence of a more conservative extraction resulting in less extreme scenarios. Panel B of Figure 14 shows the 1^{th} percentile of the simulated biomass. This percentile of the simulated paths is higher for the social rate of discount. Thus, there is even a smaller probability of observing the depletion of the resource in this case.

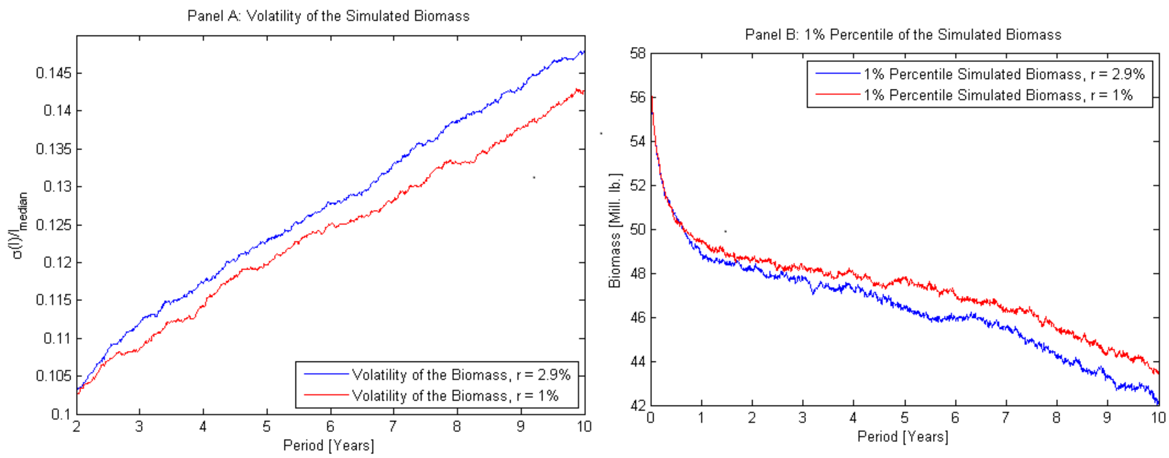

Figure 14: Volatility and 1^{th} Percentile of the Simulated Biomass for the British Columbia Halibut Fishery Using the Social Discount Rate of 1%, Compared to the Simulations Computed Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

In summary, when the social discount rate is used, the optimal harvest policy is lower and a zero harvest is more common than in the case where the private discount rate is used. Under this optimal policy the variability of the biomass paths is reduced and in most cases it is optimal to increase the biomass growth, prioritizing future resource stock over contemporary revenues.

IV. Conclusions

This article develops and implement a Real Option approach to value a renewable natural resource with two sources of uncertainty: the resource stock and the price. The solution of the model is obtained by solving a Hamilton-Jacobi-Bellman equation for the value of the Fishery. To achieve this goal we follow a value-function iteration approach. Overall, the results highlight the strong non-linear relation between the biomass and the resource price on the value of the fishery and the optimal harvesting policy, and the importance of the option to shut down and re-open the fisheries.

The solution is implemented using the estimated parameters for the British Columbia halibut fishery, for which we include the methodological details and data to help future research. The model results are used to simulate the dynamic of the studied fishery, finding that in the majority of the simulated paths it is optimal to increase the biomass. For negative shocks to the biomass growth we obtain reductions of the resource stock, but the performed simulations present evidence that with 99% probability we will not observe biomass levels close to the extinction. For the current state $I_0 = 57.82$ million pounds, $P_0 = 7.75$ CAD per pound, we found an optimal annual harvesting policy is 7.4 million pounds per year, which is comparable with the current harvesting levels.

We repeat the analysis for a social discount rate, finding that a zero harvest policy is more common over the state space, and that the variability of the simulated harvesting policies and biomass are reduced. In this case conservation becomes increasingly valuable so the optimal harvest prioritizes future resource stock over current revenues.

The model solved for a realistic set of parameters suggests that an economically viable fishery is feasible, that overfishing is indeed not optimal, even in the presence of two significant sources of uncertainty as the fish price and the biomass stock. This highlights the value of conservation and that current efforts to control overfishing are indeed efficient from a social and a financial perspective.

