Markov-Perfect Rent Dissipation in Rights-Based Fisheries

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Working Paper No. 11009
May 2011

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September 26, 2012

Abstract

We present a general, dynamic model of within-season harvesting competition in a fishery managed with individual transferable quotas. Markov-Perfect equilibrium harvesting and quota purchase strategies are derived using numerical collocation methods. We identify rent loss caused by a heterogeneous-in-value fish stock, congestion on the fishing ground, revenue competition and stock uncertainty. Our results show that biological, technological and market conditions under which rents will be dissipated in a standard individual transferable quota program are fairly special. These findings provide new insights for designing rights-based programs capable of generating resource rent in marine fisheries.

Keywords: Markov Perfect equilibrium; individual transferable quotas, production externalities, resource rent.

JEL codes: Q2

1 Introduction

Growing evidence finds that property rights-based management approaches, such as individual transferable quotas (ITQs), offer important advantages over traditional fisheries management, which has relied on input controls to prevent overfishing, e.g., vessel entry limits, gear restrictions, time and area closures (Committee to Review Individual Fishing Quotas, 1999; Grafton, et al., 2006; Costello, Gaines and Lynham, 2008). Rights-based approaches better align the incentives of individual resource users with those of managers and can eliminate common-pool inefficiencies which otherwise plague fishery resources. Some authors point out, however, that conditions may exist under which ITQs do not fully correct all externalities, and therefore, do not generate first-best economic outcomes.[1] These conditions, hereafter unattended production externalities, include a heterogeneous-in-value fish stock, congestion on the fishing ground, and situations where fishermen must gather information about the true location of fish. With a standard ITQ design, resource users are granted rights to harvest a portion of a common fish stock during a set production period. If the stock is heterogeneous in value, an inefficient *race to fish* can ensue as fishermen attempt to harvest the highest-valued units before rivals (Boyce, 1992; 2001; Costello and Deacon, 2007). It has been argued that a single quota trading price cannot reflect both the shadow price of the harvest constraint and the price of congestion on the fishing ground, and therefore congestion externalities can continue to dissipate economic rent in ITQ fisheries (Boyce, 1992, 2001; see Danielsson 2000 for an opposing view). Lastly, Costello and Deacon (2007) suggest rent dissipation can arise in decentralized ITQ fisheries if fishermen engage in redundant, costly search for information. The authors recommend granting enhanced or "fully delineated" property rights to fishery resources to correct the problems and restore first best economic outcomes.

While considerable progress has been made in understanding the role of unattended production externalities in ITQ fisheries, several unresolved questions remain. What factors cause heterogeneity in stock value and do all lead to rent dissipation? How important are congestion effects? To what extent will a well-functioning quota trading market offset the ill-effects of unattended production externalities? And what design features should be adopted to restore full economic rents in ITQ-managed fisheries?

An obstacle to answering these and other questions is the complex − strategic, dynamic and stochastic − setting in which unattended production externalities reside. Game-theoretic models and solution concepts are required for predicting fishing behavior and market outcomes. Unfortunately, dynamic games of common pool resource extraction are difficult to solve analytically. As a consequence, most previous research has relied on heuristic arguments for generating results, or have studied restrictive models to understand rent dissipation due to unattended production externalities (Fell, 2010 is an exception).

We use numerical methods to solve for Markov Perfect Nash (closed-loop) equilibria to a general model of a dynamic, within-season fishing game which nests models of Clark (1980), Boyce (1992), and others who have espoused the problem of unattended externalities in ITQ fisheries. Our approach allows direct observation of harvest patterns, quota trading outcomes, and rent loss over a range of biological and market conditions. As such, we are able to provide a fairly complete picture of the precise biological, technological and market factors that cause rent loss in ITQ-managed fisheries. The insights are important for improving the design of quota management programs in fisheries.

Our results confirm early insights by Clark (1980a), Boyce (1992), and others, that suggest ITQs will not fully remove the incentives to race to fish. We show, however, that the incentive to race and the accompanying rent losses arise under fairly special structural properties for the harvest technology and stock conditions. We show how the extent of rent losses depends on the cost-stock elasticities and economies of harvest size. Both must be large for significant rent losses to persist. Additional results show that rents are not dissipated due to congestion effects alone, a result argued in Danielsson (2000) and later questioned in Boyce (2001). We also show that marketing competition in the presence of finitely elastic fish demand does not alone cause rent dissipation in ITQ fisheries. In fact, finitely elastic demand for fish provides incentives to smooth the harvest throughout the fishing season, and effectively counters the incentive to race to fish.

We present a policy simulation to identify the impacts of modifying standard ITQ designs, toward fully delineated property rights, as has been suggested in the literature. Our simulation shows the potential downside of delineating harvest rights temporally, i.e., restricting the calendar period during which the harvest right can be used to manage temporal competition among fishermen. We find that such restrictions can reduce total rents if they limit the ability of fishermen to respond to unanticipated productivity shocks.

Our results provide guidance for managers who must decide, based on measurable characteristics of a fishery, when rent dissipation is likely to persist and when modification/enhancement of the harvest rights is warranted. Our results show that it may be difficult to identify rent dissipation due to unattended production externalities in practice. This is due to the finding that accelerated harvests early in the fishing season are not evidence of rent dissipation. Accelerated harvest can be an optimal response to structural properties of the harvest technology or capital opportunity costs. We therefore caution against ITQ rule modification until key parameters/attributes, e.g., the cost-stock elasticity parameter and the cost elasticity of size are measured and deemed empirically important.

Our paper is organized as follows. Section 2 reviews the literature on unattended production externalities in rights-based fisheries. Section 3 presents our model and describes the numerical methods used to solve for a Markov-Nash equilibrium of our within-season fishing game. Results are presented in section 4. Section 5 summarizes our findings, and discusses implications for improving the design of rights-based fisheries management programs and extensions.

2 Externalities in ITQ fisheries

Christy (1973) and Maloney and Pearse (1978) proposed using quantitative fishing rights, or individual transferable quotas (ITQs), to address common-pool inefficiencies in commercially exploited marine fisheries. Rights-based approaches are currently used throughout the world. Mounting empirical evidence suggests that rights-based approaches offer important advantages over traditional management, which relies on input controls to conserve fish stocks (see Grafton, et al., 2006; Costello, Gaines and Lynham, 2008).[2]

Clark (1980a) characterized the performance of alternative management instruments, effort restrictions, taxes, aggregate and individual vessel quotas in replicating socially optimal (economically efficient) harvesting behavior and economic rent in a decentralized fishery. In his analysis of ITQs, Clark (1980a) presented a seasonal model, and to simplify the analytical presentation, assumed that no natural stock growth occurred while harvesting operations were underway. Under a fixed total quota and with no natural stock growth, the stock size necessarily declined during the fishing season from its initial size to the end of season escapement level, which by assumption was equal to the initial stock size less the harvested quota. As is standard in the resource economics literature, Clark assumed the harvest technology exhibited a *stock effect*, where the productivity of fishing effort is greater when the stock size is large. One implication of his model is that as the total quota is extracted and the stock size declines, the net profit per unit of harvest, also the residual profit per unit of quota, also declines. Clark (1980a, p.1124) correctly observed that a fisherman operating under an ITQ regulation could lower the cost of harvesting a fixed quota allocation "by concentrating his catch at the early part of the season when the stock level is high." He also pointed out that, "This situation is suboptimal for the fishery as a whole, since vessel i's catches have an external influence on all vessels subsequent catch rates." Clark discussed briefly an extension to the case of congestion externalities and concluded that ITQs would not replicate first best outcomes in the presence of stock and congestion effects. Clark did not rigorously derive his results regarding the implications of externalities, and understood full well that to do so would require solving an N-player differential game. He left this challenging exercise for future research (see also, Clark, 1980b).

Boyce (1992) revisited the issue of unattended production externalities in ITQ fisheries. He introduced the N player differential game that Clark (1980a) alluded to. In the Boyce (1992) model autonomous agents simultaneously chose effort rates and quota purchases with the goal of maximizing individual single season fishing profits. As in Clark (1980a), Boyce featured a declining within stock and unit profits which results from the assumption that no-natural growth occurred during the fishing season. Boyce (1992) also assumed a congestion externality which operated through a primal production function. He assumed the harvest of a representative fisherman increased with the fisherman's own effort allocation and the size of the fish stock, but decreased with the effort allocations of other fishermen. The model featured both stock and congestion externalities. Boyce also did not derive the Nash equilibrium of the differential game in the paper but rather derived results by comparing necessary conditions for the optimal and equilibrium play of the game. Boyce (1992) concluded that the equilibrium trading price of quota would not reflect differences in the value of a heterogeneous fish stock, and that ITQ management will not replicate socially optimal harvesting behavior and rent in the presence of stock and/or congestion externalities (see Theorem 1 and Corollary 1, page 399).

Danielsson (2000) challenged Boyce's (1992) claim that congestion externalities alone precluded socially optimal outcomes in an ITQ fishery. Danielsson's (2000) article suggests that Clark (1980) and Boyce (1992) did not correctly incorporate the quota constraint and a well-functioning quota market in the analysis of fishing behavior. Danielsson (2000) presented his arguments in a continuous time model which could not reflect stock externalities caused by a declining (heterogeneous) fish stock. Boyce (2001) offered a response to the Danielsson (2000) critique, reiterating his earlier claim that congestion externalities alone were, in fact, enough to cause a divergence between socially optimal and ITQ outcomes.

