Resource and Energy Economics 33 (2011) 366–380

Contents lists available at ScienceDirect

Resource and Energy Economics

journal homepage: www.elsevier.com/locate/ree

Restricted capacity and rent dissipation in a regulated open access fishery

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ARTICLE INFO

Article history:
Received 1 June 2009
Accepted 1 February 2010
Available online 4 June 2010

JEL classification:
Q22
Q28
Q57

Keywords:
Fishery management
Regulated open access
Rents
Elasticity of substitution

ABSTRACT

A common strategy for limiting the total annual catch in a fishery is to restrict entry and season length. We examine the results of this strategy when entry limitation amounts to a limit on capital, but fishing firms can vary an unrestricted input, and thereby use the restricted input more intensively. Under these regulatory constraints, fishing firms will earn rents that depend on the elasticity of substitution between restricted and unrestricted inputs. Using simulations with data from the Alaskan pollock fishery, rents and season length are shown to depend on fish and variable input prices, sometimes in surprisingly non-monotonic ways.

1. Introduction

The economic literature on fishery regulation has moved away from treatments focused on understanding incentives and outcomes under open access to more recent explorations of the consequences of specific regulations and the problem of choosing the right policy instrument for a particular circumstance.[1] The question of instrument choice remains highly pertinent in the United States due to the contemporaneous presence of diverse regulations and recent moves toward ITQs,

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[1] A seminal early contribution is Gordon (1954). Boyce (2004) gives a comprehensive review of instrument choice in the fishery. Homans and Wilen (1997) comment on the transition in the economic literature from discussions of stylized open access and its inefficiencies to treatments that explicitly examine applicable technologies and regulatory constraints.

0928-7655/$ – see front matter
doi:10.1016/j.reseneeco.2010.05.003

cooperatives and other forms of rationalization in the U.S. and abroad. However, moves to rationalization through incentive-based management are tentative in the U.S., and the likelihood is that many existing management schemes will not be replaced soon (Kirkley et al., 2007). One existing form of regulation is a limit on entry (fishing permits) with an annual total allowable catch (TAC) enforced by season closure. This is common in salmon fisheries, it was the regime in place in the Alaska halibut fishery before ITQs were introduced, and will remain the regulatory system in the U.S. west coast trawl fishery until the switch to ITQs in 2010. The following analysis examines the within-season behavior of a fishery managed by a still common form of regulation: limited entry, which is here regarded as a limit on capital or fishing capacity, and a TAC that is enforced by season closure.

Several authors have made the point that capacity limitation programs can allow some of the rent accruing to the resource to be captured by industry participants. Anderson (1985) demonstrated that a gear restriction can increase rent in a context where effort is supplied at increasing unit costs. Restricting gear choice raises the unit cost of all effort employed, but reduces the number of redundant units actually used; positive net rent can emerge as a result.[2] Campbell and Lindner (1990) extend Anderson's approach by investigating the welfare consequences of input regulation when fishing firms can substitute between restricted and unrestricted inputs. Through simulations they conclude that a license limitation program will approximate a first-best solution in situations where unrestricted and restricted inputs cannot be easily substituted for one another or where restricted inputs account for a major component of the industry's total cost. Campbell (1991) empirically estimated the elasticity of substitution between restricted and unrestricted inputs for the Tasmanian rock lobster fishery and concluded that, in this case, a license limitation program could result in significant rent capture. Similar conclusions were reached by Dupont (1991) who estimated the elasticity of substitution between restricted and unrestricted inputs for the British Columbia salmon fishery, and found that substitutability varied across vessel types.

Boyce (2004) provides a unified treatment of instrument choice in the fishery to explain why suboptimal controls such as input restrictions and entry limitation persist in fisheries management. As he demonstrates, these suboptimal controls benefit input suppliers by transferring rents from the fishery resource to the owners of inputs permitted to operate. This insight provides a compelling answer to the puzzle of why such inefficient regulations are so common and durable, particularly in the U.S. where fishery management councils are heavily influenced by resident input suppliers with organized, entrenched lobbying power.

These studies have all made valuable contributions. Nevertheless, the following questions remain: How is rent affected by the level at which capacity (entry) is limited and what capacity limit maximizes rent? How does the ease or difficulty of substituting between restricted inputs (capacity or capital) and unrestricted inputs (labor or other variable inputs) affect the answers to the preceding questions? Given that a larger TAC increases revenue, but will also increase competition and increase the use of costly variable inputs, will a larger TAC necessarily increase the rents of capital owners? What about higher prices or lower wages, and do the answers depend on how substitutable fishing inputs are? We address these questions in what follows.

Two papers are of particular interest because together they shed light on the observable consequences and welfare effects of restrictions on fishing inputs and/or total catch. The first of these is Homans and Wilen (1997), who point out that most near-shore fisheries have operated under a variety of specific regulations since coastal nations extended their jurisdictions in the late 1970s. They emphasize that the details of these regulations are crucial in determining the observed behavior of fisheries and develop a model of one such regime, which they term 'regulated open access' (ROA). Under regulated open access the regulator fixes the total allowable catch based purely on biological criteria and enforces this catch limit with a season closure. Firms enter and exit the industry, taking allowable catch and season length as given, until all long-run rents accruing to the unpaid resource (the stock) are dissipated. Homans and Wilen (HW) close the model by specifying an objective function for the fishery regulator, who sets the TAC to keep the stock close to a level that is considered 'safe'.

[2] Anderson (1985) also demonstrates that a license limitation, modeled as a limit on the number of firms allowed to operate, can also yield positive rent.

