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Instrument choice in a fishery

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Abstract

This paper considers the choice of regulatory instruments in a fishery. Fishing captains, consumers, and input suppliers each attempt to influence the regulator's choice of instruments. The regulator chooses among instruments such as input restrictions, entry restrictions, or individual transferable quotas (ITQs). Regulatory instruments that result in zero fishery rents can only occur if the regulator places an extraordinary weight on the welfare of input suppliers relative to fishing captains and consumers. Indeed, heterogeneity of fishing captains is neither necessary nor sufficient to obtain regulations that fail to generate fishery rents.

Keywords: Regulation; Common property; Fishery; Common agency

1. Introduction

In fishery management, an optimal instrument, individual transferable quotas (ITQs), exists (e.g., [1,8]). In spite of this suboptimal instruments are still chosen in many fisheries. Iceland and New Zealand implemented ITQs for all commercial fisheries in the 1980s, but others have been hesitant to follow (e.g., [1,2,9]). Indeed, in the United States, there exists a moratorium on introductions of ITQs. The question is why do suboptimal controls persist in fisheries?

The literature has provided two arguments. One is that ITQs may not enhance welfare by as much as their advocates claim (e.g., [5,6,10,21]). However, these arguments are about the *size* of the net gains to society from adopting ITQs, not about whether net social gains exist. An alternative hypothesis—the one on which this paper focuses—relates to the distribution of rents under alternative regulatory regimes. Weitzman [22] and Samuelson [20] were the first to recognize that it is possible for some to be hurt by moving from open access to private ownership. Their

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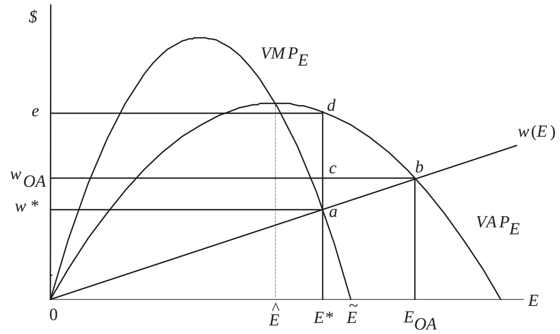

Fig. 1. Weitzman–Samuelson loss to input suppliers.

argument can be seen in Fig. 1. Suppose ''effort'' in the standard Gordon [12] model is less than perfectly elastically supplied. Under open access, effort enters until at E_{OA} the value of the average product of effort equals the opportunity cost of effort w_{OA}. In contrast, under private ownership, the owner of the resource hires effort until the value of the marginal product of effort equals the opportunity cost of effort w^*. Thus, the surplus to effort diminishes under private ownership of the resource by the area $w_{\mathrm{OA}}cbaw^*$. This led Samuelson to conclude that ''the rent collector [is not] worthy of his full hire'' [20, p. 7], since effort suppliers lose more than the portion of their surplus $w_{\mathrm{OA}}caw^*$ transferred to the rent collector (i.e., they also lose area *cab*).

One difficulty a modern economist has with the Weitzman–Samuelson model is that ''effort,'' which they treat as the single variable input, is in fact an aggregate of many inputs. Thus, the question is which owners of inputs are being hurt in the transition? One answer, suggested by Johnson and Libecap [15] and Karpoff [16,17], is that heterogeneous fishing captains possess non-transferable skill rents, which can be adversely affected by a change in regulatory regimes. However, there is current pressure to grant ''community development quotas'' to communities with a historical record of providing support to fishing grounds (e.g., [11]). This suggests that input suppliers also influence instrument choice in fisheries.[1]

In this paper, I argue that surplus to input suppliers is more important than heterogeneity of fishing captains in determining whether or not suboptimal controls are chosen. Effort in this model is decomposed into three parts: the number of vessels, the inputs used by each vessel, and the period each vessel is active. The supply of both the number of fishing captains and the inputs configuring each vessel is less than perfectly elastically supplied. Thus, under open access, both fishing captains and input suppliers earn positive rents even though the fishery resource itself earns zero rents. It is assumed that the welfare of fishing captains, input suppliers and consumers are each given a non-negative weight in the regulator's calculations (e.g., [13]). This is in contrast to models (e.g., [15–17]) that assume only fishermen are involved in the regulatory process. Thus, I evaluate the effects of regulatory instrument choices on each interest group, and use the policy choices to impute the weights the regulator places on the welfare of each interest group.