Costello and Deacon (2007) argue that rent dissipation, due to unattended externalities in ITQ fisheries, may be common in real world fisheries. The authors find that "even with homogeneous fishermen, no stock externalities and no congestion externalities, property rights assigned to harvest (ITQs) may not secure all rents in a fishery." [3] Rents are dissipated as competing fishermen *race* to the higher valued sub-stock at earlier than the optimal date. Costello and Deacon (2007) consider a new avenue for rent dissipation in ITQ fisheries, which is uncertainty over the true spatial location of the fish stock. The authors characterize the gains from coordinating search efforts among fishermen and show that such efforts can avoid redundant searches that occurs under decentralized ITQ management. The authors call for a more refined assignment of property rights to correct the inefficiencies identified in their model.

Fell (2010) studies within-season fishing behavior in the presence of stock effects, exogenously driven time-dependent harvesting costs, and ex-vessel fish prices that depend on aggregate harvest rates. Fell (2010) is the first to consider a price competition externality, i.e., fishermen in the model have an incentive to slow their individual harvest rates to avoid market gluts and low fish prices. The externality occurs because the benefits of higher prices flow to all fishermen. A second innovation is that Fell (2010) numerically derives the Nash equilibrium to a within-season fishing game. Fell (2010) uses a genetic algorithm to identify a symmetric, open-loop Nash equilibrium to the N-player differential game. He finds that rent dissipation persists under an ITQ management program, due to the simultaneous presence of stock effects and an inelastic demand for fish. Fishermen who would otherwise prefer to slow harvest and maintain high dockside prices have incentive to harvest early when stock size is largest and harvesting costs are lowest.

Bisack and Sutinen (2006) report empirical estimates of rent loss due to unattended production externalities in the New Zealand scallop fishery.[4] The authors compare a total cost minimizing harvest plan with a solution to a within-season harvest game that is derived numerically. The authors estimate that unattended production externalities caused losses in the range of 9.6% and 20.2% in the 1996-97 fishing seasons.[5]

Recent empirical work by Huang and Smith (2012) measures the impacts of stock and congestion externalities in a North Carolina shrimp fishery which is managed under open access. The authors find that shrimp fishermen dissipate rents, by an estimated 17% of annual fishery revenue, by harvesting shrimp too early in the fishing season; the value of stock would increase if left to grow during the season. Huang and Smith (2012) suggest temporally delineated effort controls could be used to dampen the race to fish and generate economic rent. Whether similar outcomes could be achieved under ITQ management, and whether similar gains might be expected in other fisheries remains an open question.

Results from the above literature impact the analysis that follows. First, there is unresolved debate as to which factors can cause rent dissipation, the magnitude of losses, and the policy prescriptions for restoring economic rent in ITQ fisheries. The question of whether congestion externalities alone are sufficient to cause rent dissipation in ITQ fisheries is an example (Danielsson, 2000; Boyce, 2001). Second, with the exception of Fell (2010), past researchers have relied on heuristic arguments and/or simplified models of behavior in an ITQ fishery to characterize the impacts of unattended externalities. The reason is that analytical solutions to general N-player differential games, in the presence of multiple externalities, are unavailable. The sections that follow introduce a general within-season model of an ITQ fishery and use numerical collocation methods to derive Markov Perfect (closed-loop) Nash equilibrium harvest patterns and rent outcomes. We are aware of the trade-offs inherent in our numerical approach, but contend that (1) the added insights from directly observing equilibrium play in a general, dynamic setting, and (2) the lack of analytical alternatives warrant their use.[6] We describe the solution algorithm and report results from a sensitivity analysis in the appendix. Additional details for the use of numerical methods in dynamic games can be found in Miranda and Fackler (2002), Judd (1998), and Vedenov and Miranda (2001).

Before we introduce the model, we briefly review the role of time in our model. Much of the analysis of unattended production externalities in ITQ fisheries is conducted in continuous time. We choose a discrete time model for two reasons. First, neo-classical production theory and concepts related to inefficiency have been developed, and are best-understood in a discrete (fixed) time production model (Luenberger 1995). Second, strategic harvesting behavior in continuous time must be modeled as a differential game. Solutions to Markov (closed-loop) differential games are often difficult to obtain even with numerical methods (Dockner, Jørgensen, Van Long and Sorger, 2000). The discrete time framework is less suited to examination of growth processes in marine fisheries. However, this shortcoming is addressed with simplifying assumptions that do not discredit our main results.

3 Model

We consider a single-stock fishery. The fishery manager issues permits to harvest a specified portion of the stock during a single, fixed length calendar period, hereafter, a fishing *season*. The fishing season is divided into $t = 1, ..., T$ equal length production periods.

The aggregate seasonal quota is denoted y, and is delineated in the same units as the stock and harvest. The determination of the optimal harvest level is a central focus of the fisheries management literature. We do not consider these factors here; y is exogenous. Our measure of economic performance is the net profit from harvesting y from the sea.

There are $N > 1$ fishermen, each operating a single fishing vessel. We assume each fisherman acts independently and non-cooperatively in pursuit of their own private profit objective. We rule out the possibility of a single fisherman purchasing the entire quota and internalizing all externalities. We do not necessarily agree with this characterization of fishing behavior in ITQ fisheries, but maintain the assumption to be consistent with previous literature. The assumption is revisited in the concluding section.

The size of the fish stock at the beginning of period t is denoted x_t. We simplify our model and assume no growth, reproduction, or mortality occurs while harvesting operations are underway. We use $h_{i,t}$ to denote the harvest of fisherman i in period t. Total harvest in the period is

$h_t = \sum_{i=1}^{N} h_{i,t}$, and period t escapement is $s_t = x_t - h_t$. In all periods and for all fishermen, harvest cannot exceed quota holdings. We use $y_{i,t}$ to denote the quantity of unfished quota held by fisherman i in period t; the quota regulation implies $h_{i,t} \leq y_{i,t}, \;\; \forall\, i, t$. There is no cheating in our model. The quota transition equation for fisherman i is given as,

$$y_{i,t+1} = y_{i,t} - h_{i,t}, \qquad t = 1, 2, \ldots, T-1. \tag{1}$$

The initial quota allocation, $y_{i,1}$ for fisherman i, is determined in a pre-season market which we describe shortly. Unfished quota is valueless following the season. Note that mid-season quota adjustments are considered in the stochastic version of the model; mid-season quota adjustment is not relevant for the deterministic case since all harvests along the equilibrium path are known by rational agents. The maximum number of production periods is fixed at T. However, fishermen choose the number of periods in which they are active, i.e., periods in which harvest are positive. For example, a fisherman may choose to cease fishing mid-season, in period $t' < T$, in which case harvest $h_{i,t} = 0, \; \forall\, t > t'$.

The within-season evolution of the fish stock, in the general case, is governed by a stochastic logistic growth function:

$$x_{t+1} = \xi_{t+1} s_t \big[1 + r(1 - s_t/\kappa)\big], \qquad t = 1, 2, \ldots, T-1, \tag{2}$$

with the initial stock size, x_1, given. In the above expression r is the intrinsic growth parameter, κ denotes carrying capacity, and $\xi_{t+1} \in [\underline{\xi}, \overline{\xi}]$ where $0 < \underline{\xi} \leq \xi_t \leq \overline{\xi} < \infty$ is a random shock unobservable in period t.

Harvesting cost for fisherman i in period t takes the general form,

$$c_i(h_{i,t}, h_{-i,t}, x_t, N_t, t),$$

where $h_{-i,t} = \sum_{j \neq i} h_{j,t}$ is the period t harvest of all fishermen other than i. Costs are assumed to be strictly increasing and convex in a fisherman's own harvest, and non-increasing in the stock size. Costs may vary exogenously throughout the season, for example, if stocks become more or less concentrated over time (e.g., Costello and Deacon, 2007). The larger is total harvest in the period, the smaller is the average stock size during the period and thus the higher are the harvesting costs for all fisherman. This is the source of the stock externality on our model. Following Smith (1968), we assume congestion externalities arise as vessels interfere with each others harvesting operations on the fishing ground; $c_i(\cdot)$ is assumed to be non-decreasing in N for $N > 1$.

Lastly, the price of fish in period t is a non-increasing function of the period's harvest h_t. We also allow the price to vary exogenously across periods to reflect the possibility of market-driven external changes in stock value (Costello and Deacon, 2007). The inverse demand for harvested fish is denoted $p_t(h_t)$.

The goal of each fisherman is to maximize seasonal expected profits (there is no discounting). Operating profits, net of quota purchase costs, are given as,

$$E\sum_{t=1}^{T}\Big[p_t(h_t)h_{i,t} - c_i(h_{it}, h_{-i,t}, x_t, N_t, t)\Big], \tag{3}$$

where E denotes expectations.

3.1 Functional forms

Implementing our numerical algorithm requires we specify functional forms for the costs and inverse demand functions. We specify the harvest cost function as (period subscripts are omitted),

$$c(h_i, h_{-i}, x, N, t) = \alpha_i(N)h_i^{\eta}\Big(x - 0.5(h_i + h_{-i})\Big)^{-\beta}, \tag{4}$$

where $\eta \geq 1$ and $\beta \geq 0$. The parameter, β, measures the percentage change in harvest cost due to a percentage change in the midpoint of the period's common stock size. The parameter

$\alpha_i(N) > 0$ takes the form

$$\alpha_i(N) = \alpha + \gamma \sum_{-i} I(h_{-i} > 0), \tag{5}$$

where $\gamma \geq 0$, and $\sum_{-i} I(h_{-i} > 0)$ is an indicator function set equal to the number of rival fishermen with strictly positive harvest during the period. As required, harvest costs increase with the number of fishermen present on the fishing ground.

Alternate parameterizations in equation (4) allow us to capture a range of structural properties for the harvest technology. Setting $\beta = 0$ turns off the stock effect, and setting $\gamma = 0$ shuts down the congestion effect. If $\eta > 1$, the technology exhibits per-period diminishing returns to harvest size.