In the ROA regime, a valuable commodity (fish that are legal to catch) are made available to fishing firms at a zero price and the available supply, which is fixed by biological and regulatory factors, is allocated among users on a first come-first served basis. This fits the circumstances studied in the second paper emphasized here, Deacon (1994).[3] When allocation is by first come-first served, competition to acquire the stock before one's competitors raises cost, and this cost increase simultaneously rations access to the stock and dissipates rent the stock could generate if managed efficiently. Deacon (1994) extends this reasoning to determine how much rent can be captured by a second-best policy of regulating some, but not all, of the inputs used to acquire the resource. Both the extent of rent dissipation and the second-best optimal input limit are found to depend critically on relative input prices and on the elasticity of substitution between regulated and unregulated inputs. If substitution is largely impossible, this policy can approach the welfare gains of optimal management. Alternatively, if substitution is easy such regulation may result in little or no rent capture.

The present paper extends the regulated open access model of HW (1997) by recognizing that an entry restriction controls only one of the inputs used to produce fishing effort, so expansions on uncontrolled margins can be expected. The analysis is analogous to Deacon's (1994) treatment of the actions individuals take when competing for access to a price controlled good, and the rent dissipation that results. The main objective here is to see how the presence of a capital constraint affects the rents earned by fishing firms and the link between rent and such economic determinants as prices, input costs and the allowed catch. Unlike HW we do not track the dynamic path of the regulator's choices to a steady-state equilibrium, but rather focus on within-season behavior for a given TAC.

The main contributions are: (i) an explicit characterization of the consequences of a TAC/season closure regulatory regime, with limited entry, on the firm's cost function, (ii) an exploration of second-best capacity restrictions and the rent capture they enable, and (iii) an examination of how rents respond to changes in prices, TAC levels and input costs.[4] Following the model development, the influence of critical parameters on rent capture under second-best regulation is examined by simulation. The results demonstrate the critical influence of the elasticity of substitution between restricted and unrestricted inputs on the efficiency gains from second-best input regulation.

2. Specifying fishery production and regulation

Under ROA the regulator limits total allowable catch (TAC) and closes the fishery when this limit is met. During the year firms experience two kinds of cost: a variable cost that is proportional to the product of effort and season length and a fixed cost that is proportional to effort but independent of season length. If rent is positive, effort expands via entry and the regulator is forced to close the season earlier. Entry raises the fixed cost required to harvest the TAC, so rent is reduced. ROA equilibrium is achieved when all long-run (season length) rent has been eliminated.

We extend this model by specifying a production function that relates fishing effort to the use of individual fishing inputs. With this extension the fixed and variable components of harvest cost can be traced to more primitive concepts, input prices and the form of the production function. This extension also allows us to consider the effect of a regulatory limit on fishing capital, e.g., a limit on the number of vessels licensed to harvest. Positive rent may persist in the long-run under this form of regulation and the source and magnitude of this rent can be traced to the degree of substitutability between regulated and unregulated inputs. The second-best limit on capital, i.e., the limit that maximizes long-run rent in the context of a fishery regulated by a TAC and season closure, can then be determined.

As HW frame the problem, fishing starts at the beginning of each year and continues until the regulator declares the season closed. Both the regulator and the fishery participants know the initial

[3] Deacon's (1994) analysis extends a model of a price control and first come-first served allocations developed in Deacon and Sonstelie (1991) to apply to an unowned renewable resource. In both cases a valuable commodity carries a price less than its marginal value to users. With a price controlled good the source of under-pricing is regulatory. With an open access resource an absence of ownership leads to an effective price of zero.

[4] Weninger and McConnell (2000) also develop a model with season closures, but emphasize different policy issues.

fish stock, N_0. Harvests during the season reduce the reproductive stock available at the end of the season and all natural population dynamics occur between seasons.

Following HW, we assume the regulator determines the total allowable catch through a biologically-driven linear decision rule. The rule only depends upon the (given) biomass at the beginning of the season, Eq. (5) in HW. Allowed catch, $\bar{H}$, relates to the biomass at the beginning of the season by the function:

$$\bar{H} = \max(a + bN_0, 0), \tag{1}$$

where b is positive and a may be positive or negative. Assuming the beginning of season stock allows a positive harvest, the regulator closes the season when the harvest reaches $\bar{H}$. Eq. (1) removes all notions of dynamic optimization from the problem and reduces it to one of a seasonal (static) problem.

We generalize HW to let the instantaneous fishing mortality rate, f, be a concave function of a variable input, L, and capital, K, committed to the fishery:

$$f = f(L, K). \tag{2}$$

In what follows we refer to f as the *instantaneous effort rate*. L and K are assumed to be fixed within a season but variable between seasons. Within a season the stock declines at a proportional rate equal to instantaneous fishing effort:

$$\dot{N}(t) = -f(L, K)N(t) \tag{3}$$

Let $T \leq 1$ indicate the fraction of the year the season is open. The cumulative harvest over a season of length T is then found by integrating Eq. (3) for given N_0. We assume the regulator fixes T for any given effort rate, $f(L,K)$, so that harvests fully exhaust the allowable catch. This implies

$$H = N_0(1 - e^{-f(L,K)T}) = \bar{H}, \tag{4}$$

which identifies the season length, T, as a function of N_0, $\bar{H}$ and $f(L, K)$.

We refer to $f(L,K)T$ as *total fishing effort* over the year. Solving (Eq. (4)), the constraint on allowable catch implies an equivalent constraint on total fishing effort:

$$f(L, K)T = \ln\left(\frac{N_0}{N_0 - \overline{H}}\right) \equiv \overline{E}. \tag{5}$$

Total effort over the season is entirely determined by the initial stock and the parameters of the regulatory rule. The regulator is concerned only that (Eq. (5)) is satisfied and has no particular preference regarding the specific values of $f(L,K)$ and T that accomplish this.