Suboptimal controls take many forms. I focus on season closures, input restrictions, and limited entry restrictions. Season closures and input restrictions alone or in combination do not solve the

[1] This argument has been extended to fish processors [18].

free entry problem, so fishery rents still vanish. Season closures and input restrictions also have other unintended consequences, such as openings that occur during storms and seaworthiness of vessels being compromised.[2] There is also considerable evidence that restricting one margin causes substitution into other inputs (e.g., [14,21,23]). However, different suboptimal instruments have varying effects on social welfare. While both input and entry restrictions tend to increase the season length, entry restrictions create some social rents, while input restrictions do not. Regulations that combine ITQs and either entry or input restrictions are suboptimal, but the ITQ portion of the regulation mitigates against the worst features of the other two by allowing fishing captains to fish over the entire possible season.

Different suboptimal controls also have varying effects on the different interest groups. Input restrictions and season closures, which result in free entry and cause fishery rents to vanish, benefit input suppliers, since a short furious fishing season requires lots of inputs. In contrast, ITQs and limited entry tend to use less aggregate inputs, substituting into the time margin and away from the input and entry margins. The main result of the paper is that regulations in which fishery rents vanish can only come about by a strong regulatory preference for input suppliers. However, in both free entry and ITQ fisheries, input restrictions are supported by fishing captains. In the free entry case, this requires heterogeneity of fishing captains, but in the ITQ case, it only requires that the input supply function be upwards sloping.

The remainder of the paper is organized as follows. Section 2 shows how the upper bound on the season length and the lower bound on the marginal entrant's profits constrain the welfare maximizing choice of the number and size of vessels made by a regulator and illustrates the maladies associated with open access. Section 3 examines how the welfare of fishing captains, input suppliers, consumers, and the regulator are affected by changes in the number of entrants and the inputs used by each entrant. Section 4 derives the effects of different regulatory instruments on the welfare of fishing captains and input suppliers. Section 5 concludes the paper with a discussion of the results.

2. The model

2.1. Assumptions

Consider a fishery operating during a particular season subject to an exogenously given aggregate season harvest quota Q.[3] For an aggregate harvest constraint Q and a constant aggregate harvest rate $H>0$, the season length $T>0$ must satisfy:

$$Q = TH. \tag{1}$$

[2] Two examples suffice. Prior to the introduction of ITQs, the Pacific halibut fishery openings, which could be less than 24 h in length, would occur at pre-determined dates, sometimes during fierce storms. The salmon fisheries in Alaska restrict vessel lengths in the drift net fisheries to be less than 32 f in length. Some captains meet this restriction by simply cutting off the forward portion of the bow, and filling in the opening with a fiberglass wall. This reduces the seaworthiness of the vessel, and serves no biological purpose.

[3] See [14] or [7] for models in which the harvest quota decision is endogenous.

Let $\bar{T}$ be the maximum season length:[4]

$$T \leqslant \bar{T}. \tag{2}$$

Constraint (1) is binding, since if it were not it is unlikely that the remaining regulations would be adopted. However, constraint (2) may or may not be binding.