To be consistent with empirical observation of vessel-level harvesting technology, and a finite equilibrium ITQ fleet structure, as we discuss shortly, we require a harvest technology that exhibits variable returns to size at the seasonal level. Unless otherwise noted, we assume fishermen incur a strictly positive fixed cost if they are active, where active implies they hold positive quota and have positive harvests during the fishing season. The seasonal cost plays a limited role in the analysis below, and therefore no new notation is introduced.

The inverse demand for fish follows:

$$p(h_t) = \overline{p} - \omega h_t.$$

Exogenous demand shocks and changes in harvesting costs are considered by allowing parameters, e.g., stock effect parameter β and the inverse demand choke price $\overline{p}$, to vary across periods. Unless otherwise stated a quadratic in harvest cost function ($\eta = 2$) is considered. Much of the analysis below considers a constant fish price; $p_t = \overline{p}$. Hereafter, we set $\kappa = 1$ to normalize the stock size on the interval $[0, 1]$.

Our general model nests previous models, and is able to isolate the various externalities that have appeared in earlier literature. Deterministic stock transitions (Bisak and Sutinen, 2006)) arise under a degenerate shock distribution with Prob($\xi_t = 1$) $= 1, \forall t$. Declining stock size (Clark, 1980a; Boyce, 1992, 2001; Fell, 2010), and thus heterogeneous-in-value stock if stock effects are present, is obtained by setting $r = 0$. The corresponding stock transition equation becomes, $x_{t+1} = s_t = x_t - \sum_i^N h_{i,t}$. Our specification for the inverse fish demand captures marketing competition (Fell, 2010). Exogenous changes in harvesting costs or harvest value (Costello and Deacon, 2007) are easily considered by allowing parameters of the cost and demand functions to vary throughout the fishing season. We are able isolate stock and congestion externalities through parametric restrictions. We are also able to examine the role of alternate structural assumptions for the harvest technology, e.g., varying returns to size. Lastly, our numerical methods do not require that we impose symmetric equilibria or strictly positive harvests in each period. With zero harvest allowed the length of the harvest period is endogenous in the model as in Fell (2010). The results below indicate that the generality and flexibility in the model is important.

3.2 Dynamic fishing game

At the beginning of each period, fishermen simultaneously choose quota-constrained harvest quantities. Each fisherman has full knowledge of the current period stock size and the quota holdings of all fishermen. In the case of stochastic stock transitions, the current period shock is known but future shocks are unobserved and follow a known distribution. The state variables in the game include the current period stock size, a fisherman's own quota holding, the quota holdings of rival fishermen, and the harvesting period.

We focus on pure strategy Markov perfect equilibrium (MPE), which exhibit the properties of dynamic consistency and subgame perfection. We therefore emphasize strategic interaction between fishermen through the evolution of state variables, which in our model include the fish stock size and the unfished quota holdings of fishermen. Open loop equilibria, or path strategies, which specify harvests as functions of time alone are not suited for analysis of stochastic stock evolution which is an important characteristic of fisheries and a key component of our model.[7] Let $y_t = (y_{1,t}, \ldots, y_{N,t})$ denote the vector of unfished quota at the beginning of period t. We seek a seasonal, expected net profit maximizing harvest strategy which maps the $N+2$-dimension state vector (x_t, y_t, t) to a harvest quantity. The equilibrium harvest policy function prescribes, for each fisherman and every feasible state, a best harvest response to the harvest choices of other fishermen. Analytical solutions to the MPE harvest policy are not available. The algorithm used to numerically solve for value functions and MPE strategies is described in appendix A.

The final step in defining equilibrium play is to specify the initial values of the state vector. The starting period and initial size of the fish stock are given exogenously. The initial quota holdings for each fisherman are determined as the outcome of pre-season quota trading. The value of the initial quota allocation $y_{i,1}$ for fisherman i is,

$$V_i(x_1, y_1, 1) = \max_{(h_{i,t}|h_{-i,t})} E \sum_{t=1}^{T} \Big[p_t(h_t) h_{i,t} - c_i(h_{it}, h_{-i,t}, \overline{x}_t, N_t) \Big], \tag{6}$$

subject to the quota constraint and state transition equations (1) and (2). The equilibrium initial quota allocation is then defined as,

$$y_1^{ne} = \underset{\sum_i^N y_{i,1} = y}{argmax} \Big(V_1(x_1, y_1, 1) + V_2(x_1, y_1, 1) + \ldots + V_N(x_1, y_1, 1) \Big). \tag{7}$$

3.3 Additional considerations

Technology

Agents in our model operate a single fishing vessel. Clark (1980a) recognized that a variable returns technology was necessary for a meaningful discussion of equilibrium fleet size in an ITQ fishery. If the technology exhibits increasing returns over the range of harvest $[0, y]$, the Nash equilibrium fleet will be made up of a single fisherman/vessel. With a single fisherman there can be no externality and therefore no rent dissipation under decentralized ITQ management. On the other hand, if the harvest technology exhibits decreasing returns over the range $[0, y]$, adding one more vessel to the fleet will always lower average costs, and increase the RHS of equation (7).[8] In this case, the equilibrium fleet size will include the entire population of vessels. For these reasons the analysis that follows will focus attention on a variable returns technology at the seasonal level.

Fleet structure

The expressions in equations (6) and (7) can be used to identify the equilibrium fleet structure in the ITQ fishery, along with the equilibrium quota price. Divide the population of fishermen into those who are active (holders of positive quota) in the ITQ equilibrium as defined in equation (7), and inactive fishermen (fishermen with zero quota). Denote the subset of active fishermen in the population as N. The maximum that an inactive fisherman can pay to enter the fishery is, $V_j(x_1, \widetilde{y}_1, 1), j \notin N$, where the notation $\widetilde{y}_1$ emphasizes that the initial quota allocation has changed to accommodate the additional participant. Entry can occur only if the entrant j can profitably purchase quota from incumbents. This requires a gain from trade, which contradicts the original definition of y_1^{ne}. Similarly, an incumbent can profitably exit the ITQ fishery only if some quota buyer is willing to pay to hold the quota. Buyers may include other incumbents or non-active fishermen. In either case, a gain from trade is required which contradicts the definition of y_1^{ne}.

Quota price

The shadow price of quota is determined by its value in the hands of other incumbents or inactive fishermen. Holding the number of participants fixed, the marginal value of additional quota to an incumbent is calculated as ,

$$
\begin{aligned}
\frac{dV_i(x_1, y_1, 1)}{dy_{i,1}} &= \sum_{j \in A} \frac{\partial V_i(x_1, y_1, 1)}{\partial y_{j,1}} \frac{dy_{j,1}}{dy_{i,1}}, \\
s.t. \qquad & \sum_{j \in A} \frac{dy_{j,1}}{dy_{i,1}} = 0.
\end{aligned} \tag{8}
$$

The above expression emphasizes the fact that in the presence of a quota constraint and production externalities that operate through harvest choices, the value of quota for fisherman i is affected by the MPE harvest choices of all fishermen, which are functions of the state vector, including the initial quota allocation y_1. The requirement that sum of quota adjustments across active firms be equal to zero highlights a crucial feature of quota-managed fisheries. When the quota constraint binds, the quota held by fishermen i can increase, only if the quota held by rival fishermen is reduced by the same amount. This feature is crucial for understanding the effects of unattended externalities in ITQ fisheries, as recognized by Danielsson (2000).

The above expression assumes the set of active fishermen is unchanged when quota is reallocated. This is a reasonable assumption for small quota changes. What is the value of quota to potential entrants? Under a variable returns technology, an entrant must acquire enough quota to exploit available economies of size. Moreover, because the aggregate quota constraint must hold, $\sum_j \widetilde{y}_{j,1} = y$ may be significantly different than y_1^{NE}.

Rent dissipation

Rent loss in a decentralized ITQ fishery requires an externality, but also a mechanism by which harvesting inefficiency occurs. The structure of the harvest technology provides this mechanism. The term "race to fish" is a euphemism for accelerated and costly harvest behavior. In the context of our model, accelerated per period harvest will raise costs under a strictly convex cost function, i.e., a decreasing returns to size technology. Under decreasing returns, higher per-period harvest implies increased marginal cost above the level that would be incurred at a slower harvest pace. To see why this property is crucial, consider the opposite case where the cost per unit of harvest is independent of harvest size. An example is $c(h, x) = c(x)h$, where $c(x)$ is a decreasing function of stock size x, and h is quantity harvested (see Clark, 1990; Reed 1979). With constant returns to size, an increase in h raises unit cost only through its effect on stock size. Racing for fish does not raise costs above the minimum feasible cost. Therefore, we consider decreasing or variable returns to size at the level of a production period and maintain the variable returns at the seasonal level, due to the presence of seasonal fixed costs, as required for a positive but finite equilibrium fleet size.

Number of players

A strength of the collocation method is its ability to accommodate a high-dimension state space. Solving the fishing game with N large is computationally demanding and yields few insights beyond those obtained under a smaller value of N. We report results for $N = 2$ and $N = 3$.[9] The number of periods is set to $T = 4$. While the number of periods can be easily increased, our preliminary analysis found that four periods were enough to illustrate the temporal forces operational in the dynamic fishing game, and allows us to report results in less space.

Initial conditions

For the results that follow, we set the beginning season stock size at $x_1 = \kappa/2$, and the seasonal quota at $y = 0.2$. The collocation method approximates value functions and MPE harvest policy functions for any feasible state. We report results for the Nash equilibrium initial quota allocations as derived in equation (7).

