A BIOECONOMIC MODEL FOR EVALUATING THE ROLE OF CONSERVATION FINANCE IN FISHERIES

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ABSTRACT

Current contributions from public and philanthropic sources, while significant, are insufficient to finance global fisheries reform. Private capital markets are a largely untapped resource that many argue can help support and sustain sustainable fisheries management. This paper explores this topic by analyzing the challenges and opportunities facing conservation finance, a growing industry seeking to balance financial returns with improvements to local environmental, economic, and social conditions. Using open access fisheries as context, we present the first application of a bioeconomic model to inform conservation finance for fisheries. We identify three strategies described by the conservation finance industry and evaluate their capacity to generate financial returns and to promote positive triple bottom-line impacts. Our model suggests that, in order for conservation finance to be effective, strong fisheries governance must first be established. If governance is not established, then conservation finance is faced with a perverse incentive in which a conservation finance project can generate value and increase employment while depleting the stock biomass. The results also suggest a tradeoff between environmental and social outcomes for fisheries operating at open access: in order to promote the recovery of the fish stock, fishing effort must be reduced. This conflicts with the stated goals of conservation finance and the broader sustainable development community to promote sustainable natural resource use without impacting the livelihoods of local stakeholders.

BIOGRAPHICAL SKETCH

Thomas received undergraduate degrees in Economics and Statistics at the University of Florida in 2015. He plans to pursue a Ph.D. in natural resource economics, focusing particularly on issues related to fisheries, aquaculture, and coastal management.

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CHAPTER 1

INTRODUCTION

Despite a rich literature on optimal resource management, over-fishing remains a key threat to the survival of coastal communities and the function of marine ecosystems [54, 91]. Fisheries support the employment of millions worldwide and are critical to the food security of countless others [29]; yet poor management continues to drive many stocks towards collapse [37, 91]. When combined with other challenges like habitat loss and global climate change, some have concluded that the future of fisheries is bleak [60].

Nevertheless, recent work seeking to quantify the gains from healthy global fisheries present a compelling case for reform: healthier ecosystems, larger harvests, and more efficient harvesting behavior could bring billions of dollars in increased profits to the seafood industry [21,89]. At the same time, a growing number of case studies provide evidence that efficient policy design can lead to local improvements to the biological, economic, and social conditions in fisheries around the world [11, 23, 38, 72]. And while reform is expensive, estimates suggest that, in the long run, the benefits could far outweigh the costs [79].

Often missing from these discussions, however, is the financing necessary to bring about and sustain desired changes in fisheries management. When available, public funds are used to support the monitoring, enforcement, and implementation necessary for successful management or to provide financial support for fishers who need to develop a new business model, purchase more sustainable fishing gear, or pursue an entirely new livelihood [52, 79]. But in many fisheries, such public support is either not available or is used to subsidize the fishing industry without consideration of sustainability [19, 79] .

As a result, non-government actors have become increasingly important as both capital providers and, more generally, as catalysts for change [31]. Citing the inability of many governments to prevent the decline of global fisheries, private foundations, Non-Governmental Organizations (NGO's), seafood wholesalers, grocery retailers, and others with an interest in sustainable seafood have effectively established their own set of tools for engaging stakeholders and influencing fisheries governance [69]. These range from assistance in the design and implementation of improved management institutions (e.g. Environmental Defense Fund's Catch Share Design Manual), attempts at leveraging the supply chain to generate demand for sustainable seafood (e.g. Marine Stewardship Council), and the provision of concessionary financing to stakeholders [31].

But many argue that these contributions are still insufficient to rebuild global fisheries [13, 65]. In fact, although the financing gap has not been directly quantified, estimates of the costs of global fisheries reform dwarf current philanthropic contributions: between 2010 and 2015, the combined contributions from philanthropic sources and from ocean-related official development assistance totaled $4.3 billion [15]; global estimates for the costs of reducing fishing effort to optimal levels (only a portion of the true costs of reform) range from $100 - $300 billion [80, 92].

Private capital markets are one of the few untapped large resources that might be able to provide financing at the scale necessary to make meaningful progress towards filling the financing gap [13, 65]. Of particular interest is the growing field of conservation finance, where private capital is used to support local improvements to environmental, social, or economic (the so-called "triple bottom-line"") conditions while also generating financial returns to capital providers [42]. Providing a platform through which philanthropic and private capital might be blended together and leveraged to finance change, conservation finance has attracted the interest of a wide variety of capital providers and, in some cases, helped to establish partnerships between foundations, NGOs, investment banks, and impact investors [42, 43, 56, 90].

To date, however, conservation finance has had comparatively little impact on seafood. Of the $5 billion in private capital committed to support sustainable food and fiber production between 2004 and 2015, only $28 million (0.5%) was invested in promoting sustainable fisheries [34]. Despite a need for capital and the development of blueprints for investment in natural resources [27, 78], too few fisheries-related projects have been able to present a salable business case for return-seeking investors. Although the long-run benefits of sustainable fisheries might exceed the costs, the costs will likely come far before the benefits can be monetized by either the fishing industry or by capital providers. As a result, the market remains largely undeveloped [85].

The purpose of this paper is to gain further insight into the challenges and opportunities facing conservation finance for fisheries. Starting with a review of the current challenges facing global fisheries, we then consider the strategies proposed by conservation finance practitioners for solving these challenges. In particular, we seek to understand if these strategies can satisfy both the financial requirements of return-seeking capital providers while also maintaining or improving the environmental, social, and economic conditions in a fishery operating at the open access equilibrium. To approach these questions, we develop a bioeconomic model of a fishery that simulates the behavior of a profit maximizing fishing fleet. Then we use the model to compare three strategies for sustainable value generation: (1) an increase in the post-harvest market value of fish, (2) the implementation of a range of optimized fishery management plans to promote stock recovery as fast as possible and (3) the implementation of gradual fishery management in which harvest price is determined by environmental outcomes. We evaluate the results based on financial outcomes and triple-bottom line impact by comparing stock size relative to maximum sustainable yield, the change in number of vessels operating, and the total profits generated at the end of a reasonable investment period. This paper contributes to the literature by providing the first application of a bioeconomic model to conservation finance for natural resource management. Although this stylized model does not represent any specific fishery, the insights from this paper can help practitioners and fishery scientists to better understand the potential of the conservation finance industry.

CHAPTER 2

CONSERVATION FINANCE FOR FISHERIES

2.1 Current Problems in Fisheries Management

The decline of global fisheries as a result of overfishing and exploitation of the marine environment is well documented [44, 50, 91]. Along with causing the decline of target fish stocks, fishing activity can incur additional environmental costs such as by-catch [24, 35], habitat destruction [36, 63, 64], and impacts on the broader trophic organization of ecosystems [53, 59]. Degraded fisheries and habitat eventually incur social and economic costs on fishing communities. Low catch per unit effort, low processing yields, product waste, and poor access to high value markets all undermine the ability of stakeholders to leverage fishing into secure livelihoods [3, 74, 86, 89].

A growing number of fish stocks are in the process of restoration and are no longer over-fished [22, 38]. But in doing so, some fisheries have failed to balance environmental objectives with economic and social outcomes [6]. To achieve success across the triple bottom-line, fisheries need sustainably managed resource stocks supporting profitable harvest and processing businesses that are integrated with and support local communities [6, 26, 33]. Accordingly, pursuit of a triple bottom-line notion of sustainability has started to reshape the priorities of governments, private firms, foundations, and other social interest groups working to promote a holistic approach to ocean health [1].

A single model certainly could not address the wide range problems facing global fisheries. To narrow the scope, we focus specifically on fisheries operating at open access, where no management institutions or agreements govern fishing behavior, as the motivating context. Open access conditions produce a problem for common-pool resources like fisheries. Faced with a rival but non-excludable resource, economic theory suggests that fishermen will compete with one another until the economic profits of harvesting are driven to zero. These conditions will drive inefficient levels of fishing effort, overinvestment in productive capital and, in many cases, overexploited fish stocks [30]. Although true open access fisheries are uncommon, fishers subject to poorly enforced regulations or whose activities are unmonitored can behave as if they were under open access. Evidence from fisheries operating under such conditions tend to follow theoretical expectations for open access resource use [45, 49, 51, 68, 81].