Let N heterogeneous fishing captains participate in the fishery. Each fishing captain's harvest per unit time, h, depends upon a single non-time variable input k_n chosen by the nth captain. Aggregate input demand is denoted as $K \equiv \sum_{n=1}^{N} k_n$, and the aggregate harvest rate is $H \equiv \sum_{n=1}^{N} h(k_n)$. The production technology is neoclassical, with a region of increasing marginal product of k followed by a region of decreasing marginal product of k.[5]

Assumption A.1. (i) *$h' \gtrless h/k$ for $k \lessgtr \hat{k}$* (ii) *$h' \gtrless 0$ for $k \lessgtr \tilde{k}$; and* (iii) *$h'' \gtrless 0$ for $k \gtrless k$; where $0 < \underline{k} < \hat{k} < \tilde{k}$.*

It is also assumed that input suppliers, fishing captains, and consumers earn non-negative surplus:

Assumption A.2. (i) *The supply curve for inputs, $r(K)$, is upwards sloping* ($r'(K) > 0$), (ii) *the supply curve for fishing captains, $w(N)$, is upwards sloping* ($w'(N) > 0$), *and* (iii) *the instantaneous demand curve for fish, $p(H)$, is downward sloping* ($p'(H) < 0$).

In addition, it is assumed that if fishing captains or variable inputs are used in fishing, they cannot be redeployed for a portion of the season in some other productive activity:[6]

Assumption A.3. *Fishing captains and variable inputs cannot be redeployed into alternative uses in the event that the season lasts less than $\bar{T}$ periods.*

Finally, competitive behavior is assumed:

Assumption A.4. *Fishing captains, input suppliers, and consumers take prices and the season length as given.*

[4] This constraint can arise because of biological conditions—it is most economical to harvest species such as salmon or herring when they are spawning—or because of bureaucratic reasons: the regulator may simply wish to allow a fixed harvest over a certain period, after which he reevaluates the stock and makes a subsequent harvest decision.

[5] The $\hat{k}$ and $\tilde{k}$ correspond to $\hat{E}$ and $\tilde{E}$ in Fig. 1: i.e., $VMP_k(\hat{k}) = ph'(\hat{k}) = ph(\hat{k})/\hat{k} = VAP_k(\hat{k})$, and $VMP_k(\tilde{k}) = ph(\tilde{k}) = 0$.

[6] For the social optimum to have an interior solution in fishing captains, some cost cannot vary with the length of the season. Assumption A.3 can be relaxed by letting either rk or w depend upon the season length without changing the result that input suppliers benefit from "significant" input restrictions (Proposition 4.1). If inputs are malleable so that, $\pi = T(ph - rk) - w$, then $dK/dk < 0$ is satisfied under the identical conditions stated in Proposition 4.1, for a sufficiently inelastic input supply function (since input suppliers' welfare is then $W_{\rm I} = T[rK - \int_0^K r(s)\,ds]$). In contrast, if the fishing captains' can easily switch into alternative employment, so that $\pi = T(ph - w) - rk$, then $dK/dk < 0$ requires the same conditions stated in Proposition 4.1, viz., the restriction be "significant" and w and w' be small.

However, the price in each market depends upon the industry quantities, as does the season length.

Given A.1–A.3, the net season profits an active fishing captain operating a single vessel earns are

$$\pi^n = Tp(H)h(k_n) - r(K)k_n - w(n) \geqslant 0, \quad n = 1, 2, \ldots, N. \tag{3}$$

The heterogeneity of fishing captains means infra-marginal fishing captains earn non-transferable rents in equilibrium, but each fishing captain chooses identical inputs and produces the same output in equilibrium. Thus, the aggregate harvest rate is $H \equiv Nh(k)$, and the aggregate input demand is $K \equiv Nk$.

2.2. The social optimum

Social welfare is maximized by choosing T, N, and $\{k_i\}$ to maximize the welfare of consumers, fishing captains, and input suppliers, whose surplus is given weights α_C, α_F, and α_I, respectively:

$$\begin{aligned} V(\{k_i\}, N, T) &= \alpha_C T\left(\int_0^H p(s)\,ds - p(H)H\right) + \alpha_F\left(Tp(H)H - r(K)K - \int_0^N w(s)\,ds\right) \\ &\quad + \alpha_I\left(r(K)K - \int_0^K r(s)\,ds\right) \\ &= T\int_0^H p(s)\,ds - \int_0^N w(s)\,ds - \int_0^K r(s)\,ds \quad \text{when } \alpha_C = \alpha_F = \alpha_I, \end{aligned}$$

subject to constraints (1) and (2). When $\alpha_C = \alpha_F = \alpha_I$, the transfers are welfare neutral. Thus, social welfare is the gross value of the harvest quota less the opportunity costs of the inputs K and N.