4 Results

Collocation methods provide a high-order polynomial approximation to an unknown value function. Our investigation reveals that the approximation is extremely accurate. The average approximation error in the terminal period value function is 0.46%. The L_∞ norm (maximum % error) is 1.87%. The largest percentage errors occur at small quota values, which tend not to be observed in equilibrium. Therefore we are fairly confident that approximation error does not significantly impact our results. Nonetheless, the results that follow should be interpreted accordingly.

Figure 1 presents the per-period value functions, net of quota purchase costs, for representative fisherman 1 under the assumptions of two active fishermen, no-within season stock growth and no congestion effects. Value functions are plotted over two dimensions of the state, x_t and $y_{1,t}$ holding $y_{2,t}$, fixed at an intermediate level.

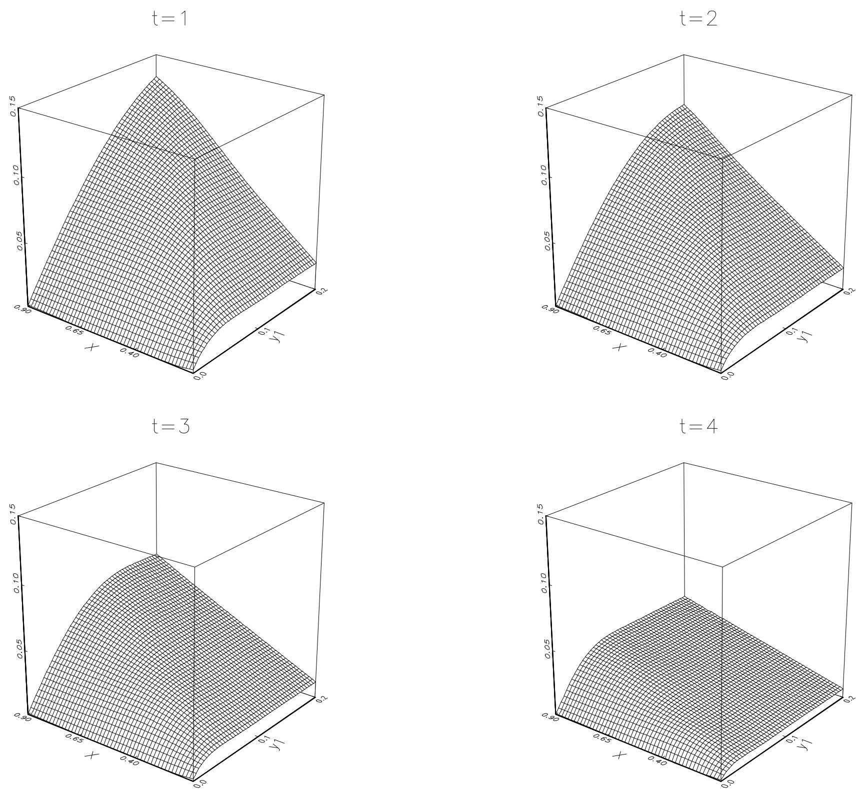

Figure 1: Value function

The value function is increasing in x_t and $y_{1,t}$ as larger stock and/or quota cannot reduce MPE profits. Notice that the value at all combinations of $(x_t, y_{1,t})$ declines throughout the fishing season as t increases. Holding a large amount of quota in the terminal period yields lower value under a decreasing returns to size technology. Marginal profits eventually decline to zero and therefore there exists a threshold quota amount at which the marginal value of additional quota is zero. This threshold quantity is smaller later in the fishing season.

Figure 2 reports the period 1, fisherman 1 value function, again net of quota purchase costs, over the range of feasible quota holdings; the stock size is held fixed. The effects of stock externalities are small but clear. The value that firm 1 places on quota declines with the quota held by a rival fisherman, since when fisherman 2 is quota constrained, fisherman 1 can earn more profit

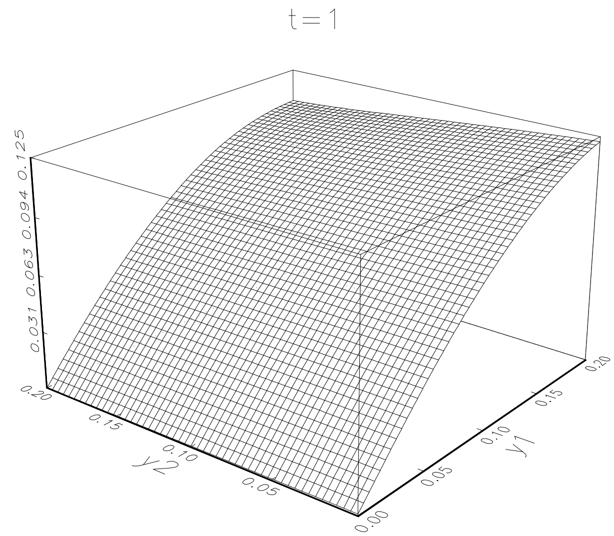

Figure 2: Value function

from a given amount of quota.

We now turn to results for some important cases of our general model. The results we present illustrate insights that may not be transparent without direct observation of MPE harvest behavior. We present additional results in an appendix to demonstrate the robustness of the main findings under a wider range of parameter values.

Table 1 reports MPE equilibrium harvests, stock size, and profits, both by period and for the full season. First-best outcomes are reported as a benchmark for assessing economic performance under ITQ management.[10] Harvest quantities are reported as percentages of the seasonal quota. Stock sizes are reported as the percentage of the stock carrying capacity. Columns under the *Performance* heading report the percentage harvest obtained for the MPE of the ITQ fishing game, relative to the first-best harvest. The final column, labeled V^{ne}/V^{*}, reports the percentage rent attained under the MPE equilibrium relative to the first-best rent.

Case 1.1 of table 1 assumes a heterogeneous in size fish stock and, with stock effect parameter $\beta = 1$ and no within-season growth $r = 0$, a heterogeneous in value fish stock. There

Case 1.1: Heterogenous stock								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	15.0	15.0	50.0	13.7	13.7	50.0	109.6	105.0
2	13.5	13.5	44.0	12.9	12.9	44.5	104.7	101.7
3	11.9	11.9	38.6	12.1	12.1	39.4	98.5	98.3
4	9.6	9.6	33.8	11.3	11.3	34.5	84.6	91.2
Total	50.0	50.0	30.0	50.0	50.0	30.0	100.0	99.6
CASE 1.2: Heterogeneous stock, congestion effects								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	14.6	14.6	50.0	13.7	13.7	50.0	106.9	102.7
2	13.1	13.1	44.2	12.9	12.9	44.5	101.5	100.0
3	11.6	11.6	38.9	12.1	12.1	39.4	95.8	97.8
4	10.7	10.7	34.3	11.3	11.3	34.5	94.6	98.1
Total	50.0	50.0	30.0	50.0	50.0	30.0	100.0	99.9
Case 1.3: Heterogenous stock, per-period capital costs								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	16.7	16.9	50.0	15.6	15.6	50.0	107.8	106.4
2	14.4	13.7	43.3	14.6	14.6	43.8	96.6	95.5
3	13.8	11.0	37.7	13.5	13.5	37.9	91.7	89.1
4	13.5	0.0	32.7	12.7	0.0	32.5	106.1	105.5
Total	58.4	41.6	30.0	56.4	43.6	30.0	100.0	99.0

Table 1: Heterogeneous-in-value fish stock

are no congestion effects, and fishermen are symmetric. Case 1 mirrors the conditions in Clark (1980a) and Boyce (1992), with the exception of congestion which is considered separately below.

The case 1.1 results indicate MPE harvests are symmetric across fishermen. Both MPE and first best harvests decline throughout the season. Under our cost specification, marginal costs increase as the stock size is reduced, i.e., $\partial^2 c(.)/\partial h \partial x < 0$. Harvesting more fish early in the season, when the stock size is larger, lowers seasonal costs.[11]

MPE harvest patterns verify that, relative to first-best outcomes, a race to fish, and rent dissipation occur under ITQs when stock-value is heterogeneous. In period 1, the combined harvest is 109.6% of the first-best harvest, whereas in period 4, the MPE harvest is 84.6% of the first-best harvest. The race to fish occurs because marginal profit associated with each unit of harvest falls as the stock size declines. With no growth, the stock size is reduced from 50% of carrying capacity to 30%, the difference being the total allowable catch that is extracted during the season. Non-cooperating fishermen increase per-period harvest and extract their quota units at a higher unit cost in order to benefit from the stock effect (Clark 1980a). Relative to the first best, this strategy raises period profits early in the season and lowers profits late in the season. The results find that total seasonal profit is lower in the ITQ fishery, as expected, at 99.6% of first best rent.

Case 1.2 in table 1 maintains the assumption of a heterogeneous in value fish stock and symmetric fishermen, but adds congestion costs. We set $\gamma = 1$, which effectively raises the marginal harvesting cost for both fishermen. Comparing MPE harvest patterns to the no-congestion results of case 1, we see that raising costs has the effect of slowing the race to fish. This finding is intuitive if we reconsider the incentive to race. ITQ fishermen prefer to extract their quota early in the season to benefit from stock effect implicit in the harvest technology. However, beating rival fishermen to the highest value comes at a cost which, all else equal, lowers unit profits. Note also that the terminal period stock size cannot fall below the escapement level, $x_1 - y$, and therefore, residual profit per unit of quota, presumably at a slower fishing pace later in the season, is bounded below. We see that congestion costs make it more costly to race and thus the incentive to do so is diminished.

Case 1.3 in table 1 maintains the assumption of a heterogeneous in value fish stock and symmetric fishermen. We introduce a per-period cost of remaining active in the ITQ fishery. For example, fishermen are often able to switch fisheries mid-season to harvest different species, oftentimes with different gear. The case 1.3 results assume that seasonal fixed cost is proportional to the time the vessel is active in the ITQ fishery. Fishermen therefore face a per-period cost of participating in the ITQ fishery, rather than a seasonal cost.