This is particularly relevant to fisheries in developing countries, where the infrastructure, regulations, or institutions necessary for effective governance might not exist [9, 69, 87]. In some cases, fishing is an occupation of last resort in which resource dependent, marginalized communities struggle with poverty and malnutrition. Fishery improvements must strike a delicate balance between supporting a vulnerable fishing community and recovering a potentially collapsed fish stock [3]. Given that roughly half of all seafood entering international markets comes from developing countries [29], open access fisheries present an important and relevant issue for sustainable seafood. It is, therefore, reasonable to believe that fisheries with these characteristics are plausible targets for conservation finance. Not only are the environmental, social, and economics needs significant but, without changes, these fisheries will likely continue to decline towards the open access equilibrium [30].

2.2 Defining the Role of Conservation Finance in Fisheries

In order to address the problems caused by open access fisheries and other management failures, project managers need to gain access to new sources of financing. In this paper, we are particularly interested in conservation finance as a source of private capital. In contrast to philanthropic capital or development assistance funding, private capital engaged in conservation finance operates in a competitive market: To attract return-seeking capital providers, conservation projects must meet investor expectations regarding financial returns and investment risk [43].

On the surface, seafood products are valuable, widely traded, and present a clear case for investment: annual global seafood exports of $148 billion represent 1% of all products traded globally [29]. Current models suggest that rising global incomes and population growth will continue to drive strong demand and support high seafood prices [83, 88]. And, as mentioned in a previous section, sustainable and efficient management of fisheries could bring billions in additional profits to the global seafood industry [89]. But international seafood markets are complex, involving hundreds of commercially important species sourced through long, fragmented supply chains [5]. Furthermore, unlike most other sources of protein, wild capture fisheries exist in the context of a broader ecosystem, making their profits sensitive to natural fluctuations in the environment [73]. Under open access conditions, these systemic risks add an additional layer of complexity to the perverse incentives already facing fishermen.

Strategies for Generating Value

With these risks as context, conservation finance deals must generate value for both stakeholders and capital providers. Holmes et al. [39], suggest that investment can be channeled towards the following drivers of increased value: the health of the fish stock, the operational efficiency of fishing activity, and the market value of harvest. The few case studies of proposed or existing conservation finance projects generally follow this framework. They exhibit investments in improved technology for regulation enforcement [27], fishing quota to reduce fishing effort [27, 52], processing plants for sustainably sourced seafood [27, 82], and distribution/marketing companies with access to international sustainable seafood markets [27, 52, 82].

To reflect these different approaches to value generation, we model three interventions in this paper.

Intervention 1: Increase in post-harvest value

The first intervention simulates the capture of increased market value post-harvest. This could reflect a number of different strategies that occur outside of the harvesting sector such as an investment in marketing efforts, distribution timing, or processing quality [69]. All else equal, higher marketing or processing margins and broader market access would increase the demand for fish, driving up dockside prices [41]. This approach is particularly relevant for impoverished communities characterized with poor economic or social conditions. Providing market access and increasing revenues from fishing might generate important improvements to lives of stakeholders without the costs of reforming management.

Intervention 2: Optimal Management Reform

The second intervention for value generation is management reform. There are a wide range of possible management reforms that, if implemented and enforced, would change the incentives faced by fishers. A significant portion of fisheries science and economics has been dedicated to evaluating biological, economic, and (to a lesser extent) social outcomes associated with these alternatives. Examples include permit and season limits [40], co-management [32], catch shares [23], individual transferable quotas [7], and marine protected areas [48]. For the purposes of this paper, we follow Anderson & Seijo [8] by aggregating these management approaches into three broad categories: input controls, output controls, and dedicated access permits (D.A.P.'s). Although economic theory suggests some policies to be more efficient than others, political and social realities often prevent most fisheries from pursuing the first-best policy. In fact, many fisheries around the world exhibit a combination of these three general management types [69].

Intervention 3: Gradual Management Reform and Endogenous Price

The third intervention models value generation through management while also incorporating both a minimum effort requirement and an endogenously determined market price. The minimum effort level prevents a complete fishery closure, slowing the recovery path of a fishery. Although complete fishery closures are, in many cases, technically optimal, the welfare costs of closure are difficult to measure and implementation may be unrealistic [17].

An endogenously determined price premium plausibly represents the impact of an ecological certification scheme on harvest price. These certifications are awarded through a rigorous approval process in which fisheries must prove that the fishery is sustainably managed. In doing so, the certifications serve as a gatekeeper to premium markets and serve as a monetary incentive for sustainable resource use. Certification, such as through the Marine Stewardship Council, have also become the goal for many fisheries improvement projects around the world [69]. Many studies have shown that retail consumers are willing to pay a premium for sustainable seafood [10,67] and that, in some cases, this can lead to higher dockside prices [77].

2.3 Characterizing Success and Model Assumptions

In a more realistic setting, project managers would likely blend public, philanthropic, and private capital together in order to match the risk preferences of different capital providers with separate stages of the improvement project [85]. For the purposes of this paper, we take a broader approach and evaluate the performance of each intervention against environmental, economic, and social outcomes - the triple bottom-line. But measuring improvements on the triple bottom-line is a complex task. Anderson et al. [6], for example, propose 68 different metrics to measure the environmental, economic, and social conditions of fisheries. For the sake of simplicity, we will define success with one indicator for each pillar of the triple bottom-line. These indicators are evaluated at the end of an investment horizon of ten years, which reflects the time preferences of return seeking investors [25]. Although a primary goal of conservation finance is to generate improvements that will last far into the future, all private financiers will have an exit strategy to limit risk and to realize investment gains [42]. To account for this, we have chosen a time horizon that is a common duration for private equity funds, a popular vehicle for aggregating private capital for use in conservation finance [42, 52, 82].

Environmental Improvements

Environmental improvements will be defined as increases in biomass relative to the open access equilibrium and evaluated by comparison to stock size at maximum sustainable yield (MSY). This reflects the benchmarks accepted by the scientific community (e.g. [72]) and matches the stated priorities of the conservation finance industry. Encourage Capital, L.L.C. (hereafter referred to as Encourage Capital) defines its ecological objectives as either increasing or preventing further declines in biomass [27]. Althelia Ecosphere, L.L.P. (hereafter referred to as Althelia) calls for projects that "involve no net loss of biodiversity" and which "drive conservation of natural habitats and wild species [4]." The Meloy Fund proposes a slightly more structured benchmark, stating that the "target species from which the investee is sourcing [must] have the biological potential for recovery throughout the life of the investment [82]." Although the Meloy Fund and others utilize MSY as a reference point, each focuses on broad incremental improvements as the core goal for interventions.

Social Improvements

We define a social improvement as an increase in the number of vessels operating (a rough proxy for employment) relative to starting values. Community health is particularly relevant for conservation finance because projects are critically dependent upon strong working relationships with local stakeholders. For example, Encourage Capital commits itself to improving community resilience (measured through financial contributions to a community trust), empowering fishing communities (measured by the number of fishing communities impacted), and increased meal production for local and regional consumption or for international export (measured through projected increases in landing volumes, increases in utilization of discarded bycatch, and reductions in supply chain spoilage) [27]. The Meloy Fund focuses on employment and their standards state that the "investee will work to minimize adverse impacts on ...employees and all stakeholders [82]." Althelia takes an even broader approach, requiring simply that all funds support projects that demonstrate no loss of income or livelihood as a result of the projects use of land or other resources [4].

Economic/Financial Improvements

Economic improvements will be combined with financial performance. Because this model does not account for distribution of profits between stakeholders and capital providers, we assume that the total returns generated by the fishery is also a measure of the financial performance. Returns will be measured relative to the gross value of the fishery at open access, simply the total revenues generated by the fishery. To be successful, it must generate positive net profits by the end of the investment period. This flexible approach also accounts for the wide-range of capital providers relevant to the conservation finance industry. Although the purpose of conservation finance is engage with private capital markets, providers of grants or concessionary financing that do not require market rate returns play an important role in conservation finance deals [85].