3. Harvester behavior and ROA equilibrium

The industry consists of a large number of identical firms, each of which takes prices, allowable catches and the regulator's season limit as given. With constant returns to scale in fishing effort, $f(L,K)$, the industry behaves like a single, price-taking firm.[5]

Firms are assumed to incur variable input costs only while the season is open, but incur capital costs for the entire year. Letting w denote the per unit price of the variable input on an annual basis, which we refer to as the wage rate, and r the annual rental price of capital, total cost is

$$C = wLT + rK = \left(wL + \frac{r}{T}K\right)T. \tag{6}$$

Capital is committed for the entire year but used only during a season of length T, hence r/T is the effective price of capital services. Using p to denote the exvessel price of harvest, or the price that firms

[5] Constant returns to scale at the industry level can be thought of as reasonable if there are multiple firms in the fishery where vessels are of similar size, horsepower and skippers of similar skill.

receive when they sell their catch, annual rent in the fishery is

$$\Pi = pN_0(1 - e^{-f(L,K)T}) - \left(wL + \frac{r}{T}K\right)T. \tag{7}$$

Revenue is fixed by the total allowable catch limit (Eq. (4)). Cost, however, is endogenously determined by the fishing firm's choice of the variable input and by the regulator's choices of capital limit and season length.

Our central focus is a regime in which the regulator fixes K and T, but firms choose L, i.e., a fishery with limited entry and a season closure, but no regulation on how intensively capital is used during the open season. It is instructive, however, to first examine two benchmark cases in which L and K are both variable for purposes of comparing: (i) an 'efficient' equilibrium in which input choices are coordinated to maximize industry rents (recognizing that the regulator will adjust the season length to satisfy (Eq. (5))), and (ii) an open access equilibrium in which the regulator does not limit entry and firms expand L and K in a cost minimizing fashion so long as rent is positive. As described below, the case of central interest lies between these benchmark outcomes. The open access equilibrium is similar to the ROA equilibrium studied by HW, but it takes explicit account of the fact that K may be employed only part of the year. The industry's choice of effort is optimal given the season length set by the regulator, and the regulator's choice of season length is optimal given the effort level set by the industry.

3.1. The efficient and open access benchmarks with capital variable

We begin by examining the industry's profit maximizing choice of inputs L and K contingent on the regulator's choice of T. Recalling the cost equation (6), this choice solves:

$$\begin{aligned}&\min_{L,K}\left(wL + \frac{r}{T}K\right)T\\ &\text{s.t.}\quad f(L,K) = f\end{aligned}.$$

The cost minimizing L/K ratio satisfies the familiar condition that the marginal rate of substitution between the variable input and capital equals the input price ratio:

$$\frac{w}{r/T} = MRTS_{LK} \tag{8}$$

With constant returns to scale in f the cost function can be written

$$C\left(w, \frac{r}{T}, f\right)T = c\left(w, \frac{r}{T}\right)fT, \tag{9}$$

where $c(w, r/T)$ is the unit cost of effort and fT is total effort over the year.[6]

In our 'efficient regime' benchmark a central coordinator, e.g., a single firm facing constant prices or a cooperative group representing vessel owners, chooses L and K to maximize industry rent, taking into account that the regulator will set T to satisfy (Eq. (5)). Substituting the regulatory constraint on catch (Eq. (4)) and the cost function (Eq. (9)) into the profit equation (Eq. (7)), industry profit becomes

$$\Pi = p\overline{H} - c\left(w, \frac{r}{T}\right)fT. \tag{10}$$

The efficient coordinator recognizes that the regulator's constraint on catch fixes total effort according to $f(L,K)T = \overline{E}$, as in Eq. (5), so the industry's choice of $f(L,K)$ effectively determines T. Recognizing this, industry profit in the 'efficient' case can be written:

$$\Pi = p\overline{H} - c\left(w, \frac{r}{T}\right)\overline{E} \tag{11}$$

[6] Cost can also be written more conventionally as a function of the stock and total catch by substituting for fT from Eq. (5).

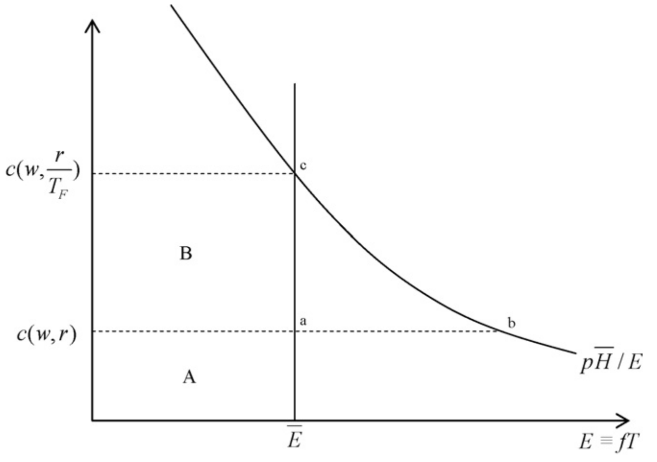

Fig. 1. Equilibrium in efficient and free access cases.

and T can be regarded as a choice variable for the coordinator. The industry's best choice clearly minimizes r/T subject to $T \leq 1$. The obvious solution is $T=1$, or full season fishing.[7] To summarize, the efficient allocation uses an L, K mix that minimizes cost given the effective factor prices, w and r/T, and scales *total effort* to allow fishing throughout the year.

Fig. 1 illustrates the efficient allocation. The horizontal axis measures total effort over the season. The downward sloping curve $p\overline{H}/E$ is the industry's average revenue product of effort, taken as parametric by firms in the industry. The marginal cost of effort is $c(w, r)$ because the industry effectively chooses an efficient season length, $T=1$. The industry's instantaneous effort rate, $f(L,K)$, is coordinated to ensure that $E = \overline{E}$. Point 'a' indicates the scale of effort and level of unit cost that obtain in the efficient equilibrium. Area A is total cost and area A+B is total revenue, so equilibrium rent equals area B.