The results indicate asymmetric MPE harvest policies, even though fishermen are otherwise identical. Fisherman 1 harvests during all production periods and harvests more fish per-period (with the exception of period 1) than his counterpart. Fisherman 2 harvests in the first three periods only. There are, of course, two equilibria; a second asymmetric equilibrium exists where the fishermen exchange roles. The first best harvest policy follows a similar pattern, although when both fishermen are active they share the per-period harvest equally under the first-best. The entire total allowable catch is extracted in both cases. Rents under the MPE are 99.0% of the first-best rent.

A per-period capital cost provides an incentive to concentrate harvesting activity into fewer periods, i.e., by increasing the harvest rate, fishing is completed early, which saves the per-period fixed cost. This can be seen by comparing MPE harvest patterns in case 1 of the table, where period fixed costs were absent.

Summarizing the results in table 1, we find that the general insights of Clark (1980a) and Boyce (1992) are confirmed; in the presence of a heterogeneous-in-value fish stock, non-cooperating ITQ fishermen have incentive to engage in a costly race to fish. Extracting quota before rival fishermen lowers unit harvest cost, and increases the residual profit to each quota unit. This behavior raises costs above the minimum required to extract the total quota, and thus dissipates rents in the ITQ fishery. We find that adding congestion effects improves the rents outcomes by raising the cost of competition for the higher-valued units of the stock, and, in fact, improves rent outcomes. Lastly, the results show that patterns of accelerated harvest early in a fishing season when stock size is high may be optimal, depending on the structure of the harvest technology and the opportunity cost of remaining active.

Case 2.1 in table 2 introduces within-season stock growth (Bisack and Sutinen, 2006). We consider a case of symmetric fishermen, and no congestion effects. The growth rate is chosen such that the first best escapement at the end of the fishing season is equal to beginning season stock size ($r = .202$). The scenario is intended to represent a stock that grows continuously and a fishery managed under a sustainable harvest policy.

Case 2.1: Within-season stock growth								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	12.2	12.2	50.0	11.5	11.5	50.0	106.6	104.2
2	12.4	12.4	50.1	12.2	12.2	50.4	101.9	101.0
3	12.6	12.6	50.1	12.8	12.8	50.6	98.4	98.7
4	12.7	12.7	50.2	13.5	13.5	50.4	94.2	96.2
Total	50.0	50.0		50.0	50.0		100.0	99.9
Case 2.2: Elastic demand								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	14.0	14.0	50.0	13.2	13.2	50.0	106.3	101.5
2	13.1	13.1	44.4	12.8	12.8	44.7	102.4	100.2
3	12.0	12.0	39.2	12.3	12.3	39.6	97.3	98.9
4	10.9	10.9	34.4	11.8	11.8	34.7	93.0	98.3
Total	50.0	50.0		50.0	50.0		100.0	99.8
Case 2.3: Varying stock elasticity								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	15.8	15.8	50.0	14.5	14.5	50.0	108.8	104.7
2	13.5	13.5	43.7	13.2	13.2	44.2	102.7	100.8
3	11.3	11.3	38.3	11.8	11.8	38.9	96.1	97.2
4	9.3	9.3	33.7	10.5	10.5	34.2	88.9	93.8
Total	50.0	50.0		50.0	50.0		100.0	99.8

Table 2: Stock Growth, Price and Cost Effects

The results show, not surprisingly, that within-season stock growth slows the race to fish. The explanation is simple: growth replenishes the stock before subsequent period harvesting begins. Within-season growth creates temporally homogeneous stock abundance, and restores the conditions under which ITQs are known to generate first best outcomes.

Case 2.2 in table 2 introduces payoff interaction on the revenue side; the demand for fish is assumed to be finitely elastic. The parameters of the linear fish demand function are set such that a demand elasticity of -5 results when the total allowable catch is spread evenly across harvest periods. Case 2.2 assumes identical fishermen and no congestion effects.

The downward sloping demand introduces an incentive to distribute the harvest evenly throughout the season. This slows the rate of harvest relative to the case of a perfectly elastic demand for fish. Notice that there are no revenue-side market distortions in case 2.2 as the entire seasonal quota is harvested. The strategy of holding back quota to maintain high fish prices will raise profits only if the residual demand facing an individual fishermen is inelastic. Additional results (not reported here) show that market power distortions can arise in a MPE if the demand for fish is sufficiently inelastic. For example, at a demand elasticity of -0.5, we find seasonal MPE less than the total allowable catch.

It should be noted that price effects alone do not cause rent dissipation in our model *when we* solve for MPE harvest behavior with the stock elasticity parameter set to zero. For these cases, the MPE outcomes matched first-best outcomes for various demand elasticities, and over a range of other parameter values (see appendix). Costello and Deacon (2007) suggest rent dissipation can occur in an ITQ-managed fishery, in the absence of stock externalities and congestion effects. We consider scenarios where the price of fish changes exogenously throughout the season. In these cases, MPE harvest rates respond to seasonal price changes in obvious ways. However, in the absence of stock effects, rent dissipation does not occur. If stock effects are absent, nothing is gained by fishing when the stock size is large or small. In fact, there is no strategic interaction in the model when $\beta = 0$. Fishermen optimally tradeoff the gains of harvesting when prices are high with the cost savings from spreading the catch evenly throughout the season. MPE harvests and rents mirror first-best outcomes.

Case 2.3 in table 2 assumes no within-season stock growth or congestion effects, and homogeneous fishermen. The scenario assumes that the stock effect varies throughout the season to approximate naturally varying stock conditions (Costello and Deacon, 2007). For example, salmon concentrate in bays at the mouths of streams prior to swimming upstream to spawn. We approximate heterogeneous stock concentrations by allowing the stock elasticity parameter to vary across periods. In case 2.3, the stock elasticity parameter $\beta = 0.9,\ 0.95,\ 1,\ 1.1$ in periods 1-4.

Results show that MPE harvests increase early in the season due to the higher stock size. The results, while unsurprising, demonstrate how biological forces alter temporal harvest patterns in ITQ fisheries. Separating these effects from rent seeking behavior by fishermen is likely to be difficult in practice particularly if temporal movements of fish stocks are not fully known.

4.1 Stochastic stock evolution

Case 3.1: Stock uncertainty, no stock growth								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	14.9	14.9	50.0	14.1	14.1	50.0	106.0	102.8
2	13.1	13.1	44.1	12.8	12.8	44.4	102.8	100.6
3	11.6	11.6	38.8	11.8	11.8	39.3	98.7	98.3
4	10.1	10.1	34.2	10.8	10.8	34.6	93.4	96.2
Total	49.7	49.7		49.3	49.3		100.7	99.8
Case 3.2: Stock uncertainty, within-season stock growth								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	13.6	13.6	50.0	13.0	13.0	50.0	104.5	102.4
2	12.8	12.8	47.0	12.6	12.6	47.2	101.8	100.5
3	12.1	12.1	44.2	12.3	12.3	44.6	98.9	98.9
4	11.4	11.4	41.7	11.9	11.9	42.0	95.3	97.3
Total	49.9	49.9		49.8	49.8		100.2	99.9
Case 3.3: Temporally-delineated ITQs								
	Time-delineated ITQs			Standard ITQs			Performance	
Period	h_1	h_2	x	h_1	h_2	x	$h^{ne,c}/h^{ne}$	$V^{ne,c}/V^{ne}$
1	13.3	13.3	50.0	14.9	14.9	50.0	89.2	94.0
2	11.7	11.7	44.7	13.1	13.1	44.0	89.4	94.0
3	12.9	12.9	40.0	11.6	11.6	38.8	111.2	107.1
4	11.4	11.4	34.8	10.1	10.1	34.2	113.4	107.2
Total	49.3	49.3		49.7	49.7		99.3	99.9

Table 3: Stochastic Stock Growth and Enhanced Rights

Table 3 reports results for a fish stock that evolves stochastically. Case 3.1 assumes no within-season stock growth, symmetric fishermen, and no congestion. The one-period-ahead stock size is subject to multiplicative shock, which take values, $\xi = 0.85$, 1, and 1.15 with equal probability.[12]

The case 3.1 results are similar to the deterministic model studied above, with a few exceptions. A race to fish and rent dissipation occurs in the ITQ fishing game. Expected harvests under ITQs and under the first best policy are both less than the total allowable catch. Net fishing profits are concave in the stock size. Stock uncertainty lowers expected net profits by Jensen's inequality, and lowers expected harvest. Notice that expected seasonal harvests in the ITQ game are slightly larger (100.7%) than first-best harvest. The race to fish caused by the stock externality increases MPE harvests early in the season. Under case 3.1 parameters, the higher MPE early on more than offset the lower harvests in later periods. The decline in expected harvest is explained by poor growing conditions throughout the season, i.e., with positive probability, a series of low growth shocks are realized in which case extracting the entire quota is not profitable. We examined additional cases where harvesting is more profitable, e.g., within-season growth, lower harvest costs and smaller stock effects and found that MPE outcomes involve harvesting all available quota (these results are not reported to conserve space).

Case 3.2 assumes with-season stock growth ($r = 0.1$). Relative to the no-growth case, within-season stock growth results in lower expected harvests early in the season and higher harvests later in the season. Under stochastic stock conditions, harvest quota can be viewed as an option to be exercised at any time during the fishing season. If the fish stock grows during the season, the return from exercising the option later can be higher. As the season progresses however, exercising the option later risks the possibility of a low growth shock and low quota return. Notice that under within-season growth, the sum of expected harvests falls only slightly below the aggregate quota. Stock growth counters the effects of low growth shocks leading fishermen to harvest a larger share of the total quota than under the no growth case, 3.1.