CHAPTER 3

METHODS

Bioeconomic models have been used extensively to describe fisheries and other marine resources under a variety of conditions. Applications include fisheries operating under open access [12, 30, 76] and a variety regulation types [8, 16, 40]; the derivation of optimal dynamic utilization [18]; the incorporation of spatial connectivity [14,61,70,75]; and the consideration of stochastic environmental or economic processes [20, 23, 66]. More recently, bioeconomic models have been used to analyze strategies for rebuilding fish stocks [2, 47] and to estimate the economic and biological impacts of global fishery management reforms [21, 89].

We employ the discrete-time bioeconomic model described by Anderson and Seijo [8] to simulate a single species fishery at open access. Their stylized approach is useful in that it explicitly accounts for vessel-level behavior in addition to fish population dynamics. The profit-maximizing behavior of each vessel serves as the driver for both the optimization of alternative management strategies as well as for simulation under open access. Each fisher/vessel owner is identical and operates in a perfectly competitive market. We assume that the demand for fish is perfectly elastic, meaning that a change in the amount of fish harvested will not impact dockside prices. This is a reasonable assumption for a fishery that is a small supplier for a much larger seafood market.

3.1 Bioeconomic Model Under Open Access

Stock size is determined by Schaefer's model of density-dependent growth [71]. We assume that a single fish stock is harvested by identical fishermen where harvest is a function of stock size and aggregate fishing effort. Accordingly, the fish stock is modeled using the following recursive equation:

$$X_{t+1} = X_t + F(X_t) - Y(X_t, f_t, v_t) \tag{3.1}$$

where X_t is stock size in year t, F is the natural recruitment function of the fish stock (Appendix A), and Y is the fishery production function, defining the relationship between stock size, the number of vessels in the fishing fleet (v_t), and individual vessel effort (f_t) in year t. The profits for an individual vessel for a given year are modeled with the following function:

$$\tilde{NR}_t = \rho\gamma\delta f_t X_t - \delta[\alpha f_t + \beta f_t^2] - \Phi \tag{3.2}$$

where ρ is dockside price, γ, α, β are constants, δ is number of days fished, and Φ is fixed costs. In the absence of regulations, each vessel is free to choose the level of fishing effort that maximizes profits during each season. We assume that, on each day fished, vessels operate where marginal revenue from fishing is equal to the marginal costs of fishing:

$$\rho\gamma X_t = \alpha + 2\beta f_t \tag{3.3}$$

Solving for the profit-maximizing level of daily effort,

$$f_t^* = \frac{\rho\gamma X_t - \alpha}{2\gamma} \tag{3.4}$$

We can then rewrite equation 3.2 using f_t^*:

$$NR_t = \rho\gamma\delta f_t^* X_t - \delta[\alpha f_t + \beta f_t^{*2}] - \Phi \tag{3.5}$$

This assumes that fishing vessels produce the same amount of effort each day over the course of the year. Or, on average, vessels maximize profits over the course of the year. Additional details are described in Appendix A.

New vessels enter the fishery at a rate proportional to vessel profits generated by the fishery in the previous year. Changes in the size of the fishing fleet are defined by:

$$v_{t+1} = v_t + \phi NR(X_t, f_t^*) \tag{3.6}$$

where ϕ is a positive constant and NR_t is net revenue in period t: To evaluate the economic outcomes of each intervention, we calculate the net present value of profits over the investment horizon ($T^* = 10$) using the following equation:

$$NPV_{T^*} = \sum_{t=0}^{T^*} \left(\frac{1}{1+i}\right)^t NR_t v_t \tag{3.7}$$

where i is the discount rate, NR_t is the total profit per vessel in year t, and v_t is the number of vessels operating in the fishery in year t.

3.2 Interventions

Intervention 1: Increase in Post-Harvest Value

In the first intervention, we simulate the impact of an increase in the market value of fish. As stated in a previous section, one of common strategies proposed by the conservation finance industry is to capture lost value by investing in the supply chain [69]. Improvements to the processing, distribution, and marketing of products from the fishery can generate value by creating higher margin products and engaging premium markets. This exogenous shift in the perfectly elastic demand curve can be modeled by multiplying the base price parameter by a positive constant, $\theta > 1$. Individual vessel profits can now be written

$$NR_t = \theta \rho q \delta f_t X_t - \delta[\alpha f_t^* + \beta f_t^{*2}] - \Phi \tag{3.8}$$

Under the new price conditions, the fishery is simulated for the course of the investment horizon. At the end of the investment horizon, we calculate the net present value of fleet profits by substituting equation 3.8 into equation 3.7.

Intervention 2: Optimal Management Reform

In the second strategy, we consider an investment in fisheries management reform. Specifically, we model three management alternatives: input controls on fishing effort, output controls that identify a total allowable catch per season, and output controls using dedicated access permits (D.A.P.'s). In structuring the model to consider many different possibilities, our results apply to a broad typology of fisheries.

Instead of simulating the fishery as under Intervention 1, here we are able to calculate the optimal dynamic utilization of the fishery for each policy type by maximizing the net present value of harvesting profits over a finite period ($T = 30$). T is chosen to reflect the fact that the goal of conservation finance is to produce improvements that last far beyond their involvement; however, the results will be evaluated at the end of the investment horizon, T^*. A generalized form of the optimization objective function is

$$\max\{NPV_T\} = \max\left\{\sum_{t=0}^{T}\left(\frac{1}{1+i}\right)^t NR_t v_t\right\} \tag{3.9}$$

where i is the discount rate, NR_t is the total profit per vessel in year t, and v_t is the number of vessels operating in the fishery in year t. The optimization routines are described in table 3.1 with additional details provided in Appendix A. At the end of the investment horizon, we calculate the net present value of fleet profits utilizing equation 3.7.

Table 3.1: Intervention 2 Summary

	Input Constraint	Output Constraint	D.A.P.'s
Objective	Maximize Net Present Value of Harvest	Maximize Net Present Value of Harvest	Maximize Net Present Value of Harvest
Control Variable	Total Fleet Effort	Total Harvest	Total Harvest
Constraints	$0 \leq E_t \leq E_{MSY}$ $X_0 \leq X_t$	$0 \leq Y_t \leq Y_{MSY}$ $X_0 \leq X_t$	$0 \leq Y_t \leq Y_{MSY}$ $f_t^* = f_{MIN}$ $X_0 \leq X_t$

The key distinctions between each management approach come in the optimization constraints, particularly in the mechanisms driving individual fishing effort. Under each management intervention, we assume that enforcement is perfect, that harvest must remain below the maximum sustainable yield (Y_{MSY}), and that the stock size must remain at or above the initial stock size (X_0). The optimal daily fishing effort, occurs where marginal cost equals both marginal revenue and average cost [7]. Under input or output constraints, there is no mechanism could maintain individual fishing effort at this level. D.A.P.'s, however, will eventually achieve this optimal level of effort, regardless of the starting stock size [7]. For the purposes of optimization, therefore, we assume that vessel owners under D.A.P.'s operate at both the profit maximizing and cost minimizing levels of fishing effort at every time period. At the same time, only the optimal number of vessels are allowed to operate in a given period (see Appendix A for details). While this ignores some of the nuances of D.A.P.'s, the resulting harvest path is the most efficient solution possible and is sufficient for this analysis.

Intervention 3: Gradual Management Reform and Endogenous Price

In order to account for potentially high social costs associated with intervention 2, we consider a third, more moderate recovery approach for Intervention 3. Here, we use the same optimization framework as in Intervention 2 but with two main differences: (1) a constraint that prevents total fishing effort from falling by more than 50% from the open access equilibrium (see supplement for details) and (2) and endogenous price function with the following functional form:

$$P_t = \begin{cases} \rho & X_t < X_{MSY} \\ \rho(1+\tau) & X_t \geq X_{MSY} \end{cases} \tag{3.10}$$

When the stock size is less than stock size at maximum sustainable yield, the base parameter is used for dockside price. When stock size rises above maximum sustainable yield, a premium $\tau > 0$ is added to the price. This price premium is applied to all three of the management reforms described in intervention 2: input controls, output controls, and dedicated access permits. At the end of the investment horizon, we calculate the net present value of fleet profits utilizing equation 3.7.