In the open access case firms again combine inputs in a cost minimizing way, but do not internalize the link from the scale of input use to season length. Taking T and factor prices as given, their input choices are reflected in the unit cost function for effort, $c(w, r/T)$. The scale of effort, and hence season length, is determined by a zero profit condition, facilitated by entry and exit:

$$\Pi = p\overline{H} - c\left(w, \frac{r}{T_F}\right)\overline{E} \equiv 0. \tag{12}$$

T_F, the equilibrium season length under open access, varies positively with w, negatively with $p\overline{H}/\overline{E}$ and is proportional to r.

Point 'c' in Fig. 1 illustrates the open access equilibrium. At point 'c' the unit cost of effort, $c(w, r/T_F)$, equals the average revenue product of effort, resulting in zero profit. The TAC constraint is satisfied because total effort equals $\overline{E}$. To better understand why this is an equilibrium, suppose the industry happened to start at point 'a', where profit is positive and $T=1$. The average revenue product of effort exceeds its unit cost at point 'a', so industry effort will expand. If T remained fixed effort would expand

[7] The optimality of full-season fishing requires that the marginal product of the variable input be less than the average product ($MP_L < AP_L$), and this follows from our homogeneous, constant returns production function. $MP_L < AP_L$ is possible for a wide range of production functions, and is always the case for some production functions. For example, if f is homogeneous in K and L, then $MP_L < AP_L$ for decreasing and constant returns and may be for increasing returns, although a shorter season may be optimal for increasing returns. The optimality of full-season fishing with a homogeneous, constant returns production function is easily illustrated. From Eq. (5) and by linear homogeneity $T\,f(K, L) = f(TK, TL) = \bar{E}$. Suppose $T=0.5$ indicating half-season fishing, then increasing to full-season fishing, and letting $T'=2T$, we get $(T'/2)\,f(K, L) = f(T'(K/2), T'(L/2)) = \bar{E}\bar{E}$. In other words, doubling the season means that both inputs can be reduced by half for lower cost, and because revenue does not change, higher profit. However, the industry will choose to reduce K disproportionately more than L, since increasing season length effectively makes labor relatively more expensive by Eq. (7).

to point 'b', which violates the regulatory constraint, i.e., catch would exceed the TAC. The regulator must respond by reducing T, which raises the rental price of capital, r/T, shifting the unit cost of effort up. This process would result in the equilibrium at point 'c', where season length is T_F. The rent captured in the efficient case, area B, is exactly dissipated under open access by excessive capital costs resulting from a shortened fishing season.

3.2. Regulated open access with capacity regulation

This is the case of primary interest, where the regulator limits the number of vessels (K) but not their intensity of use (L).[8] The degree to which regulated and unregulated inputs can be substituted for one another is a key factor in what follows. To parameterize such substitution possibilities we assume $f(\cdot)$ has the CES form

$$f = \left(\delta L^{\beta} + (1-\delta)K^{\beta}\right)^{\frac{1}{\beta}} \tag{13}$$

where $\beta \leq 1$, the elasticity of substitution is $\sigma = 1/(1-\beta)$ and a scale parameter, q, has been normalized to unity.

Each firm, being a small part of the fishery, regards both the regulator's season length, T, and the average revenue product of effort, $p\overline{H}/f$, as given. The industry expands f by expanding the variable input, L, until the marginal cost and average revenue product of effort are equal. The implications are that when the variable input can be chosen by the industry the fixed input will be used more intensively while the fishery is open, via a larger crew, more sophisticated equipment, fishing more intensively, etc. With a fixed input, the marginal cost of effort is increasing. This upward sloping marginal cost moderates the open access race to fish relative to what it would be if no inputs were fixed. However, the derby is not entirely eliminated. Firms wish to increase the variable input up to the point where the marginal cost of effort equals average revenue product of effort. Unless the fixed input constraint is so severe, or input substitution possibilities so limited, that it is infeasible for the industry to exceed the TAC by expanding the variable input, the only way the regulator can maintain the TAC is to close the season before firms are ready to stop fishing.

To derive the marginal cost function in the presence of a constraint on capital, start by letting $\overline{K}$ denote the limit on capital and invert (Eq. (13)) to express L as a function of $\overline{K}$ and f, $L = ((1/\delta)(f^{\beta} - (1-\delta)\bar{K}^{\beta}))^{1/\beta}$.[9] Substituting this expression for L into the cost equation, $C = wLT + r\overline{K}$, yields the 'K-constrained' cost function for effort

$$C^{\overline{K}} = wT\left(\tfrac{1}{\delta}\left(f^{\beta} - (1-\delta)\overline{K}^{\beta}\right)\right)^{1/\beta} + r\overline{K}. \tag{14}$$

$C^{\overline{K}}$ is homogeneous of degree 1 in w and r and increasing in f.

Equilibrium effort and season length with fixed capital must satisfy two conditions: (i) equality of the marginal cost and average revenue product of f, which reflects a profit maximizing choice of the variable input, L and (ii) the regulatory constraint on total effort, $fT = \overline{E}$. Equating the marginal cost of f, found by differentiating (Eq. (14)), to the average revenue product of f yields, after simplifying:

$$wT\left(\delta^{-1/(1-\beta)}\left(1-(1-\delta)\left(\frac{\overline{K}}{f}\right)^{\beta}\right)\right)^{(1-\beta)/\beta} = \frac{p\overline{H}}{f}. \tag{15}$$

Dividing both sides of (Eq. (15)) by the season length produces

$$\frac{p\overline{H}}{fT} = w\left(\delta^{-1/(1-\beta)}\left(1-(1-\delta)\left(\frac{\overline{K}}{f}\right)^{\beta}\right)\right)^{(1-\beta)/\beta}. \tag{16}$$

8 We assume vessels are unable to switch to other uses during the off season.

9 If $\beta < 0$ we require $\overline{K} > (1-\delta)^{-1/\beta} f$, so there is a positive L that suffices to produce f.