Our case 3.3 (table 3) results report the findings of a policy experiment. We simulate the effect of a finer delineation of harvest rights. In the experiment, the fishery manager issues temporally delineated rights with the total allowable catch split evenly between the first and second half of the harvest season.[13] Case 3.3 assumes no congestion, a constant fish price, and symmetric fishermen.

To isolate the effect of the temporal delineation, case 3.3 compares MPE harvest policies with and without the temporal rights delineation in place. $h^{ne,c}$ and $V^{ne,c}$ denote, respectively, the MPE harvest and profit with the temporal quota constraint in place. Not surprisingly, the results show that temporal delineation slows the race to fish, relative to the unconstrained case. We also see that the under temporally delineated rights fishermen harvest less $h^{ne,c}/h^{ne} = 99.3\%$ and earn lower seasonal profit, $V^{ne,c}/V^{ne} = 99.9\%$ than under an unconstrained quota. The temporal delineation limits the ability of fishermen to respond to unanticipated growth shocks throughout the fishing season. The result is reduced harvest and lower economic rent in the fishery.

4.2 Further results

We solved for MPE harvest policies and rent outcomes for the case of three fishermen, and under a range of stock growth and demand conditions with and without stock and congestion effects. The results are qualitatively similar to the two fisherman results. We present a subset of our findings in an appendix. There is one quantitative difference worth pointing out when moving from two to three active fishermen. Relative to the first best outcomes, we find smaller rent losses under the MPE harvest policies when $N = 3$. Recall that rent is dissipated in our model when fishermen increase per-period harvest, which causes marginal costs to rise under a diminishing returns technology, i.e, a strictly convex cost function. When the total quota is spread across three fishermen, racing for fish continues to increase marginal costs, but to a lesser extent since there is less variation in marginal costs at lower per-fishermen harvests levels. The implication is that rent losses in decentralized ITQ fisheries will decline with the number of active fishermen.

We thoroughly examined the role or congestion externalities in our model. Congestions effects where included under a host of biological, technological and market conditions. A subset of these results appear in an appendix. Two key findings emerge. First, introducing congestion externalities to the model quantitatively affects MPE harvesting patterns but does not change our general findings. Congestion and stock effects are non-separable in our harvest technology and therefore including both effects alters but does not remove the incentive to race to fish. We find that the combined effect of congestion and stock effects is ambiguous. Congestion may increase the costs of racing to fish and counter the rent seeking motive.

A second result, which holds over all model parameterizations that we examined (appendix B) is that congestions effects alone do not cause rent to be dissipated. This result supports the analysis of Danielsson (2001) and can be understood as follows. Congestion effects influence the harvest productivity and the costs of all active fishermen. As shown in the derivation of equation (8), these effects are internalized under a binding quota constraint. A fishermen whose actions lower the productivity of others will bear the cost of this action because the shadow price of all quota, including his own, will be reduced. Congestion costs can be lowered by removing active fishermen from the fishing ground. However, removing fisherman i during period t, implies $h_{i,t}^{ne} = 0$, which in a quota-managed fishery, and assuming the quota binds, alters the valuation of quota for all active fishermen. Adding and removing fishermen from the fishing grounds affects each fisherman's valuation of quota and is fully captured in the quota trading market (Danielsson, 2000).

5 Conclusion

We have used numerical collocation to identify Markov-Perfect Nash equilibrium harvesting behavior in a dynamic fishing game. Our approach allows direct examination of MPE harvest patterns and rent dissipation outcomes in a general model of an ITQ-managed fishery. Our findings refine some earlier insight regarding unattended production externalities in ITQ fisheries, and offer new insights for the design of quota management programs.

We find that conditions can exist in which rights-based management programs do not replicate first-best economic outcomes. A race to fish by non-cooperating fishermen can persist under decentralized ITQ management when the fish stock is heterogeneous in size and the harvest technology exhibits stock effects. When these conditions hold, fishermen will find it privately optimal to increase harvest rates to extract quota units before rival fishermen deplete the stock. Rents are dissipated under diminishing returns technology as unit costs increase above the minimum required to harvest the quota.

Overall, we find that rent dissipation occurs under fairly special technological and biological conditions. The harvest technology must exhibit decreasing returns. Stock effects bust be large enough to induce cost-inefficient competition for the highest-valued units of the stock. Within season changes in the stock size or value must be significant induce inefficient production.

We show that accelerated harvest early in a fishing season is not a sufficient condition for rent dissipation, e.g., fishermen may speed harvest to exploit available cost economies, save on capital costs, or respond to exogenous changes in prices and stock conditions. Our results find that congestion effects alone do not cause rent dissipation in ITQ-managed fisheries, a result noted in Danielsson (2000). All else equal, congestion effects slow the race to fish for the highest valued units of a heterogenous fish stock. This result is supported empirically in Huang and Smith (2012).

Our results show that rent dissipation in ITQ fisheries will not arise due to price competition alone. Elastic demand provides incentives to smooth the harvest throughout the fishing season, and all else being equal, will slow a race to fish. Rent loss due to market power can occur if fishermen reduce their harvest to maintain high prices at the dock. However, this strategy raises profits only under sufficiently inelastic fish demand.

A question we do not resolve in this paper is whether some form of enhanced property rights, e.g., time- or spatially-delineated rights, will be required to secure the full economic benefits promised by rights-based fisheries management programs. A stochastic policy simulation is presented to demonstrate the potential negative effects of imposing constraints in the form of temporally-delineated fishing rights. We do not incorporate spatial competition in our model, but have reason to suspect similar problems would arise if quota is spatially delineated. If regulations prohibit fishermen from responding to unanticipated movements of fish stocks over time and across space, rents can be dissipated. Our results suggest the benefits from fully delineating fishing rights is an empirical question that will depend on the characteristics of the fishery under consideration. Managers should assess, and if possible, empirically measure stock effects, returns to size, and within-season stock declines, to determine if rent dissipation is likely to be significant under a *standard* ITQ design. Managers should also consider alternate motives to race to fish before labeling accelerated harvest patterns as evidence of rent dissipation.

Enhanced property rights are likely to be information intensive, adding to administrative and monitoring costs. Alternatively, managers may wish to consider the potential for fishermen to devise their own solutions to the problem of unattended externalities in ITQ fisheries.[14] Program designs with low transactions costs, i.e., minimal restrictions on quota trading and ownership, and long-term security may allow fishermen to coordinate their activities and correct the effects of unattended externalities (Coase, 1960). Externalities create problems when fishermen cannot coordinate their actions. ITQ programs that place limits on quota trading and ownership may prevent such coordination and may increase problems related to unattended externalities.

As demonstrated, numerical methods offer a powerful tool to study economic behavior and the impacts of regulation in complex settings. These methods can be extended to consider additional sources of uncertainty, e.g., price and cost uncertainty, games with many players (e.g., Farias, Saure and Weintraub, 2008), and can provide a basis for econometric estimation of strategic interactions among competing fishermen (see Bajari, Benkard, and Levin, 2007). Such extensions could provide further insights to improve rights-based management programs in fisheries and other natural resources.

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7 Appendix A

This appendix describes the collocation method used in our analysis. Additional details are Miranda and Fackler (2002), Judd (1998), and Vedenov and Miranda (2001).

7.1 Application of collocation methods to an ITQ fishing game

To simplify the presentation, we first describe the algorithm for the case of deterministic stock growth. The modification required for uncertain stock growth follows.

7.1.1 Step 1

The state space in our fishing game is naturally bounded. The stock size is contained in the interval $[0, \kappa]$. Seasonal quota holdings for any fishermen in any period cannot exceed the total quota y. The maximum number of discrete fishing periods is finite. The stock-quota state space is continuous. In the first step, we discretize the stock and quota state space using the method developed by Chebychev (see Miranda and Fackler, 2002, ch. 6). Our approach solves for MPE harvest strategies recursively. The numerical algorithm is best described in the same sequence.

Consider the terminal period harvest choices. To ease notation, we drop the period index momentarily. Let $z^q = (z_1^q, z_2^q, , ..., z_{N+1}^q) = (x^q, y_1^q, y_2^q, ..., y_N^q)$ denote a particular element of the stationary stock-quota state space. We can solve for the pure strategy Cournot-Nash harvest for each fisherman given the state z^q. We make an initial guess, $h_{-i}^0(z^q) \leq y_{-i}^q$ for all $-i$. A hill-climbing algorithm is used to obtain i's best response to $h_{-i}^0(z^q)$. We iterate across fishermen and repeat until the best harvest responses for all fishermen satisfy a convergence criterion:

$$\sum_{i}^{N} |h_i^{\tau}(z^q) - h_i^{\tau-1}(z^q)| \leq \varepsilon,$$

where $\varepsilon > 0$ is small. We next evaluate profit for each fisherman at the equilibrium harvest vector. These steps are repeated for each element z^q, $q = 1, \ldots, Q$ of the state space.

Let $\pi_{i,T}^{ne}(z^q)$ denote the MPE profit for fisherman i in the terminal period given z^q.

7.1.2 Step 2

We next approximate MPE profits over the full state space using a series of Chebychev polynomial basis functions (Miranda and Fackler, 2002, ch. 6). Application of the collocation methods using cubic splines generated virtually identical results.