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Appendix A: Value-Function Algorithm Scheme

In this section we sketch the solution algorithm, describing the key steps, but abstracting from detailed calculations. Broadly, we start from an initial value function and iterate over the policy space until a maximum is attained. The outcome of the process is the maximized value-function, and the optimal policy, for each point in our two-dimensional state space.

Step 1: Initialize v_0.

To define the initial value of the value function, we use a coarse grid on the defined interval $[I_1, I_N] \times [P_1, P_M]$, and compute using our algorithm. Then, we use our desired grid, interpolate using the coarse grid, and the estimated value function, to obtain an initial value function on the finer desired grid.

Step 2: Compute a new value function v_1, and the policy q_1.

For each $(n, m) \in \{(1,1), (1,2), .., (N, M)\}$ repeat the following steps:

Step 2.1: Initialize the policy $q^*(I_n, P_m) = q_1$

Step 2.2:Find the index i^* that maximizes:

$$w_{i^*} = \pi(I_n, P_m, q_{i^*}) + e^{-r\Delta t} \sum_{k,j} \lambda_k^I \lambda_j^P \hat{v^0} \left(I_n + G(I_n) - q_{i^*} + I_n \sigma_I \sqrt{\Delta t} Z_k^I, P_m e^{\mu_P \Delta t + \sigma_P \sqrt{\Delta t} Z_j^P} \right)$$

Where q_{i^*} is $q^*(I_n, P_m) = q_{i^*}$, and $\hat{v^0}$ is the interpolated value function, for the state $\left(I_n + G(I_n) - q_{i^*} + I_n \sigma_I \sqrt{\Delta t} Z_k^I, P_m e^{\mu_P \Delta t + \sigma_P \sqrt{\Delta t} Z_j^P} \right)$, computed using the initial value function v_0. Piecewise Cubic Hermite Interpolating Polynomial are used to compute these values.

Step 2.3: Replace v^1 by the respective elements w_{i^*}, for each point in the state space (n, m).

Step 3: Check for convergence. If:

$$\max_{(n,m) \in \{(1,1),...,(N,M)\}} \mid v_{n,m}^1 - v_{n,m}^0 \mid \leq \varepsilon^{tol} \quad \varepsilon^{tol} > 0$$

stop iterating, else, replace v^0 with v^1, and return to step 2.

When the algorithm converges we have the optimal v and q for our problem.

Appendix B: Numerical Solution with Alternative Cost Parametrization

The model is solved for an alternative set of parameters for the cost function, presented in Table X.

Table X: Alternative Cost Parameters for the British Columbia Halibut Fishery
This table is a summary of the parameters estimated on the previous subsections. Details on each parameter estimation can be found there.

Parameter	Estimated Value	Description
c_0	0.02	Daily Cost Function Estimation
c_1	37.61	Daily Cost Function Estimation
c_2	55	Daily Cost Function Estimation