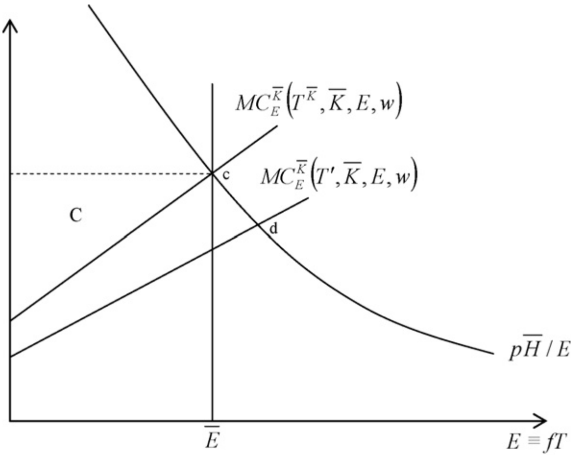

Fig. 2. Equilibrium in capacity limitation case.

Incorporating the regulatory constraint on total effort $fT = \overline{E}$, Eq. (16) becomes

$$\frac{p\overline{H}}{\overline{E}} = w\left(\delta^{-1/(1-\beta)}\left(1-(1-\delta)\left(\frac{\overline{K}T^{\overline{K}}}{\overline{E}}\right)^{\beta}\right)\right)^{(1-\beta)/\beta}. \tag{17}$$

where $f^{\overline{K}}$ and $T^{\overline{K}}$ denote the equilibrium effort rate and season length with a capital constraint. Eq. (17) implies that the product $\overline{K}T^{\overline{K}}$ is independent of the regulator's choice of $\overline{K}$. Because the lhs of Eq. (17) is fixed by the regulator's TAC constraint, any increase in $\overline{K}$ must be matched by a proportionate decrease in T; Weninger and McConnell (2000, p. 400) make the same point. Combining this observation with the TAC constraint, $f(L, K)T = \bar{E}$, implies that a doubling of K (with a consequent halving of T) will cause the equilibrium level of L to double as well. The equilibrium condition (Eq. (17)) also implies that, given $\overline{K}$, higher values of p/w imply shorter season lengths; this is sensible because a higher profit opportunity encourages using vessels more intensively, and the regulator must counteract this by shortening the season.

Fig. 2 illustrates this equilibrium. The season length and capital constraint jointly determine the position of the marginal cost curve. As with a short-run curve, marginal cost slopes up due to the capital constraint (Campbell and Lindner, 1990). For a given capital constraint, the season length is in equilibrium only if marginal cost equals average revenue product at effort level $\overline{E}$ that satisfies the TAC constraint. This occurs at point c. The second marginal cost curve, drawn for season length $T' > T^{\overline{K}}$, is included to illustrate how the equilibrium at point c might be established. With the longer season, the industry wishes to expand total effort to point d. This violates the TAC constraint, however, so the regulator shortens the season. Reducing T shifts marginal cost up, reducing effort and moving us toward equilibrium at c.

The area under $MC_E^{\overline{K}}$ in Fig. 2 is variable cost. The area under the dotted line is total revenue. The industry's rent therefore equals area C minus the fixed cost $r\overline{K}$, which is not shown. This rent represents a return to fishery capital in excess of opportunity costs, made possible by the regulatory limit $\overline{K}$. The size of the rent depends on p and w, on the specific limits on capital and allowable catch, and on the elasticity of substitution between controlled and uncontrolled inputs. The latter parameter determines the slope of the marginal cost curve: it is steeper (and rents greater) when substitution is difficult, and is flatter (and rents smaller) when substitution is easy.

The equilibrium level of rent, given the capital constraint, is found by substituting equilibrium values of f and T into total cost, Eq. (14), and subtracting the result from total revenue. This yields

$$\pi^{\overline{K}} = p\overline{H} - w\left(\tfrac{1}{\delta}\left(\left(f^{\overline{K}}T^{\overline{K}}\right)^{\beta} - (1-\delta)\left(\overline{K}T^{\overline{K}}\right)^{\beta}\right)\right)^{1/\beta} - r\overline{K}. \tag{18}$$

Surprisingly, the relationship between equilibrium rent and p need not be monotonic. An increase in p clearly increases total revenue given that catch is fixed by the TAC. A higher price induces firms to increase the variable input, L, however, which increases effort and causes the regulator to shorten the season. A shorter season raises total cost due to less efficient use of K and this cost increase may outweigh the increase in revenue. That is, a higher exvessel price may actually reduce the equilibrium rent to capital. Similarly, an increase in w may cause equilibrium rent to rise: effort decreases and the season is lengthened, and the cost reduction from a longer season may outweigh the cost increase caused by a higher wage.[10] These anomalous non-monotonic comparative static possibilities are illustrated with simulations in the next section.

What limit on capital is optimal in this context? The answer is obvious by inspection of Eq. (18). Recall that p, w and r are constant, and that the product $f^{\bar{K}}T^{\bar{K}}$ is independent of $\bar{K}$ due to the TAC constraint. As explained in discussing (Eq. (17)) the product $\bar{K}T^{\bar{K}}$ is also independent of the capital constraint. Accordingly, the revenue and variable cost components of (Eq. (18)), the first two quantities on the rhs of Eq. (18), are independent of the capital limit chosen by the regulator. The optimal capital regulation, therefore, makes $\bar{K}$ as small as possible in order to minimize $r\overline{K}$. Because $\overline{K}T$ is fixed in equilibrium, however, reductions in $\bar{K}$ are limited by the logical constraint $T \leq 1$. The lower bound for $\bar{K}$, and therefore its optimal value, is found by substituting $T = 1$ in (Eq. (17)) and solving for $\bar{K}$. The solution is

$$\overline{K}^* = \overline{E}\left(\tfrac{1}{1-\delta}\left(1-\delta\left(\frac{\delta p\overline{H}}{w\overline{E}}\right)^{\frac{\beta}{1-\beta}}\right)\right)^{1/\beta} \tag{19}$$

and allows year round fishing. Even with K fixed optimally, equilibrium rent with a capital limit cannot exceed the first-best rent because L is in general not optimally chosen. There is one case in which rent will be the same in the two situations, however. If the elasticity of substitution is zero the L/K ratio is fixed technologically. The input mix used in the first-best solution will therefore also be used in the second-best, K-constrained solution. If the regulator sets the capital constraint at the first-best optimum, the levels of both inputs will be optimally chosen and the first-best level of rent will be achieved. When no substitution is possible, the regulator can effectively control the entire outcome with a capital constraint.