Reintroducing the period index we have,

$$\pi_{i,T}^{ne}(z^q) = \sum_{j=1}^{Q} b_{i,j,T} \phi_j(z_j^q), \qquad q = 1, \ldots, Q,$$

where $\{b_{i,j,T}\}_{j=1}^{Q}$ are the collocation coefficients, and $\phi_j(z_j^q)$ is the j'th basis polynomial. Using upper case to denote vector notation, the above system of linear equations can be written as:

$$\Pi_{i,T}^{ne} = \Phi(z) \cdot B_{i,T},$$

Collocation coefficients are obtained as

$$B_{i,T} = \Phi^{-1}(z) \cdot \Pi_{i,T}^{ne}.$$

7.1.3 Step 3

We next examine MPE equilibrium harvest behavior in period $T-1$. Recall, $v_i(z_t, t)$ denotes the expected profit for fisherman i given state z_t in period t. This value can be written in Bellman equation form:

$$v_i(z_t, t) = max_{h_{i,t} \leq y_{i,t}} \Big\{ p(h_t)h_{i,t} - c_i(h_{it}, h_{-i,t}, x_t, N_t, t) + v_i(z_{t+1}, t+1) \Big\}. \tag{9}$$

At the MPE, equation (9) incorporates the shadow prices of the quota and fish stock. An increase in current period harvest affects current revenues and costs, reduces $y_{i,t+1}$, and affects stock size x_{t+1} in the subsequent period. The continuation value $v_i(z_{t+1}, t+1)$ quantifies the future costs associated with the current harvest decision.

To solve the problem in equation (9) for periods $t = 1, \ldots, T-1$, we substitute the estimate of $v_i(z_{t+1}, t+1)$, which is obtained from the collocation procedure,

$$\widehat{v}_i(z_{t+1}, t+1) = B_{i,t+1}\Phi(z_{t+1}).$$

The iterative hill-climbing procedure (step 1) is then repeated to obtain period t MPE harvests. The reader will notice that in the terminal period, the collocation method approximates the operating profit only since there is no period $T+1$ continuation value. The collocation method approximates the right hand side of equation 9 in all earlier periods, $t = 1, 2, \ldots, T-1$.

Steps 2 and 3 are repeated to obtain MPE equilibrium harvest policies and numerical value functions for all periods. MPE equilibrium harvest strategies for any state and period are then easily calculated.

7.2 Stochastic stock evolution

To introduce stochastic stock evolution we discretize the shock space and introduce stock transition probabilities. We divide $[\underline{\xi}, \overline{\xi}]$ equally into $l = 1, \ldots, L+1$ intervals. Let ξ_l denote the midpoint of interval l. We assume $Prob(\xi = \xi_l | z) = \theta_l$. Under stock uncertainty we replace the Bellman equation in equation (9) with the following:

$$max_{h_{i,t} \leq y_{i,t}} \Big\{ p(h_t) h_{i,t} - c_i(h_{it}, h_{-i,t}, x_t, N_t, t) + \sum_{l}^{L} \theta_l \widehat{v}_i(z_{t+1}, t+1 | \xi_l) \Big\}. \tag{10}$$

7.3 First best harvest policies

Under deterministic stock conditions, the first best harvest policy is calculated directly as the solution to the following optimization problem:

$$max_{\{h_{i,t}\}} \sum_{t=1}^{T} \sum_{i=1}^{N} \Big[p(h_t) h_{i,t} - c_i(h_{1,t}, h_{2,t}, \ldots, h_{N,t}, x_t, N_t, t) \Big].$$

If stock evolution is stochastic, we utilize the collocation algorithm described above, but modify the objective to maximize the sum of fisherman profits in each production period.

8 Appendix B

Case 4.1: Heterogenous stock, 3 fishermen										
	ITQ game				First best				Performance	
Period	h_1	h_2	h_3	x	h_1	h_2	h_3	x	h^{ne}/h^*	V^{ne}/V^*
1	9.5	9.3	9.5	50.0	9.1	9.1	9.1	50.0	103.5	102.6
2	8.8	8.6	8.8	44.3	8.6	8.6	8.6	44.5	101.5	101.0
3	8.0	7.9	8.1	39.1	8.1	8.1	8.1	39.4	99.0	99.1
4	7.2	7.1	7.2	34.3	7.5	7.5	7.5	34.5	95.2	96.5
TOTAL	33.5	32.9	33.6	30.0	33.3	33.3	33.3	30.0	100.0	100.0
CASE 4.2: No stock effect, congestion, 3 fishermen										
	ITQ game				First best				Performance	
Period	h_1	h_2	h_3	x	h_1	h_2	h_3	x	h^{ne}/h^*	V^{ne}/V^*
1	8.3	8.3	8.3	50.0	8.3	8.3	8.3	50.0	99.9	99.9
2	8.3	8.3	8.3	45.0	8.3	8.3	8.3	45.0	99.9	100.0
3	8.3	8.3	8.3	40.0	8.3	8.3	8.3	40.0	99.8	99.9
4	8.4	8.4	8.4	35.0	8.3	8.3	8.3	35.0	100.3	100.3
TOTAL	33.3	33.3	33.3		33.3	33.3	33.3		100.0	100.0
Case 4.3: No stock effect, congestion, 2 fishermen										
	ITQ game				First best				Performance	
Period	h_1	h_2	h_3	x	h_1	h_2	h_3	x	h^{ne}/h^*	V^{ne}/V^*
1	12.5	12.5	-	50.0	12.5	12.5	-	50.0	100.0	100.0
2	12.5	12.5	-	45.0	12.5	12.5	-	45.0	100.0	100.0
3	12.5	12.5	-	40.0	12.5	12.5	-	40.0	100.0	100.0
4	12.5	12.5	-	35.0	12.5	12.5	-	35.0	99.9	100.0
TOTAL	50	50	-		50	50	-		100.0	100.0

Table 4: Three Fishermen, Congestion Effects

Case 4.1 of table 4 adopts the same assumptions of case 1.1 of table 1 (no within-season stock growth, no congestion), but adds a third fishermen. As in the 2 fishermen example, The MPE harvest exhibits a race to fish relative to the first-best policy. Notice that the rent loss is insignificant with 3 fishermen. The reason is that all are now operating at lower per-period harvest quantities. The increase in marginal harvest costs caused by a race to fish are only slightly larger than the first best marginal costs. The difference is not noticeable at the seasonal level in the presence of numerical approximation error.

Cases 4.2 reports results for 3 fishermen, no stock effects ($\beta = 0$), and congestion effects ($\gamma = 3$). The results show that MPE harvest outcomes mirror first-best outcomes apart from numerical approximation error. Case 4.3 replicates the conditions in case 4.2, but with 2 fishermen. Again MPE harvest outcomes mirror first-best outcomes. Which fleet structure will emerge in the pre-season quota trading equilibrium? The total (absolute) variable profit is higher with three fishermen than with two. With strictly convex costs, variable cost of harvesting the quota is less with three active fishermen. The fleet structure that will emerge in equilibrium will depend on the magnitude of the seasonal fixed cost, favoring the fleet structure with lowest total costs. If for example, total costs are lower with $N = 2$, a third fishermen will be unable to profitably purchase quota since the unit value (rent) will be highest when y is divided among two active fishermen. If fishermen are identical, multiple Nash equilibria exist. Similar arguments suggest that if fixed costs are small, so that total costs are less with $N = 3$, the Nash equilibrium will involve three active fishermen.

CASE 5.1: Elastic demand, congestion, no stock effect								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	12.5	12.4	50.0	12.5	12.5	50.0	99.5	99.7
2	12.5	12.4	45.0	12.5	12.5	45.0	99.4	99.6
3	12.3	12.3	40.1	12.5	12.5	40.0	98.7	99.2
4	12.6	13.0	35.1	12.5	12.5	35.0	102.4	101.5
Total	49.9	50.1		50.0	50.0		100.0	100.0
CASE 5.2: Declining fish price, congestion, no stock effect								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	16.3	16.3	50.0	16.3	16.3	50.0	100.3	100.2
2	13.8	13.8	43.5	13.8	13.8	43.5	99.9	99.9
3	11.5	11.5	37.9	11.3	11.3	38.0	100.4	100.3
4	8.4	8.4	33.4	8.8	8.8	33.5	99.3	99.3
Total	50.0	50.0	30.0	50.0	50.0	30.0	100.0	100.0

Table 5: Demand and Price Effects

Case 5.1 isolates the effects of revenue competition. The per-period price of fish depends on the total period harvest. Congestion effects are present but there are no stock effects. In this setting each fisherman prefers that his counterpart(s) make zero deliveries to maintain high prices. In equilibrium, the total catch is spread evenly (with the exception of approximation error) throughout the season, with each fisherman harvesting half the quota.

In case 5.2, the price of fish is perfectly elastic, but falls exogenously throughout the season. The MPE and first-best harvest patterns are identical, except for approximation error. Both show a predictable pattern of declining harvest throughout the season. Both policies optimally tradeoff the gains from higher prices early on, with the added costs from increasing harvest rates in early periods under strictly convex harvest costs.

Case 6.1 of table 6 considers a heterogeneous stock, but allows for asymmetric fishermen; fisherman 1 costs are set lower than fisherman 2 costs. Asymmetry is introduced by lowering α for fisherman 1 and increasing α for fisherman 2. The cost parameters are adjusted such that the first best rent under the asymmetric fishermen case is equal to first best rent generated under the case 1.1 parameter values. The results show that MPE harvests are asymmetric as expected, with the bulk of the harvesting responsibility falling to the lower cost fisherman 1. The race to fish continues in the ITQ fishery, also as expected, which results in rent dissipation. These results are not surprising. The results demonstrate the role of quota trading on economic performance, and the flexibility of our numerical approach.

Case 6.2 combines a per-period capital cost and congestion effects. Case 6.3 increases the curvature of the harvest cost function, increasing the value of η to 2.2. These results are included as further robustness checks on the model.