Table 3.2: Intervention 3 Summary

	Input Constraint	Output Constraint	D.A.P.'s
Objective	Maximize Net Present Value of Harvest	Maximize Net Present Value of Harvest	Maximize Net Present Value of Harvest
Control Variable	Total Fleet Effort	Total Harvest	Total Harvest
Constraints	$0 \leq Y_t \leq Y_{MSY}$ $E_{BE}/2 \leq E_t$ $X_0 \leq X_t$	$0 \leq Y_t \leq Y_{MSY}$ $E_{BE}/2 \leq E_t$ $X_0 \leq X_t$	$0 \leq Y_t \leq Y_{MSY}$ $E_{BE}/2 \leq E_t$ $f_t^* = f_{MIN}$ $X_0 \leq X_t$

Model Parameters

The model parameters were chosen using relevant values chosen from the literature and are displayed in 3.3. Economic parameters are normalized to the ex-vessel price of fish and biological parameters are normalized to the carrying capacity in order to maintain generality. The model is initialized at the open access equilibrium, where $X_{t+1} = X_t = X_{OA}$ and $v_{t+1} = v_t = v_{OA}$. Under the base parameters, stock size at open access is 29% of natural carrying capacity and 58% of stock size at maximum sustainable yield. Under these conditions, the fishery is not able to produce the maximum sustainable yield and is therefore "overfished [58]."

Table 3.3: Parameter Values

Parameter	Description	Value	Source
σ	Stock Productivity	0.300	Anderson & Seijo [8]
κ	Carrying Capacity	1.000	Anderson & Seijo [8]
ρ	Price of Fish	1.000	Anderson & Seijo [8]
γ	Catchability Coefficient	$5.000\text{x}10^{-5}$	Anderson & Seijo [8]
α	Vertical Intercept of Daily Marginal Cost	0.294	Anderson & Seijo [8]
β	Slope of Daily Marginal Cost	0.294	Anderson & Seijo [8]
Φ	Fixed Costs	176.471	Anderson & Seijo [8]
δ	Number of Days Fished	150.000	Anderson & Seijo [8]
f_{MAX}	Maximum Daily Effort	3.200	Anderson & Seijo [8]
f_{MIN}	Minimum Daily Effort	2.000	Calculated (Eqn. A.13)
ϕ	Entry/Exit Coefficient	0.002	Bjørndal & Conrad [12]
X_0	Initial Stock Size (X_{OA})	0.294	Calculated (Eqn. A.14)
v_0	Initial Fleet Size (v_{OA})	14.117	Calculated (Eqn. A.15)
X_{MSY}	Stock at Maximum Sustainable Yield	0.500	Calculated (Eqn. A.25)
Y_{MSY}	Maximum Sustainable Yield	0.075	Calculated (Eqn. A.24)
θ	Intervention 1 Premium	25%	Encourage Capital [27]
τ	Intervention 3 Endogenous Multiplier	18%	Stemle, Uchida, & Roheim [77]
i	Discount Rate	5%	World Bank [89]
T^*	Investment Horizon	10	de Malherbe [25]
T	Optimization Horizon	30	By Assumption

Although the model parameters were chosen as representative estimates, global fisheries are incredibly diverse, particularly in regard to biological characteristics. The level of stock productivity used in this model is considered "medium productivity" by Musick [55]. To account for the broad diversity in life history strategies, a sensitivity analysis (see Appendix B) has also been conducted for stocks ranging from “high” to “very low” productivity [55].

CHAPTER 4

RESULTS

The table below outlines the results at the end of the investment period. Financial outcomes are presented as the net present value of profits at the end of the investment horizon (NPV_{T^*}) relative to the gross value of the fishery at open access (ρY_0). Environmental outcomes are measured as stock size at the end of the investment period (X_t) relative to stock at maximum sustainable yield (X_{MSY}). Social outcomes are measured by the number of vessels operating at the end of the investment period (v_{T^*})relative to the number of vessels operating at open access (v_0).

Table 4.1: Model Results

	Financial/Econ. Outcomes	Environmental Outcomes	Social Outcomes
Measure	$NPV_{T^*}/\rho Y_0$	X_{T^*}/X_{MSY}	v_{T^*}/v_0
Intervention 1: Increase in Post-Harvest Value			
Open Access	0.676	0.461	1.109
Intervention 2: Optimal Management Reform			
Input	1.904	1.236	0.357
Output	1.571	1.268	0.538
DAPS	2.150	1.240	0.581
Intervention 3: Gradual Reform with Endogenous Price			
Input	1.671	1.100	0.313
Output	1.156	1.080	0.500
DAPS	1.875	1.080	0.639

Interventions 2 and 3 generate significant profits by the end of the investment period. The net present value of these profits range from 1.2-2.2 times the gross value of the fishery at open access. Interventions 2 and 3 also generate positive environmental outcomes, with each management strategy producing fish stocks at

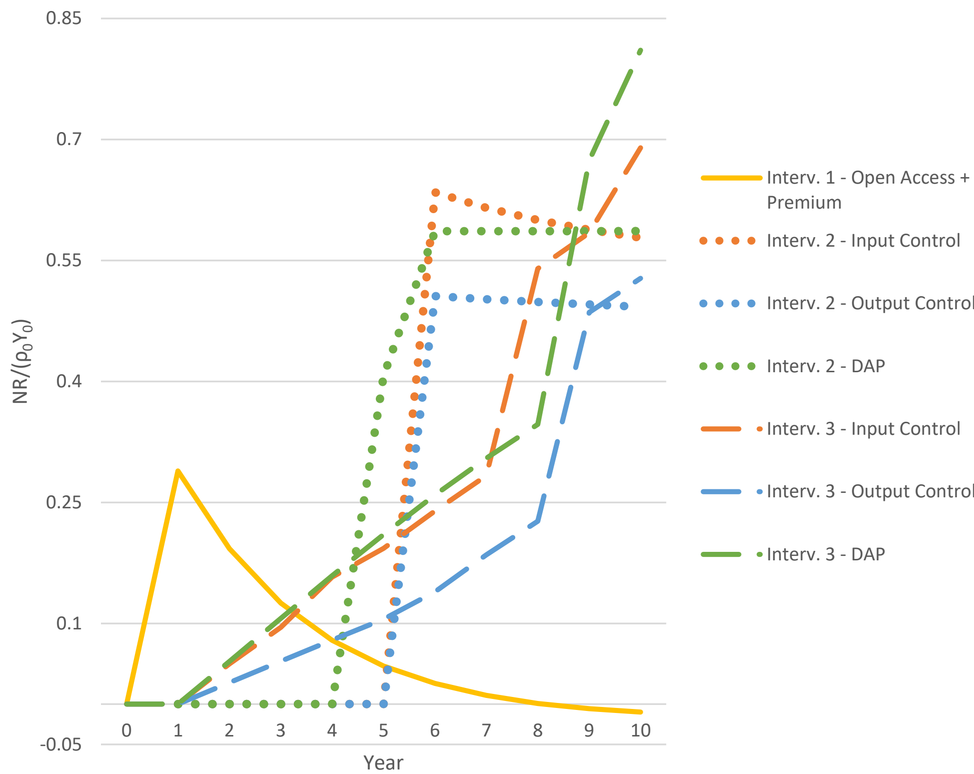

Figure 4.1: Profits as Percentage of Gross Value at Open Access

or above stock size at maximum sustainable yield. This is significant because it indicates that a recovering fishery can generate value within a reasonable investment horizon as long as effective governance is in place. This stands in contrast to Intervention 1. Under open access, the fishery generates some value (0.676 times gross value) but only at the expense of the environmental health of the fish stock. Furthermore, profits are only generated during the first eight years of the investment horizon: By the end of the investment horizon, increases in the number of vessels operating dissipates any profits generated.