In the next section we illustrate the relationship between equilibrium rent and price for different values of the elasticity of substitution. We also simulate the relationship between equilibrium season length and price for different values of the elasticity of substitution.

4. Simulations

Parameters: Simulations are based on the Eastern Bering Sea (EBS) and Aleutian Island (AI) walleye pollock (*Theragra chalcogramma*) fishery in Alaska. This is the largest fishery by volume in the U.S. (Hiatt et al., 2004) and provides a reasonable illustration of the model because it has been managed in a fashion similar to the cases considered in this paper. The fishery has been limited to domestic vessels since the early 1990s and heavily regulated under the Bering Sea/Aleutian Island (BSAI) Fishery Management Plan (FMP). Prior to 1999 the FMP regulated the fishery by allowing no foreign entry, requiring each participating vessel to have a permit (a partial entry restriction), limiting the allowed catch, restricting season length, and restricting gear used.

In 1999 the American Fisheries Act (AFA) extended these regulations to include a moratorium on entry and a buyout of some vessels, area restrictions and bycatch limits (Witherell, 2000). Importantly, the AFA allowed for the formation of cooperatives with TAC allocations for selected vessel classes to further temper the race for fish in these sectors (American Fisheries Act, 2008). The fact that cooperatives had dedicated TAC allocations meant they had incentives to impose individual catch limits for their members, potentially allowing them to reach efficient outcomes (Sullivan, 2000; Wilen and Richardson, 2008). This progression from a state approaching regulated open access to a

[10] Higher values of r clearly reduce rent, up to the point where rent is exhausted.

Table 1
Parameter values for simulations.

	Parameter values					
	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6
σ	0.177	0.479	0.782	1.085	1.388	1.691
δ	0.999	0.967	0.522	0.203	0.101	0.062
q	5.4×10^{-5}	13×10^{-5}	48×10^{-5}	91×10^{-5}	116×10^{-5}	131×10^{-5}
N_0	11,262,400[a]					
H	652,718[b]					
L	3515[c]					
K	59[d]					
T	0.431[e]					
p	$489[f]					
w	$55,587[g]					
r	$3,957,334[h]					

[a] Average annual biomass of age 3+ Eastern Bering Sea pollock, in tons 1994–1998.
[b] Average annual total catcher-processor landings, in tons 1994–1998.
[c] Average annual total catcher-processor crew members, 1994–1998.
[d] Average annual number of catcher-processor vessels, 1994–1998.
[e] Average annual catcher-processor pollock season as a proportion of a year (365 days, inshore and offshore).
[f] Average (exvessel) price per ton of pollock, 1994–1998, in 2001 dollars.
[g] Average annual wage per crew member, 1994–1998, in 2001 dollars.
[h] Average annual capital cost per vessel, 1994–1998, in 2001 dollars.

potentially efficient outcome allows an excellent context for illustrating the model's implications. However, being a recent phenomenon and given significant differences in reporting requirements, data on all necessary variables are available only for 1994–2004. Given this limitation, parameter estimation was considered infeasible and a calibration procedure was employed instead.

Parameter values for the pollock fishery, shown in Table 1, were used to simulate the model's comparative static properties. Raw data were provided by Terry Hiatt at the National Marine Fisheries Service (National Marine Fisheries Service, 1998, 2000a,b,c) and pertain to catcher-processor trawlers in the pollock fishery. Vessel level information was gathered from an observer program, weekly processing reports, federal vessel and state registration files, U.S. Coast Guard data, and the 2004 NMFS Stock Assessment and Fishery Evaluation Report.

A range of values for the elasticity of substitution σ_i ($i=1$–6) was considered, based on results from McDermott and Finnoff (2008) who estimated the Morishima Elasticity of Substitution (MES) between regulated and unregulated inputs for the same fishery.[11] Their estimated elasticity prior to the AFA of 0.177 is used as the lower bound for three relatively low elasticities (σ_1, σ_2, σ_3) and their post-AFA elasticity of 1.388 is used as the middle value of three high elasticities (σ_4, σ_5, σ_6).[12]

Given the elasticities, the share parameter δ and efficiency parameter q in the effort function (Eq. (13)) were calibrated using the first-order conditions from the cost minimization problem and the rent exhaustion condition under open access.[13] This required data on biomass, harvests, inputs, and input and output prices. All of these except input prices were directly available. To estimate input prices, a three-step procedure was employed. First, during the period of regulated open access rents are completely dissipated, so cost equals revenue (which is known). Second, because most crew

[11] The MES is identical to the Hicks elasticity of substitution for a CES production function (Blackorby and Russell, 1981).

[12] The increase in the elasticity estimate due the AFA is likely due to a combination of factors. Felthoven (2002) noted that following the AFA the number of days at sea by vessels increased to record levels for the fishery. At the same time crew size did not change significantly following the AFA. Vessels had a longer time to fish with relatively the same amount of crew post-AFA, while they had shorter seasons and similar employment rates pre-AFA. An implication is that when the race for fish subsided with the establishment of the AFA the increased season length made it technically easier to substitute days at sea for crew. This resonates with Felthoven (2002) also demonstrating an increase in technical efficiency following the AFA, with vessels post-AFA using closer to the minimum amount of inputs for a given level of harvest.