Let λ denote the social planner's marginal valuation of the stock associated with the constraint (1). The following Proposition characterizes the social optimum when $\alpha_C = \alpha_F = \alpha_I$.

Proposition 2.1. *The social optimum* $\{T^*, N^*, k^*, \lambda^*\}$ *satisfies* (1) *and*:[7]

$$T^* = \bar{T}, \quad \bar{T}[pH^*) - \lambda^*]h'(k^*) = r(K^*), \quad \text{and} \quad \bar{T}[p(H^*) - \lambda^*]h(k^*) = r(K^*)k^* + w(N^*). \tag{4}$$

Thus, the social optimum fully utilizes the available season, implying the aggregate harvest rate is $H^* = Q/\bar{T}$, and hires variable inputs and fishing captains to the point where the social value of the marginal product of each equals its marginal cost. The aggregate input demand is $K^* = N^*k^*$. Additionally, (4) may be combined to show that at k^*, $h/k^* > h'$, or $\hat{k} < k^* < \tilde{k}$:

$$\bar{T}[p(H^*) - \lambda^*][h(k^*) - h'(k^*)k^*] = w(N^*) > 0.$$

2.3. Regulated open access

In a harvest constrained regulated open access fishery, fishing captains choose k, entry determines N, and constraint (1) determines T. Thus, the regulated open access equilibrium

[7] Proofs of all propositions appear in Appendix A.

$\{T_O, N_O, k_O\}$ includes:[8]

$$T_O N_O h(k_O) = Q, \quad T_O p(H_O) h'(k_O) = r(K_O), \quad \text{and} \quad T_O p(H_O) h(k_O) = r(K_O) k_O + w(N_O). \quad (5)$$

Fishing captains implicitly treat the shadow value of the harvest quota λ as equal to zero in regulated open access, while λ^* is positive under the social optimum. Following Clark [8], we can compare (4) and (5) by differentiating (1) and the second and third expressions in (4) with respect to λ, yielding:

Proposition 2.2. *Relative to the social optimum, the regulated open access equilibrium has more vessels* ($N_O > N^*$), *less capital per vessel* ($k_O < k^*$), *a larger aggregate capital* ($K_O > K^*$), *a larger aggregate harvest rate* ($H_O > H^*$), *and a shorter season* ($T_O < T^*$).

Under open access each fisherman ignores the costs he imposes upon his fellow fishing captains, and the result is *over-capitalization* ($N_O > N^*$ and $K_O > K^*$) and a *race for fish* ($H_O > H^*$ implies that $T_O < T^*$). In addition, relative to the social optimum, fishing captains earn higher infra-marginal rents (i.e., $N_O > N^*$ implies $w(N_O) \geqslant w(N^*)$), the input price is higher ($K_O > K^*$ implies $r(K_O)\ r(K^*)$), and the price of fish harvested is lower ($H_O > H^*$ implies $p(H_O) < p(H^*)$. Finally, combining the second two equations of (5) yields $T_O p(H_O)[h(k_O) - h'(K_O)k_O] = w(N_O)$. Thus, $h(k_O)/k_O > h'(k_O)$, so that $\hat{k} < k_O < k^* < \bar{k}$.