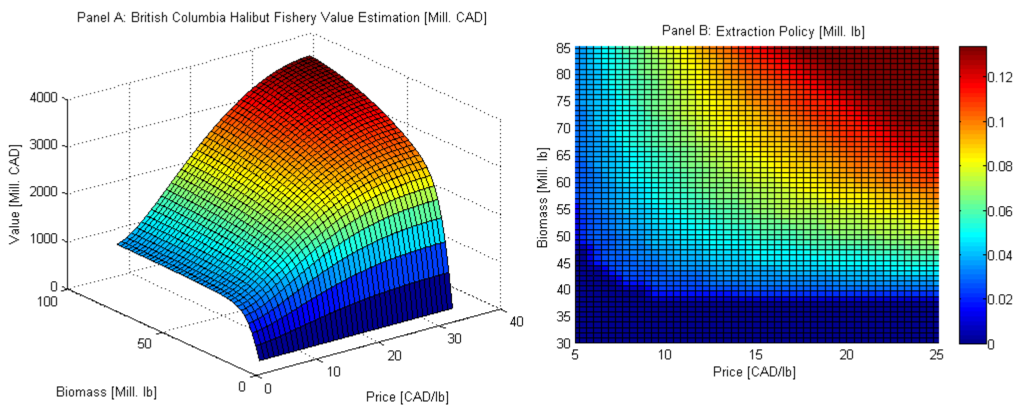

Figure 15: Value and Optimal Harvesting Policy for the British Columbia Halibut Fishery for the Alternative Cost Function $c_2 = 55$ and Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 15 illustrates that the value function is similar to the baseline case in shape, but the optimal harvesting policy exhibits a smaller region of no-extraction and of high production.

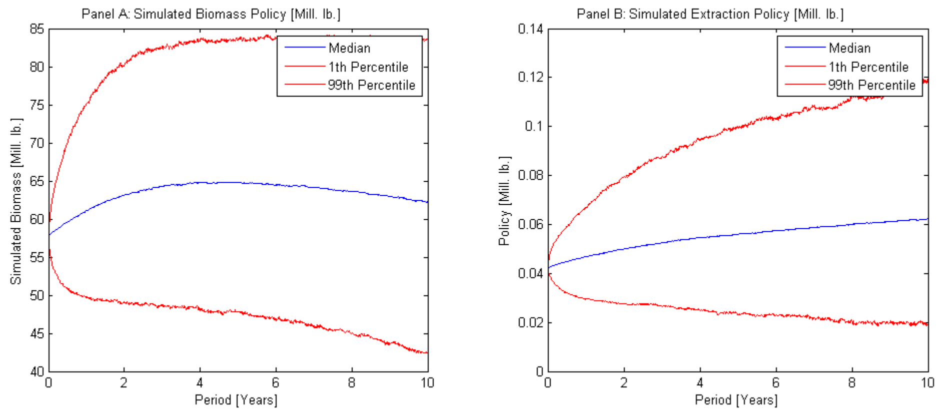

Figure 16: Simulated Biomass and Harvesting Policy for the British Columbia Halibut Fishery for the Alternative Cost Function $c_2 = 55$ and Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 16 shows the simulated biomass and optimal harvesting policy with the new parametrization of the cost function. The optimal harvesting policy is in general lower than in the case presented in the main text. For example, for the current state space the optimal harvesting is 6.27 million pounds per year versus 7.44 million pounds per year for the previous case. As a consequence, the level of the biomass is higher for the median and the 1% and 99% percentiles.

Appendix C: Numerical Solution with Costly Shutdown

This section includes a solution of the model using a cost function with costly shutdown using the private discount rate:

$$\hat{c}(I,q) = \begin{cases} c_0 + \frac{c_1}{\phi I} \times q + c_2 \times q^2 & if\ q > 0 \\ c_0 & if\ q = 0 \end{cases} \tag{18}$$

Where c_0 is the fixed cost, c_1 is the variable cost, c_2 is the quadratic cost reflecting an increasing marginal cost, and ϕ is the fishing power parameter, or catchability, which captures the efficiency of the extraction technology. Results are presented in the following figures.