Case 6.3 reports results under increased harvesting costs (α is increased by 40%). Case 6.4 reports the results under a higher stock elasticity parameter (β is increased by 20%).

Case 6.1: Heterogenous stock, asymmetric fishermen								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	18.4	11.1	50.0	17.2	10.2	50.0	107.8	104.1
2	16.2	9.7	44.1	16.2	9.6	44.5	100.4	99.7
3	14.8	8.6	38.9	15.2	9.0	39.4	96.9	97.9
4	13.4	7.7	34.2	14.2	8.4	34.5	93.4	96.5
Total	62.9	37.1		62.8	37.2		100.0	99.9
CASE 6.2: Per-period capital costs, congestion effects								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	16.1	16.5	50.0	15.2	15.2	50.0	107.6	104.5
2	14.6	13.2	43.5	14.2	14.2	43.9	98.0	96.3
3	12.9	11.4	37.9	13.2	13.2	38.3	92.0	91.6
4	15.3	0.0	33.1	14.9	0.0	33.0	102.6	100.9
TOTAL	58.9	41.1	30.0	57.4	42.6	30.0	100.0	99.0
CASE 6.3: Heterogeneous stock, $\eta = 2.2$								
	ITQ game			First best			Performance	
Period	h_1	h_2	x	h_1	h_2	x	h^{ne}/h^*	V^{ne}/V^*
1	13.5	13.5	50.0	13.6	13.6	50.0	99.6	99.7
2	12.7	12.7	44.6	12.9	12.9	44.6	99.0	99.2
3	12.3	12.3	39.5	12.1	12.1	39.4	101.0	100.8
4	11.5	11.5	34.6	11.4	11.4	34.6	100.5	100.4
Total	50.0	50.0		50.0	50.0		100.0	100.0
CASE 6.4: Heterogeneous stock, $\alpha = 6.5$								
	ITQ game			First best			Performance	
1	14.3	14.3	50.0	13.7	13.7	50.0	104.1	101.3
2	12.9	12.9	44.3	12.9	12.9	44.5	100.2	99.7
3	11.6	11.6	39.1	12.1	12.1	39.4	95.8	98.5
4	11.2	11.2	34.5	11.3	11.3	34.5	99.3	99.9
Total	50.0	50.0		50.0	50.0		100.0	99.9
CASE 6.5: Heterogeneous stock, $\beta = 0.5$								
	ITQ game			First best			Performance	
1	13.3	13.3	50.0	13.1	13.1	50.0	101.3	101.0
2	12.8	12.8	44.7	12.7	12.7	44.8	100.9	100.6
3	12.2	12.2	39.6	12.3	12.3	39.7	99.1	99.3
4	11.7	11.7	34.7	11.9	11.9	34.8	98.6	98.9
Total	50.0	50.0		50.0	50.0		100.0	100.0
CASE 6.5: Heterogeneous stock, $\beta = 1.2$								
	ITQ game			First best			Performance	
1	15.0	15.0	50.0	13.9	13.9	50.0	107.7	103.0
2	13.1	13.1	44.0	13.0	13.0	44.4	101.2	99.7
3	11.4	11.4	38.7	12.0	12.0	39.2	94.9	97.4
4	10.5	10.5	34.2	11.1	11.1	34.4	94.5	98.1
Total	50.0	50.0		50.0	50.0		100.0	99.8

Table 6: Sensitivity Analysis

9 Extended Appendix

This appendix contrasts our model and results to the case where the fishery is managed under (1) a common total allowable catch (TAC) policy, hereafter TAC management, and (2) open access management. Under TAC management, the fishery remains open to fishing until the aggregate quota is harvested. Thus, all fishermen compete to harvest a common quota from a common stock. Under open access the fishery remains open irrespective of the aggregate harvest. Clearly in this latter case, there is no way to prevent fishermen from harvesting more than the TAC. We first present the modified fishermen's optimization problem under these alternate management regimes. Equilibrium harvests and profits for a case of no-within-season stock growth and no congestion are presented next

Under TAC management, seasonal operating profits for fisherman i are given as,

$$E \sum_{t=1}^{T} \Big[p_t(h_t) h_{i,t} - c_i(h_{i,t}, h_{-i,t}, x_t, N_t, t) \Big], \tag{11}$$

where E denotes expectations. The optimization is subject to the within-stock evolution and the constraint,

$$\sum_i \sum_t h_{i,t} \leq y, \tag{12}$$

where y is the (common) aggregate seasonal quota. The optimization problem in an open access fishery is again given in (11), however, the quota constraint (12) is dropped.

	Sole ownership		ITQs		TAC		Open Access	
Period	h_t	V_t	h_t	V_t	h_t	V_t	h_t	V_t
1	27.4	3.54	27.5	3.55	32.8	3.75	33.7	3.77
2	25.8	3.22	25.1	3.19	29.2	3.27	30.1	3.27
3	24.2	2.96	22.7	2.85	27.2	2.85	27.0	2.83
4	22.6	2.59	24.7	2.65	10.9	1.25	23.7	2.41
Total	100.0	12.26	100.0	12.24	100.0	11.12	114.5	12.28

Table 7: Comparisons with TAC and open access management

Table 7 reports aggregate (summed across two fishermen) per-period harvests as a percentage of the aggregate quota and profits under four management scenarios: sole ownership, ITQs, TAC management and open access. Consider the sole owner, ITQ and TAC management regimes which each limit the total allowable catch in the fishery. The race to fish is most pronounced, and profits are lowest under the TAC management regime. TAC management attains only 90.7% of the first best profit; 99.8% of first best profit is attained under ITQs. This result confirm consensus in the literature that ITQs reduce the race to fish relative to TAC and open access management (e.g., Boyce, 1992).

The harvest rate under ITQ management is considerably slower that under TAC management. This result is consistent with Fell (2010) and highlights an important benefit of ITQ management where slower harvest rates avoid market gluts and low ex-vessel prices.

The final columns report MPE harvests and profit under open access. Open access does not control aggregate harvest and we see that 114.5% of the managers target quota is harvested. Seasonal profit is higher under open access than under sole ownership management, also the first best outcome. Of course, this result masks the longer term costs of exceeding the manager's target quota. The result is an illustration of the tragedy of the commons and teh well-known result where under open access, excessive harvest yield initial high payoffs but deplete resource stock eventually driving fishing profit to zero (Gordon. H. S., The Economic Theory of a Common Property Resource: The Fishery, Journal of Political Economy, 62 (1954):124-142).

Notes

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[1]Clark, 1980; Boyce, 1992, 2001; Holland, 2004; Bisack and Sutinen, 2006; Cancino, Uchida and Wilen, 2007; Costello and Deacon, 2007; Deacon, Parker and Costello, 2008; Fell, 2010.

[2]Copes (1986), and more recently Pinkerton (2009), provide critiques of rights-based management approaches in fisheries.

[3]Costello and Deacon (2007) present a model in which fishermen compete to harvest a fixed number of stock units, or sub-stocks. Sub-stock values vary exogenously throughout a fishing season, with each sub-stock having its own optimal and unique harvest date. Harvesting a sub-stock before or after the unique optimal date results in lost value. The model is static; fishermen simultaneously announce the date that they plan to visit each sub-stock and the amount of quota that dedicated to each sub-stock. The authors are able to solve for a Nash equilibrium for the special case where the value of a sub-stock falls to zero for any fishermen arriving late to a sub-stock, i.e., after some other fisherman has visited the sub-stock, and fishermen dedicate their full quota holding to a single sub-stock.

[4]The authors caution that these estimates are likely influenced by data limitations.

[5]A data fitting approach was used to overcome missing cost data. The implications for the author's results are not clear. It is also not clear how the author derive Nash equilibrium harvesting behavior in their simulations of fishing behavior. Page 243 states "we use a GAMS numerical algorithm to solve for the harvest and effort path that maximizes profits for each firm, given that every other firm is maximizing its profits."

[6]Judd (1998) discusses the use of numerical methods for analyzing complex economic problems.

[7]See Fudenberg and Tirole for a discussion of open-loop, closed loop and Markov strategies in dynamic games (p.501). Reinganum and Stokey (1985) study the role of commitment and discuss alternate equilibrium concepts in the context of common property resource games.

[8]The optimal fleet size would be finite in the presence of congestion effects.

[9]The number of active fisherman we consider is clearly smaller than would be observed in an actual fishery. Our results illustrate qualitative strategic interactions only.

[10]Our model can be used to study outcomes under alternate management regimes. We derive MPE harvests and profits in a fishery that is managed under a common quota, also called a total allowable catch policy, and under open access. Results are reported in an extended appendix and are available, upon request, from the authors.

[11]While our assumptions for cross-derivative cost effect are reasonable, empirical evidence for second-order properties of resource extraction costs is scarce.

[12]Stock uncertainty is common to all identical fishermen and therefore no within-season quota trading takes place. If uncertainty was fishermen-specific, quota trades based on pre-season expectations could become ex post

sub-optimal, providing incentives for further trade. An analysis of within-season quota trading is left for future work.

[13]Costello and Deacon (2007) suggest that redundant and costly searches for uncertain, spatially located fish stocks could be reduced by allocating spatially delineated harvest rights. We do not incorporate space or search costs in our model, and therefore cannot examine the performance of spatially-delineated rights. Salmon bycatch permits issued for the Bearing Sea pollock fishery are delineated bi-seasonally (NOAA, 2010)

[14]British Columbia groundfish trawl fishermen have demonstrated remarkable willingness to coordinate harvesting activities to secure available quota rent (Grafton, Nelson and Turris, 2007). Evidence of cooperation among fishermen, and between fishermen and managers in rights-based-managed fisheries, although anecdotal, has also emerged (Munro, 2007).