[13] The calibration procedure requires cost information which can only be inferred during the period of open access in the fishery. Recall that the efficiency parameter, q, was normalized to unity in Eq. (13) and, therefore, did not appear in subsequent expressions.

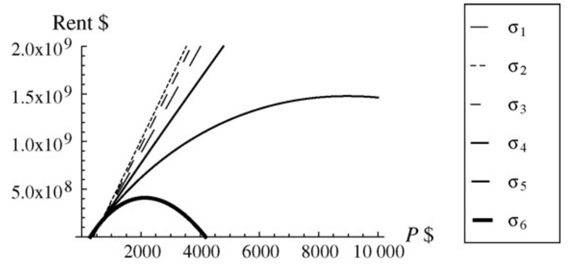

Fig. 3. Equilibrium rent as a function of price ($\bar{K} = 40$).

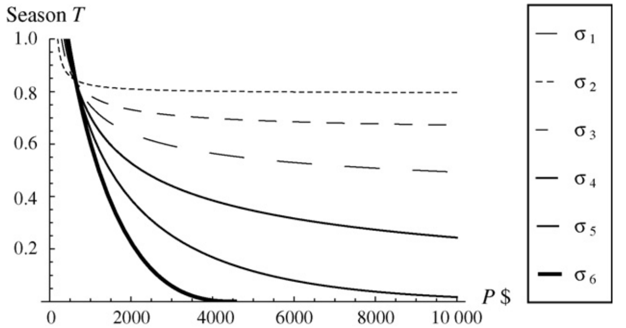

Fig. 4. Equilibrium season length as a function of price ($\bar{K} = 40$).

members are paid a share of the value of the catch, total labor cost can be determined from typical crew shares and from total revenue. Knapp (2006) estimates the crew share in this fishery to be 26%; from this figure, total capital cost can be determined as a residual. This determines the share parameters. Third, given these total labor and capital cost estimates, unit input prices can be determined directly using input levels.

Simulations: Our primary interest is to investigate the model's predictions on how season length and equilibrium rent respond to variations in input and output prices, in a context where capital is limited. The model indicates that the relationships between rent and prices may be non-monotonic and that all of these relationships should depend on the elasticity of substitution between constrained and unconstrained inputs. Our simulations are based on a capacity limitation of $\overline{K} = 40$, which equals the number of vessels allowed in the fishery post-AFA. We find that the results are highly sensitive to the magnitude of the elasticity of substitution.

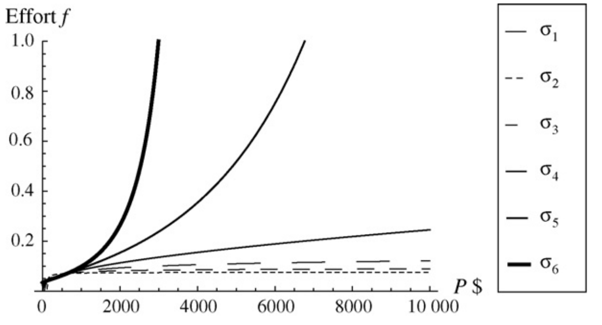

Fig. 5. Equilibrium effort as a function of price ($\bar{K} = 40$).

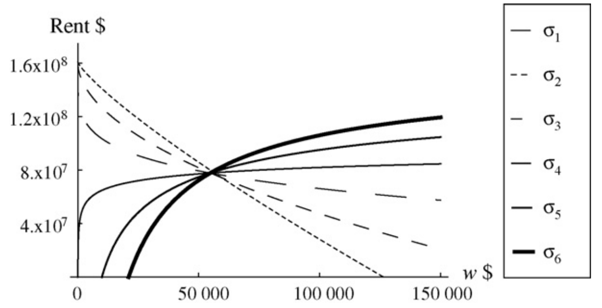

Fig. 6. Equilibrium rent as a function of wage ($\bar{K} = 40$).

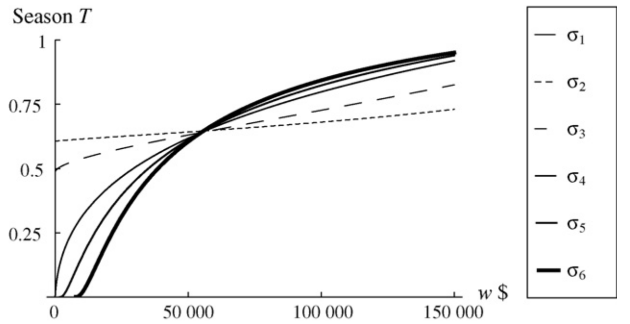

Fig. 7. Equilibrium season length as a function of wage ($\bar{K} = 40$).

Figs. 3–5 display the simulated results for equilibrium rent, season length and the effort rate (f) as functions of price (p), for a range of values for σ. The capital constraint imposed is $K=40$ in each set of results. Fig. 3 shows that when the elasticity of substitution is low (σ_1, σ_2, σ_3), rents increase at approximately constant rates as price increases, with the steeper increases for lower σ_{i} values. For higher elasticities (σ_4, σ_5, σ_6), however, the rent increase tapers off and rent can actually decrease as price rises for sufficiently high σ_i values. The reason for the non-monotonic response is as described earlier. When price increases revenues increase and the industry seeks to expand effort by increasing the variable input; this forces the regulator to close the season earlier, which increases cost. Whether rent is increased or decreased depends on magnitudes of the revenue and cost effects. If the elasticity of substitution is low, the effort expansion is small and the reduction in T required to meet the TAC constraint is also small. With limited substitution possibilities, the increase in variable cost is small, so the net effect of the price increase is a larger rent. When the elasticity of substitution is high, a price increase brings forth a large increase in effort and a large increase in expenditure on the variable input. If these increases are sufficiently large, the net result can be a decrease in rent.