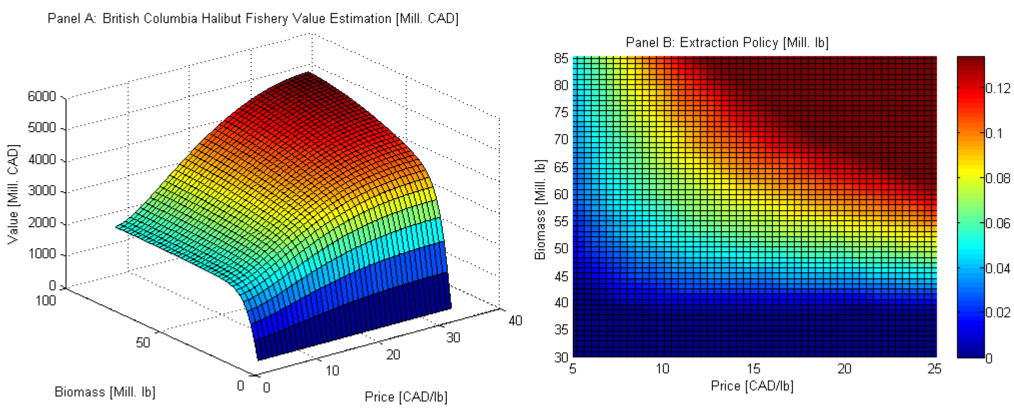

Figure 17: Value and Optimal Harvesting Policy for the British Columbia Halibut Fishery for the Alternative Cost Function with Costly Shutdown and Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 17 illustrates that the value function and the harvesting policies are similar to the previously presented cases, being the main difference that when closing is costly the no harvesting region is smaller, but this differences are observed only in low price states, which are in most of the cases not highly probable. Overall, these results indicate that the costlessly shutdown assumption is not critical for the results presented in the main text.

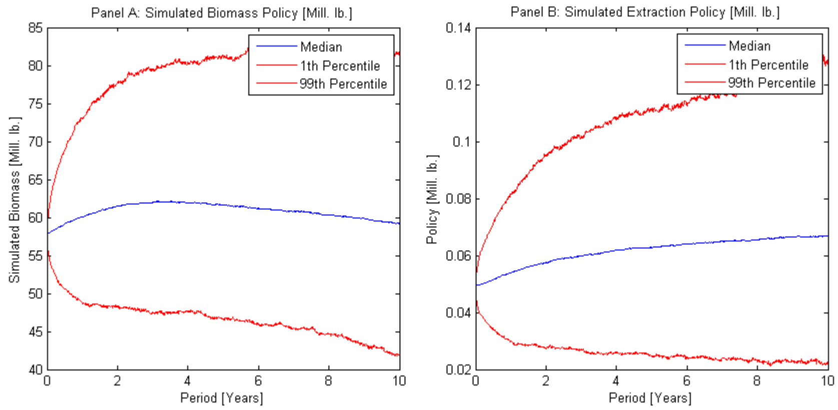

Figure 18: Simulated Biomass and Optimal Harvesting Policy for the British Columbia Halibut Fishery for the Alternative Cost Function with Costly Shutdown and Using The Real Risk Adjusted Fishery Discount Rate 2.8%.

Figure 18 shows that the simulated biomass and harvesting policies are similar to the previously presented cases. The main differences are observed for low price- low biomass states which are not highly probable. Thus the simulation results and their results remain similar to the ones presented in previous sections.

Appendix D: Sample Data

Table XI: Sample Data for the British Columbia Halibut Fishery

This table shows the sample of data collected from International Pacific Halibut Commission (IPHC) and the Department of Fisheries and Oceans of Canada (DFO) for the stock assessment (estimation of the biomass), the annual landings, the halibut ex-vessel prices, and the real log return, computed using the British Columbia CPI.

Year	Biomass [Mill. lb]	Landings [Mill. lb]	Halibut Prices [CAD/lb]	Real Price Log Return
1996	119.52	9.55	2.69	-0.11
1997	93.50	12.42	2.51	-0.08
1998	76.96	13.17	1.84	-0.31
1999	63.64	12.71	2.39	0.25
2000	67.18	10.81	2.80	0.14
2001	76.02	10.29	2.76	-0.03
2002	71.88	12.07	2.69	-0.05
2003	54.95	11.79	3.48	0.24
2004	47.37	12.16	2.77	-0.25
2005	51.03	12.33	2.69	-0.05
2006	47.99	12.01	3.42	0.22
2007	53.69	9.77	3.87	0.11
2008	56.75	7.76	3.55	-0.11
2009	62.78	6.64	3.52	-0.01
2010	63.54	6.73	4.06	0.13
2011	58.19	6.69	4.05	-0.02
2012	64.17	5.98	4.05	-0.01
2013	79.61	6.04	5.40	0.29
2014	71.79	5.88	6.40	0.16
2015	74.78	5.99	7.30	0.12
2016	73.75	6.14	7.75	0.04