While Interventions 2 and 3 achieve the economic and environmental outcomes, they also require 34% - 64% decreases in the number of vessels operating. As a result, they fail to meet the benchmark for social improvement. In contrast, Intervention 1 leads to 10.9% increase in the number of vessels operating which

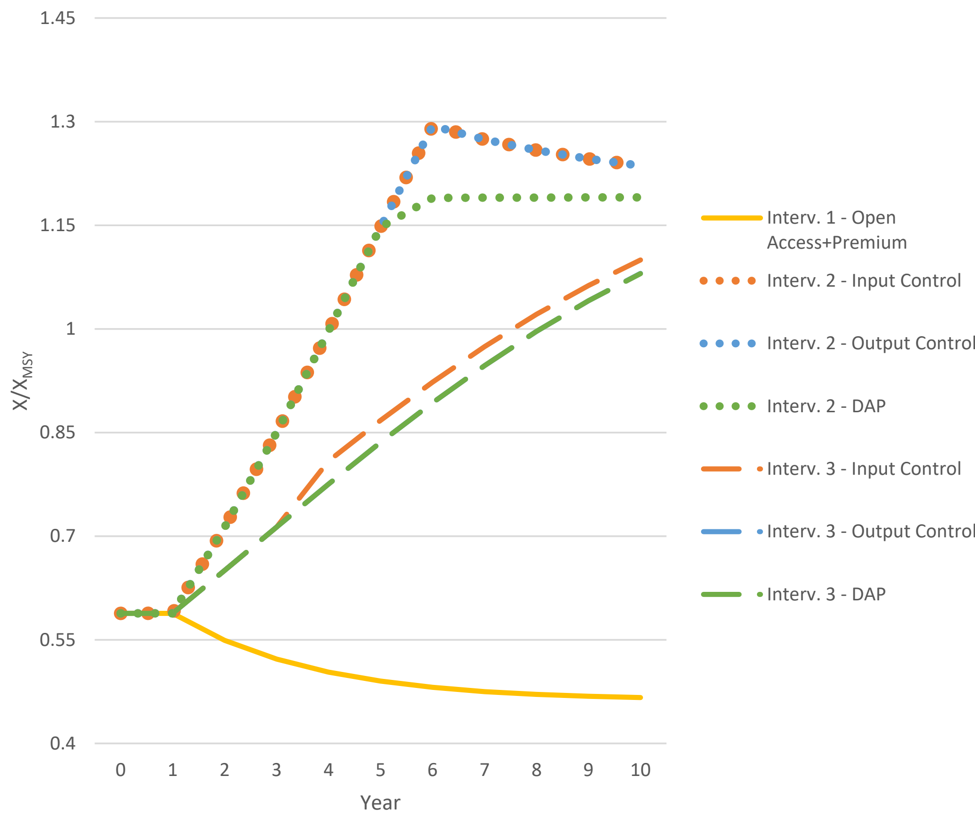

Figure 4.2: Stock Size Relative to Stock at MSY

meets the criteria for social improvement. The apparent tradeoff between social and environmental/financial objectives is also apparent in the optimal approach paths for Intervention 2, where the optimal solution in each management strategy for Intervention 2 is the complete closure of the fishery for multiple years. This represents the fastest possible recovery time for the fish stock but would likely impose significant costs on the fishing community not adequately captured by this model. The results from intervention 3 indicate that some of these impacts can be mitigated through a more moderated recovery path and the addition of a price premium. By preventing a full closure of the fishery, Intervention 3 takes a slower recovery trajectory; however at the end of the investment horizon, the environmental and financial outcomes are similar to those of Intervention 2.

The sensitivity analysis in Appendix B indicates that these results are sensi-

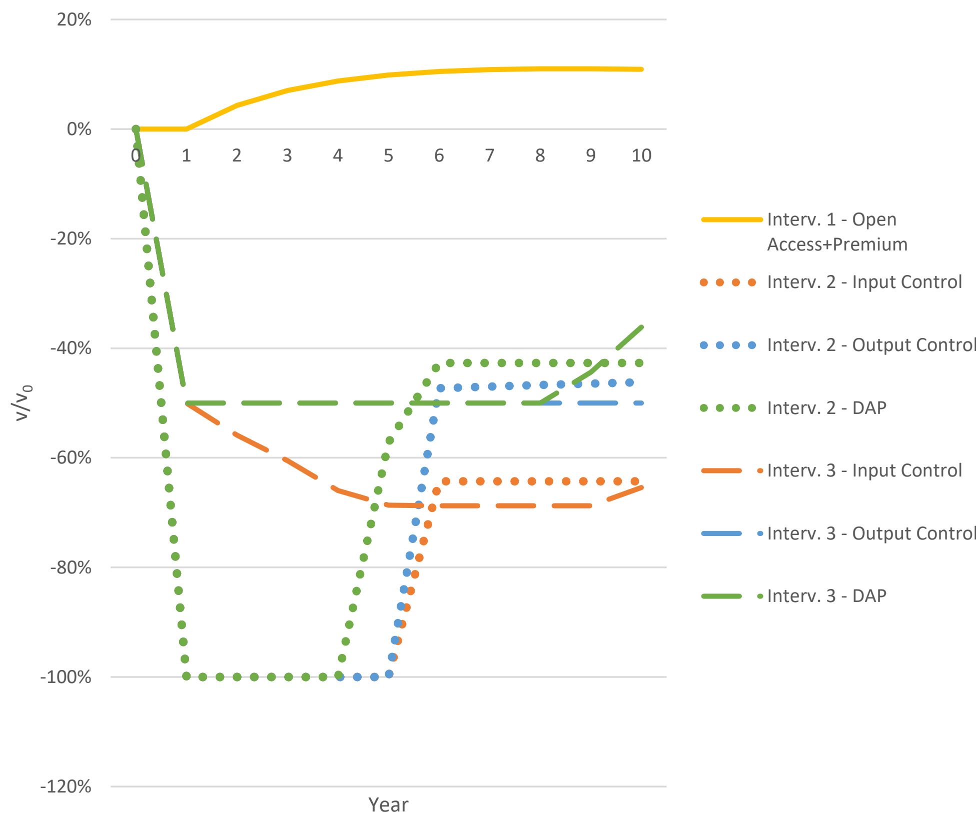

Figure 4.3: Fleet Size

tive to the biological productivity of the fish stock (σ). In intervention 1, low productivity stocks generate much larger financial gains than do high productivity stocks. To some extent, this simply be numerical: All else equal, low productivity fish stocks under open access support a smaller fleet than do high productivity fish stocks. A smaller fleet will harvest less than a larger fleet when the capacity of each vessel is finite. This also means that the smaller fleet can generate less total revenue and a less valuable fishery. When the value of harvest is increased through Intervention 1, the percentage increase in profits is, therefore, much larger for low productivity stocks than for high productivity stocks.

Interventions 2 and 3 are also sensitive to productivity but in the opposite direction. In Intervention 2, very low productivity stocks produce a fishery closure that lasts for the entire investment period. This produces no financial returns for either fishers or capital providers while the stock size remains below X_{MSY} by the end of the investment period. Highly productive stocks are also highly profitable, with financial returns between two and three times gross value at open access. Although these high productivity stocks also reach a sustainable stock size within the investment period, the social outcomes are far less sensitive to productivity: even high productivity stocks require significant reductions in fleet size.

The size of the price premia from Interventions 1 and 3 are also important to consider. As the price premium from Intervention 1 (θ) increases, financial outcomes over the course of the investment horizon initially increase but become negative when $\theta = 100\%$. Because vessels enter the fishery at a rate that is proportionate to profits from fishing, an increasingly large price premium drives faster fleet growth. A larger fleet generates larger profits initially but also leads to faster profit dissipation. When premiums are low, the present value of profits over the investment horizon is positive and large. But at very high premiums, profits are dissipated too quickly leading to negative financial outcomes. In contrast, increases in the premium in Intervention 3 (τ) lead directly to increased profits. Once governance is in place, an increase in the value of fish leads directly into value for both fishers and capital providers. The environmental and social outcomes, however, appear invariant to the size of the premium.

CHAPTER 5

DISCUSSION

The dynamic behaviors displayed by the model have many implications for conservation finance in fisheries. In this section, we focus on three main insights: the role of fisheries management in supporting conervation finance, the tradeoffs existing between environmental and social objectives in reforming fisheries at open access, and the importance of relationships between private, public, and philanthropic actors to the efficacy of conservation finance for fisheries.