2.4. The feasible region

The equilibrium number of fishing captains and variable inputs are bounded by constraints (2) and (3). Using (1) to eliminate T, (2) and (3) may be rewritten entirely in terms of N and k as follows:

$$T = \frac{Q}{Nh(k)} \leqslant \bar{T}, \quad (6)$$

$$\pi^N = \frac{Qp[Nh(k)]}{N} - r(Nk) - w(N) \geqslant 0. \quad (7)$$

In Fig. 2, the inequality (6) is satisfied for all points above the $T \leqslant \bar{T}$ constraint, and inequality (7) is satisfied for all points below the $\pi^N \geqslant 0$ constraint. The slope of the constraint (6) is $\frac{dN}{dk}\big|_{T=\bar{T}} = \frac{-Nh'}{h}$, which is decreasing for $k < \tilde{k}$ and increasing for $k > \tilde{k}$. The zero profit condition (7) for the Nth fisherman—taking into account that the identity of the marginal fisherman is changing as N changes—has slope

$$\left.\frac{dN}{dk}\right|_{\pi^N=0} = -\left(\frac{Qp'h' - r - r'Nk}{\frac{Q}{N^2}(p'Nh - P) - r'k^2 - w'}\right).$$

[8] The notation X_R is used to indicate the equilibrium value of variable X under a particular regulation set of regulations, $\boldsymbol{R}$, for $X = k$, N, H, K, and T. The subscript 'O' indicates open access, 'k' indicates input restrictions, 'N' indicates entry restrictions, and 'Q' indicates ITQs. An entry-restricted ITQ season length is denoted as T_{NQ}, etc.

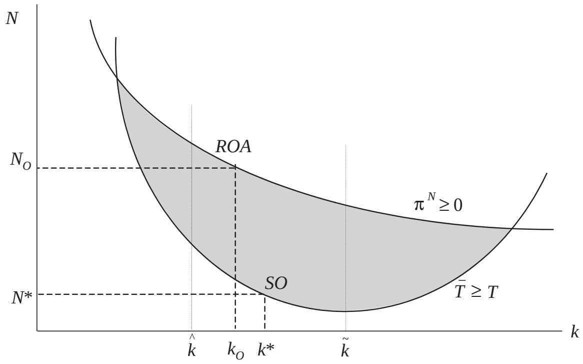

Fig. 2. Feasible region for fishers regulation.

The denominator of the expression in brackets on the right-hand side of this expression is everywhere negative, and the expression in brackets is negative whenever $k < \tilde{k}$. Thus, for $k < \tilde{k}$, the slope of (7) is negative. Together constraints (6) and (7) form the boundaries of a (non-convex) feasible region. The open access equilibrium and social optimum occur on the opposite boundaries of this region.

3. Welfare effects of changes in the industry equilibrium

In addition to season length controls, a fishery regulator may impose input restrictions ($k \leqslant \bar{k}$), entry restrictions ($N \leqslant \bar{N}$), or individual transferable quotas. Denote the regulatory instrument as $\boldsymbol{R} \equiv \{\bar{k}, \bar{N}, \text{ITQ}\} \in^+ \times^+ \times \{0,1\}$. For example, a policy that includes input restrictions and ITQs, but no entry restrictions is denoted as $\boldsymbol{R} = \{\bar{k}, \cdot, \text{ITQ}\}$. A '$\cdot$' indicates that an instrument is not used. Thus, regulated open access is denoted as $\boldsymbol{R} = \{\cdot, \cdot, \cdot\}$.

3.1. Welfare effects of changes in regulations

Given $\boldsymbol{R}$, the gross welfare of fishing captains is simply the aggregate surplus to fishermen:

$$W_{\mathrm{F}}(\boldsymbol{R}) = Qp(H_R) - r(K_R)K_R - \int_0^{N_R} w(s)\, ds. \tag{8}$$

The effect of an arbitrary regulation change, $\Delta\boldsymbol{R} = \{\Delta\bar{k}, \Delta\bar{N}, \Delta\text{ITQ}\}$, on fishing captains' welfare is

$$\begin{aligned} \nabla W_{\mathrm{F}} \Delta\boldsymbol{R} &= Qp'(H_R)\nabla H_R \cdot \Delta\boldsymbol{R} - [r(K_R) + r'(K_R)K_R]\nabla K_R \cdot \Delta\boldsymbol{R} - w(N_R)\nabla N_R \cdot \Delta\boldsymbol{R}. \\ &= [Qp'h - k_R(r + K_R r') - w]\nabla N_R \cdot \Delta\boldsymbol{R} + [Qp'N_R h' - N_R(r + K_R r')]\nabla k_R \cdot \Delta\boldsymbol{R}. \end{aligned} \tag{9}$$