Fig. 4 illustrates how the season length varies with price. When the elasticity of substitution is low, T is not very responsive to increases in p because the industry is limited in how much it can expand effort in response to a price increase. (This effect is shown by the relatively flat effort lines for low σ_i values.) If the elasticity of substitution is high, the responsiveness of T becomes more dramatic.

Fig. 5 confirms earlier statements about the responsiveness of the equilibrium effort rate, f, to changes in price, a phenomenon we described as the "derby effect". When the elasticity of substitution is low there is little room to expand effort and the derby effect is small; as Figs. 3 and 4 show, the regulator needs only to decrease the season slightly and cost increases are kept low, allowing rents to continually rise with price. However, if the elasticity of substitution is high, the industry is able to expand effort substantially by increasing the variable input. The derby effect is large in this case and the increased effort forces the regulator to reduce the season length dramatically to meet the TAC.

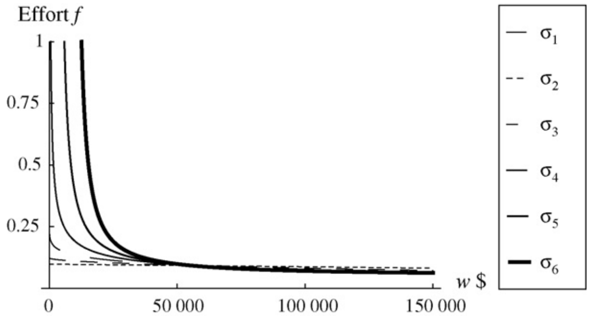

Fig. 8. Equilibrium effort as a function of wage ($\bar{K} = 40$).

The influence of the wage rate on the capacity limitation equilibrium also provides interesting results. Figs. 6–8 show that for low elasticities of substitution, rents fall with increases in the wage rate as expected. As the wage increases there is little flexibility in the industry to adjust to the input price increase so that effort and season length remain fairly constant. As revenues are invariant, rents fall with rising costs. However, with high elasticities and a high degree of flexibility, as the wage rate increases firms release labor, which causes total effort to decline. To reach the TAC, the regulator increases the season length, and rents increase as the effective price of capital is lowered.

5. Discussion

These results demonstrate that the derby effect can have counterintuitive effects on behavior and on equilibrium outcomes that, to our knowledge, are not in the received literature. The derby effect pushes the industry toward too much effort when exvessel price increases; but if an input is constrained by regulation and the elasticity of substitution between inputs is low, this response is limited. If the elasticity of substitution is high, the derby effect can be prominent with well known consequences for effort. What is novel in our findings, however, is that this can cause rents to fall when exvessel price increases.

The fall in rents can be exacerbated if payments to labor include a compensating differential that was not modeled here. Finnoff and Tschirhart (2008) develop a computable general equilibrium (CGE) model of the Alaskan economy that incorporates a fishing sector. The CGE framework requires tracking how fishing labor is engaged in the off season. The authors account for a compensating differential, empirically supported, that must be paid to labor for the transactions cost of working short seasons, which are often a hallmark of fishing employment. With high elasticities of substitution, the rise in exvessel prices and the associated drop in season length (Fig. 4) would increase the compensating differential and this would reinforce the fall in rents.

Our results in Fig. 3 are consistent with Dupont (1991) who found that owners of seine and troll vessels that were subject to tonnage restrictions dissipated rents. The author recommended that input restriction regulations are better suited for fisheries in which substitution possibilities are limited. An interesting extension would be to examine whether input restrictions tend to be more prevalent when technologies allow only limited substitution. Since regulation of inputs can give rise to rents, they are likely to give rise also to rent-seeking behavior by input owners (Anderson, 1989). For capital restrictions as modeled here, ease of substitution implies excessive effort which is consistent with excessive labor inputs. Although rents are dissipated, some stakeholders may see this as a positive outcome because it delivers higher employment in fishing communities (Hilborn, 2007). Alternatively, limited substitution yields potential rents, although these too may be dissipated if high employment is a primary goal, and rent-seeking stakeholders are successful in moving production from the efficient, short-run input ratios modeled here.

The simulation results are also of interest for the EBS/AI pollock fishery that was the vehicle for our simulations. For a range of substitution elasticities, the optimal capacity regulation (number of vessels as given by Eq. (19)) is approximately 25 and the equilibrium season length resulting from that limit is roughly 0.64, expressed as a fraction of a 365-day year. In the post-AFA period, the fishery has been restricted to 40 vessels, which is obviously greater. This raises several interesting policy questions. Our model does not account for the fact that adverse weather conditions make it infeasible to operate in this fishery over the entire year, and there are two, separate, part-year seasons, so the relevant upper bound on season length is presumably less than 1, and possibly substantially less. This would necessitate operating with a larger fleet (larger than 25), which may account for the apparent discrepancy in number of vessels operating. A natural extension, therefore, would be to determine what the relevant upper bound for season length is for this fishery, and then determine the optimal capacity limit based on this.

Another extension would be to compare the model's predictions to the detailed behavior of the cooperatives that have operated in this fishery in the post-AFA period. If these organizations are able to optimally coordinate input use in their members' fleet, then their mix of fixed and variable inputs should approximately equal the optimal value indicated by the model. Alternatively, if they are not able to coordinate effectively, the input mix should be closer to the capital-constrained equilibrium. If the latter outcome is observed, it should be possible to estimate the potential rent increase that could be realized by moving from the uncoordinated outcome to efficient management.

Acknowledgements

This work, like much of our work, is shaped by the notions and diligence of our creative colleagues in resource economics so well personified by Tom Crocker. We also thank our discussant, Chuck Mason, and other participants at the University of Wyoming's Crockerfest for helpful comments, and Jay Shogren for organizing the Crockerfest, and who, as Tom's former graduate student, has carried on Tom's economic prowess and fondness for Hank Williams.

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