Governance Must be a Priority

Without effective fisheries management, the strategies proposed by the conservation finance industry will fail to generate lasting value and will not support triple bottom-line improvements in the fishery. An increase in the value of catch will increase the value of an open access fishery during th investmeent horizon. But it will not change the underlying incentives driving fishing behavior. If effective governance is not in place before a strategy to monetize fishery improvements is implemented, any short-term profits will eventually be dissipated as new vessels enter the fishery. This is particularly relevant for project managers seeking to build relationships with local stakeholders. As described by Sampson et al. [69], many fisheries improvement projects in developing countries are given access to higher margin, sustainable seafood markets before making any improvements to fisheries management. While this might help to foster cooperation between local stakeholders and project managers, many fisheries retain this market access for years before making any meaningful changes to the fisheries management process.

Worse still, projects that ignore governance can generate value and support a larger number of fishers during the investment horizon while hastening the decline of the fish stock. Further, low productivity stocks (those that take the longest to recover), produce the largest short term gains relative to gross value at open access (Appendix B). With perfect information, this strategy is clearly self-defeating: it is not the goal of conservation finance to cause further environmental harm. But in the context of a data poor and economically impoverished fishery, a strategy that can quickly generate value for both stakeholders and capital providers might be appealing to project managers attempting to balance profitability, risk, and triple bottom-line impacts. Existing and proposed fisheries related projects utilize increases in fisher revenue [27, 82], market premium paid to fishers [27], and the number of fishers/fishing communities engaged [4, 27, 82] as metrics for social or economic success, while proposed investment time horizons can be as short as five years [27]. The strategy modeled in Intervention 1 might reasonably produce increases in each of these metrics over a short investment horizon, providing quick improvements in local economic or social conditions, while actually contributing to declines in the fishery in the long run.

Tradeoffs Across the Triple Bottom-Line

The increase in the number of vessels in Intervention 1 and the decrease in the number of vessels in Intervnentions 2 and 3 illustrates a tradeoff between environmental and social objectives. In order to recover a fish stock at the open access equilibrium, the models show that it is necessary to reduce aggregate fishing effort. This result is not impacted by an increase in the price premium in Intervention 3 (Appendix B). If fishers need to be removed from the fishery, then those fishers must either enter a new fishery or find a new livelihood altogether. However, this type of transition is rarely costless. In cases where fishers have few economic alternatives, the alternative livelihood approach may not be effective and effort reduction can project unacceptably high costs on fishing communities [62]. These potential welfare impacts present a challenge for conservation finance. Many practitioners have followed the broader international community by making strong commitments to improving environmental outcomes without jeopardizing social conditions. In the Principles for Investment in Sustainable Wild-Caught Fisheries announced at the World Ocean Summit 2018, the founding adopters call for both "sustainable management of targeted fisheries" and projects that "should not have a negative overall impact on local communities food, nutrition, and livelihood security [28]." These declarations echo the United Nations Sustainable Development Goals (SDGs) to "restore fish stocks in the shortest time feasible" (Goal 14.4), while supporting "inclusive and sustainable economic growth, employment, and decent work for all" (Goal 8) [84].

Conservation finance can help to reconcile these objectives by supporting new livelihoods for fishers that provide income without causing significant social or cultural disruption. Some fishery improvement projects have proposed voluntary fishing gear buy-back programs to compel fishers to exit the fishery [27,57]. Though not always successful, conservation finance and related improvement projects have worked to transition fishers to new industries such as aquaculture and ecotourism [57,82].

The "shortest time feasible" described by the SDGs might imply a long-term closure that would certainly have impacts on the livelihoods of coastal communities with few alternatives. The results of Intervention 3, however, indicate that slower recovery strategies can be effective at generating significant financial returns without closing the fishery altogether. Although Intervention 3 still requires a reduction in fishing effort, the more moderate recovery can provide many important benefits such as retaining expertise and malleable capital in the harvesting and processing sectors, maintaining local seafood markets, and reducing the costs of any alternative livelihood strategy [46]. Although the model indicates that Intervention 2 is more efficient, Intervention 3 might be more realistic while providing additional benefits not adequately captured by the model.

Partnerships and Capital Structure

The focus on management and alternative livelihood strategies in the context o stoks that might take years to recover suggest that the success of conservation finance will depend upon continued partnerships between private capital providers and public entities, NGOs, and multilateral institutions. These organizations currently provide most of the technical support (operational assistance, monitoring, training) as well much of the capital (philanthropic and concessionary) to facilitate fisheries management reform. Private capital providers are not likely to assume these roles. Instead, the private sector offers an additional source of capital that can help to expand current fisheries reform efforts [85].

These partnerships will also be important as the conservation finance industry seeks strategies to increase the scale of impact and capital provided. Currently, conservation finance for fisheries has attracted relatively small, impact-focused, specialized investment funds. In order to attract capital at a larger scale, conservation finance strategies must be either scalable or easily replicable across different fisheries [85]. Although investment in improvements to a fishery supply chain may be easily replicable, fisheries management reform and alternative livelihood strategies are not. They are regionally specific and, as stated above, require assistance and oversight from public entities, NGOs, or multilateral institutions. Thus, the rate at which effective strategies for conservation finance for fisheries can expand is limited by the resources of these organizations.

Biological characteristics might also become relevant to the allocation of capital. Low productivity fish stocks generate value much more slowly than do high productivity stocks. It might, therefore, be easier to attract return-seeking capital providers to highly productive fish stocks as they are able to produce significant returns within a reasonable investment horizon. On the other hand, conservation finance may be less suited to supporting interventions in slow-growing, collapsed fisheries. In these cases, public entities, NGOs, and foundations are likely to continue to shoulder most of the financial costs associated with reform before they are able to attract private capital.

CHAPTER 6

CONCLUSION

The purpose of this paper is to analyze the challenges and opportunities facing conservation finance to support sustainable fisheries. Illustrating the need for new sources of capital to fund sustainable fisheries management, we identify three strategies proposed by the conservation finance industry for generating value and define appropriate measures for financial performance and triple-bottom line impact. Using open access fisheries as motivating context, we simulate each intervention using a bioeconomic model of a single-species fishery and evaluate the performance and impact of each intervention at the end a relevant investment period.

We find that strategies which do not reform fisheries management are able to generate positive profits with a ten year present value of 0.676 times the gross value of the fishery at open access while supporting a 10.9% increase in the number of fishers operating. These gains, however, fail to restore the fish stock to sustainable levels. Interventions which focus on management reform are able to generate profits with a ten year present value between 1.1 and 2.1 times gross value at open access while, in all cases, restoring the fish stock to sustainable levels. These strategies require a 34% to 64% decrease in the number of vessels operating.

The model results suggest that some conservation finance strategies are effective at generating value as well as producing positive economic and environmental outcomes; but effective fisheries governance is key to generating value and for sustainable improvements in the conditions of the fishery. Conservation finance in fisheries without effective governance face a perverse incentive in which short term financial gains and increased employment can lead to further degradation of the fish stock. Our findings illustrate a broader tradeoff between environmental and social goals present in conservation finance for open access fisheries: In order to improve the health of the fish stock operating at open access, fishing effort must be reduced. A key role for conservation finance will be to help support sustainable and profitable alternative livelihoods for fishers displaced by conservation efforts. Furthermore, financial returns are sensitive to stock productivity. This may be an important barrier in matching conservation needs with return-seeking capital. These results are the first attempt to use some of the conventional tools from fisheries economics to inform the development of the burgeoning conservation finance. In identifying these key challenges, we hope to inform the agenda of the broader sustainable development community.

Although a simple model can illustrate the most important dynamics in a fishery, there are several areas where future research can build upon the current analysis. The current model parameters illustrate a representative fishery, future work could map these results onto existing fisheries to estimate the true value of potential conservation finance deals. In addition, many of the interventions proposed by the conservation finance industry focus on increasing market value through investments in the seafood supply chain. The current model focuses only on the harvesting sector and does not capture the value generated by these downstream firms. Future work should also focus on new ways to consider evaluate triple-bottom line impacts. The simple measures used in this paper provide only the most basic insights into the economic, environmental, and social conditions of the fishery. A more nuanced view would greatly improve our understanding of the opportunities and tradeoffs associated with conservation finance.

APPENDIX A

MODEL SPECIFICATIONS

A.1 Open Access Dynamics and Equilibrium

We utilize a discrete-time model of a single fish stock that is exploited by homogenous fishers over time (t), where t represents years. Over time, model dynamics are determined by a range of endogenous variables (represented by English letters) and exogenous parameters (Greek letters). All parameter values are defined in Table (). The model will then determine the harvest and effort combination that maximizes the discounted value of the net economic benefits associated with harvesting activities.

The biological component of the model is built upon Schaefer's model [71] for logistic growth.

$$F(X_t) = \sigma X_t \left(1 - \frac{X_t}{\kappa}\right) \tag{A.1}$$

where σ =growth rate, κ =carrying capacity. This model generates the key biological dynamic of interest - density dependent growth. In each time period, harvesting effort is applied to the fish stock. Assuming that the initial stock size ($X_{t=0}$) is known, the model is advanced over time according to the following recursive equation:

$$X_{t+1} = X_t + F(X_t) - Y(X_t, E_t) \tag{A.2}$$

where $Y(X_t)$ =harvest as a function of stock size and fishing effort (E_t). $Y(X_t)$ serves as the production function for the fishery and assumes that catch-per-unit-effort is proportional to stock size:

$$Y(X_t, E_t) = \gamma X_t E_t \tag{A.3}$$

where γ is a constant parameter.

Following Anderson & Seijo [8], we disaggregate annual effort (E_t) to the level of individual vessels:

$$E_t = \delta v_t f_t \tag{A.4}$$

where $\delta =$ the number of days fished per year, $v_t =$ the number of vessels operating in the fishery in year t, and $f_t =$ the amount of effort produced each day by each vessel in year t. It is assumed that each vessel and vessel owner is identical face the following annual cost function:

$$c_t = \delta[\alpha f_t + \beta f_t^2] + \Phi \tag{A.5}$$

where α and β are constants and Φ represents the fixed costs of effort [16]. In order to simulate economic decision making in the fishery, we also must assume that vessel owners/operators are also seeking to maximize profit. The vessel-level profit function is determined by transforming equation A.4 and subtracting the annual cost function

$$NR_t = \rho\delta\gamma X_t f_t - \delta(\alpha f_t + \beta f_t^2) - \Phi \tag{A.6}$$

where $\rho =$ ex-vessel price.

Under open access (i.e. no management), there are no restrictions on the operators except the technical limitations of the gear and the marginal costs of fishing effort. The economic model will achieve an equilibrium when total revenue is equal to total profit. Dropping the time subscripts for a moment, for $E > 0$,

$$\rho\gamma XE = cvE \tag{A.7}$$

$$X = \frac{cv}{\rho\gamma} \tag{A.8}$$

$$X = \frac{v(\delta[\alpha f_t + \beta f_t^2] + \Phi)}{\rho\gamma} \tag{A.9}$$

This gives the combinations of effort and stock size that will produce an economic equilibrium; but to fit the disaggregate model above, we also need to account for the profit-maximizing behavior or individual vessels. In any given year, a profit maximizing vessel will operate where marginal revenues are equal to marginal costs:

$$\rho\gamma X_t = \alpha + 2\beta f_t \tag{A.10}$$

Solving for the profit-maximizing level of daily effort,

$$f_t^* = \frac{\rho\gamma X_t - \alpha}{2\gamma} \tag{A.11}$$

For positive parameter values, f^* is an increasing function of stock size. It is not reasonable to allow fishing capital be infinitely productive [8]. Therefore, we assume that daily effort is bounded above at f_{MAX} and below by 0. Economic theory suggests that, in the long run, a firm will eventually reach an equilibrium where marginal revenue is equal to both the marginal cost and the minimum of average cost of fishing. We can solve for the equilibrium daily fishing effort that occurs at this point by setting equation A.10 equal to the average cost of fishing in a given season:

$$\alpha + 2\beta f_t = \alpha + \beta f_t + \frac{\Phi}{f_t\delta} \tag{A.12}$$

$$f_{min} = \sqrt{\frac{\Phi}{\delta\beta}} \tag{A.13}$$

For an economic system to reach equilibrium, the total revenues must equal the total costs. Substituting equation A.13 into A.12, the stock size at the open access equilibrium is

$$X_{OA} = \frac{\alpha + \beta f_{min} + \frac{\Phi}{f_{min}\delta}}{\rho\gamma} \tag{A.14}$$

supporting vessels defined by

$$v_{OA} = \frac{F(X_{OA})}{\delta f_{min}\gamma X_{OA}} \tag{A.15}$$

A final consideration for the model is the advancement of effort over time when there is no management in place. We model vessel entry and exit decisions such that changes in effort will be proportional to net returns per vessel:

$$v_{t+1} = v_t + \phi N R_t \tag{A.16}$$

where ϕ =constant entry-exit parameter.

A.2 Maximum Sustainable Yield

We will derive the maximum sustainable yield using the aggregated model. A 'sustainable' yield occurs when the current harvest rate equals to the natural growth of the stock and can be maintained indefinitely.

$$X_{t+1} - X_t = F(X_t) - Y(X_t, E_t) = 0 \tag{A.17}$$

This relationship is a function of E_t: there is a sustainable yield for any level of aggregate fishing effort. Any sustainable yield must satisfy

$$F(X_t) = Y(X_t, E_t) \tag{A.18}$$

Substituting in equations A.1 and A.3 and solving for X_t:

$$\sigma X_t \left(1 - \frac{X_t}{\kappa}\right) = \gamma X_t E_t \tag{A.19}$$

$$X_t = k - \left(\frac{\gamma \kappa E_t}{\sigma}\right) \tag{A.20}$$

Equation A.20 can then be substituted into A.3 to obtain a function for sustainable yield as a function of effort:

$$Y_t = \gamma \kappa E_t \left(1 - \frac{\gamma E_t}{\sigma}\right) \tag{A.21}$$

For a given $\kappa, \gamma, \sigma > 0$ and $E < r/q$, this relationship is smooth, differentiable, and has a unique,non-zero maximum (Y_{MSY}):

$$\frac{dY_t}{dE_t} = \gamma\kappa - \frac{2E_t\gamma^2\kappa}{\sigma} = 0 \tag{A.22}$$

Solving for E and Y:

$$E_{MSY} = \frac{\sigma}{2\gamma} \tag{A.23}$$

$$Y_{MSY} = \frac{\kappa\sigma}{4} \tag{A.24}$$

And solving for stock size at MSY:

$$X_{MSY} = \frac{\kappa}{2} \tag{A.25}$$

A.3 Optimal Input Constraints

In this model, utilized in both Interventions 2 and 3, total fishing effort is constrained by limiting the number of vessels that can participate in fishery. If the total amount of effort in year t is set exogenously, the number of vessels in the fishery is now determined by

$$v_t = \frac{E_t}{\delta f_t^*} \tag{A.26}$$

The target total effort is determined by solving for the optimal by solving the following maximization problem:

$$\begin{aligned} \max_{\{E_t\}} \quad & \sum_{t=0}^{T} \left(\frac{1}{1+i}\right)^t NR_t v_t \\ \text{subject to} \quad & X_{t+1} = X_t + F(X_t) - Y(X_t, E_t), \; \forall \, t \in T. \\ & v_t = \frac{E_t}{\delta f_t^*}, \; \forall \, t \in T. \\ & 0 \leq E_t \leq E_{MSY}, \; \forall \, t \in T \\ & X_0 \leq X_t, \; \forall \, t \in T \\ & X_0, Y_0, v_0 \text{ given} \end{aligned} \tag{A.27}$$

When the endogenous price premium is introduced in Intervention 3, the following constraint is added to the optimization problem.

$$P_t = \begin{cases} \rho & X_t < X_{MSY} \\ \rho(1+\tau) & X_t \geq X_{MSY} \end{cases} \tag{A.28}$$

Where X_{MSY} is the stock size at maximum sustainable yield (derived in Appendix B) and $\tau > 0$.

A.4 Optimal Output Constraints

This model, used in interventions 2 and 3, considers the implementation of a seasonal harvest constraint or Total Allowable Catch (TAC). The intuition is simple: before the start of each fishing season, the TAC is determined based upon the estimated stock size. Fishing proceeds throughout the season until the aggregate catch reaches the TAC, after which, the fishery is closed for the remainder of the season. Instead of remaining fixed, the length of the season is now an endogenous variable in the model and is a function of stock size and the number of vessels.

The number of vessels is determined before the start of the season and remains fixed through the season according to

$$v_t = \frac{Y_t^{TAC}}{\gamma \delta X_t f_t^*} \tag{A.29}$$

If we assume that each vessel is operating at a profit maximizing level of effort, then, we can solve for the length of the season δ_t (the length of the season is now endogenous):

$$d_t = \frac{Y_t^{TAC}}{\gamma X_t v_t f^*} \tag{A.30}$$

The season length now becomes becomes endogenous to the system. The TAC for each year (Y_t^{TAC}) can now be determined through by the following optimization problem:

$$\begin{aligned}
\max_{\{Y_t^{TAC}\}} \quad & \sum_{t=0}^{T} \left(\frac{1}{1+i}\right)^t NR_t v_t \\
\text{subject to} \quad & X_{t+1} = X_t + F(X_t) - Y^{TAC}(X_t, E_t),\ \forall\, t \in T. \\
& v_t = \frac{Y_t^{TAC}}{\gamma \delta X_t f_t^*} \\
& d_t = \frac{Y_t^{TAC}}{\gamma X_t v_t f_t^*} \\
& 0 \leq Y_t^{TAC} \leq Y_{MSY},\ \forall\, t \in T \\
& X_0 \leq X_t,\ \forall\, t \in T \\
& X_0, Y_0, v_0 \text{ given}
\end{aligned} \tag{A.31}$$

When the price premium is introduced to the system, the following constraint is added to the optimization problem.

$$P_t = \begin{cases} \rho & X_t < X^{MSY} \\ \rho(1+\tau) & X_t \geq X_{MSY} \end{cases} \tag{A.32}$$

Where X_{MSY}, the stock size at maximum sustainable yield, is defined in Appendix 2 and $\tau > 0$.

A.5 Dedicated Access Permits

There are a few key differences between a simple output constraint and transferable quotas. Unlike the output constraints described in the previous section, we assume that each permit operator is guaranteed a share of the harvest. This eliminates the 'race' to fish and allows us to reset the season length as an exogenous variable. The number of vessels that can be supported at a given level of harvest is therefore determined by:

$$v_t = \frac{Y_t^{DAP}}{\gamma \delta X_t f_{min}} \tag{A.33}$$

We now assume that the profit maximizing daily effort decision, f_t^{DAP}, now corresponds to the minimum of the average total costs. The quota system compels fishers to operate at the minimum of the average total costs (assuming zero transaction costs)

$$\begin{aligned}
\max_{\{Y_t^{DAP}\}} \quad & \sum_{t=0}^{T} \left(\frac{1}{1+i}\right)^t NR_t v_t \\
\text{subject to} \quad & X_{t+1} = X_t + F(X_t) - Y^{DAP}(X_t, E_t), \ \forall\, t \in T. \\
& v_t = \frac{Y_t^{DAP}}{\gamma \delta X_t f_{min}} \\
& 0 \leq Y_t^{DAP} \leq Y_{MSY} \\
& f_t = f_{min} \ \forall\, t \in T \\
& X_0 \leq X_t, \ \forall\, t \in T \\
& X_0, Y_0, v_0 \text{ given}
\end{aligned} \tag{A.34}$$

When the price premium is introduced to the system, the following constraint is added to the optimization problem.

$$P_t = \begin{cases} \rho & X_t < X_{MSY} \\ \rho(1+\tau) & X_t \geq X_{MSY} \end{cases} \tag{A.35}$$

APPENDIX B

SENSITIVITY ANALYSIS

Stock Productivity: σ

Table B.1: Sensitivity of Financial/Economic Outcomes (σ)

	$\sigma = 0.05$	$\sigma = 0.10$	$\sigma = 0.30$	$\sigma = 0.50$
Intervention 1: Increase in Post-Harvest Value				
Open Access	1.411	1.036	0.676	0.588
Intervention 2: Optimal Management Reform				
Input	0.000	0.000	1.904	3.324
Output	0.000	0.000	1.571	3.120
DAPS	0.000	0.522	2.150	3.442
Intervention 3: Gradual Reform with Endogenous Price				
Input	0.261	0.497	1.671	2.708
Output	0.131	0.262	1.156	2.339
DAPS	0.168	0.524	1.875	2.687

Table B.2: Sensitivity of Environmental Outcomes (σ)

	$\sigma = 0.05$	$\sigma = 0.10$	$\sigma = 0.30$	$\sigma = 0.50$
Intervention 1: Increase in Post-Harvest Value				
Open Access	0.438	0.443	0.461	0.479
Intervention 2: Optimal Management Reform				
Input	0.789	1.007	1.236	1.492
Output	0.789	1.007	1.268	1.255
DAPS	0.789	0.933	1.240	1.548
Intervention 3: Gradual Reform with Endogenous Price				
Input	0.686	0.783	1.100	1.535
Output	0.682	0.775	1.080	1.226
DAPS	0.663	0.775	1.068	1.423

Table B.3: Sensitivity of Social Outcomes (σ)

	$\sigma = 0.05$	$\sigma = 0.10$	$\sigma = 0.30$	$\sigma = 0.50$
Intervention 1: Increase in Post-Harvest Value				
Open Access	2.081	1.46	1.109	1.057
Intervention 2: Optimal Management Reform				
Input	0.000	0.000	0.357	0.214
Output	0.000	0.000	0.538	0.534
DAPS	0.000	0.470	0.581	0.598
Intervention 3: Gradual Reform with Endogenous Price				
Input	0.415	0.354	0.313	0.207
Output	0.500	0.500	0.500	0.547
DAPS	0.501	0.500	0.639	0.627

Price Premia: θ, τ

Table B.4: Sensitivity of Financial Outcomes (θ)

	$\theta = 10\%$	$\theta = 25\%$	$\theta = 50\%$	$\theta = 100\%$
Intervention 1: Increase in Post-Harvest Value				
Open Access	0.372	0.676	1.537	-0.263

Table B.5: Sensitivity of Environmental Outcomes (θ)

	$\theta = 10\%$	$\theta = 25\%$	$\theta = 50\%$	$\theta = 100\%$
Intervention 1: Increase in Post-Harvest Value				
Open Access	0.534	0.461	0.381	0.262

Table B.6: Sensitivity of Social Outcomes (θ)

	$\theta = 10\%$	$\theta = 25\%$	$\theta = 50\%$	$\theta = 100\%$
Intervention 1: Increase in Post-Harvest Value				
Open Access	1.047	1.109	1.201	1.424

Table B.7: Sensitivity of Financial Outcomes (τ)

	$\tau = 8\%$	$\tau = 18\%$	$\tau = 28\%$	$\tau = 38\%$
Intervention 3: Gradual Reform with Endogenous Price				
Input	1.511	1.671	1.832	1.992
Output	0.979	1.156	1.187	1.290
DAPS	1.567	1.875	1.885	2.097

Table B.8: Sensitivity of Environmental Outcomes (τ)

	$\tau = 8\%$	$\tau = 18\%$	$\tau = 28\%$	$\tau = 38\%$
Intervention 3: Gradual Reform with Endogenous Price				
Input	1.100	1.100	1.100	1.100
Output	1.080	1.080	1.080	1.080
DAPS	1.080	1.080	1.080	1.055

Table B.9: Sensitivity of Social Outcomes (τ)

	$\tau = 8\%$	$\tau = 18\%$	$\tau = 28\%$	$\tau = 38\%$
Intervention 3: Gradual Reform with Endogenous Price				
Input	0.313	0.313	0.313	0.313
Output	0.500	0.500	0.500	0.500
DAPS	0.500	0.527	0.639	0.666

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