where $\nabla f \equiv \{\partial f/\partial\bar{k}, \partial f/\partial\bar{N}, \Delta f/\Delta\text{ITQ}\}$, and $\Delta\boldsymbol{R} = \{\Delta\bar{k}, \Delta\bar{N}, \Delta\text{ITQ}\}$ is the direction of the regulation change, given regulation $\boldsymbol{R}$. The first line of (9) shows that fishing captains benefit from changes in regulations that reduce H (because price rises), that reduce K (because input costs drop), or that reduce N (because opportunity costs decline). However, as a given regulation change affects each of the variables, it is necessary to keep track of the *total* effect, which is what

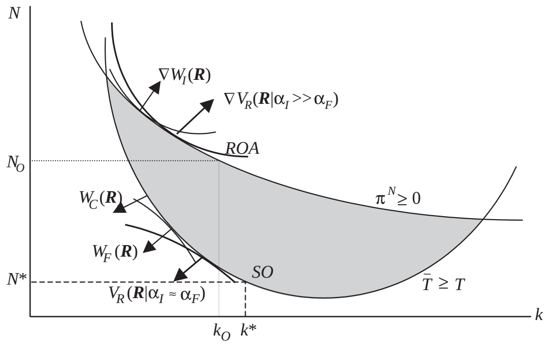

Fig. 3. Preferences of fishing captains, consumers, input suppliers, and the regulator.

the second line shows. Signing each term in square brackets reveals that fishing captains' surplus increases with regulations that reduce N and k.[9]

From (9), it is possible to determine the shape of the fishing captains' iso-welfare curves in N and k space. Totally differentiating $W_F(R)$ with respect to N and k yields:

$$\left.\frac{dN}{dk}\right|_{dW_F=0} = -\left(\frac{Qp'Nh' - N(r - r'K)}{Qp'h - k(r - r'K) - w}\right).$$

The denominator of the expression in brackets is negative for all k, as an increase in N decreases welfare of fishing captains. The numerator is negative for $h' > 0$, implying that fishing captains also benefit from reductions in k. An iso-welfare curve for fishing captains is shown in Fig. 3. The direction of increasing welfare is $\nabla W_F(\boldsymbol{R})$. Thus, to maximize fishing captains' welfare, the $T = \bar{T}$ constraint must be binding.[10] However, so long as fishing captains face an upwards sloping supply curve for inputs, their preferences diverge from the social optimum.

Proposition 3.1. *Fishing captains' prefer regulations on the $T = \bar{T}$ constraint, characterized with less k and more N than is socially optimal if the supply curve for variable inputs k is less than perfectly elastic.*

Thus, maximization of fishing captains' welfare is not synonymous with the maximization of social welfare because fishing captains value the cost of inputs at rK, society values it at $\int_0^K r(s)\,ds$.

The gross welfare of input suppliers is the surplus they earn from supplying K_R inputs:

$$W_I(\boldsymbol{R}) = r(K_R)K_R - \int_0^{KR} r(s)\,ds. \tag{10}$$

[9] Fishing captains support regulations that decrease their number only if those who exit get to *share* the wealth with those who remain. In practice, both limited entry and ITQ programs have this characteristic, since fishing captains who exit can sell their entry permit or quota, and the quotas and entry permits are allocated gratis [21]. Indeed, any ITQ or limited entry program that attempted to sell the permits or quotas to fishermen would be opposed, since their welfare would be limited to infra-marginal rents which would be decreased by either ITQs or limited entry.

[10] So long as fishing captains face either a downward sloping demand for harvested fish or an upwards sloping supply curve for variable inputs, their preferences diverge from the social optimum.

The effect of a regulation change on the welfare of input suppliers is

$$\nabla W_{\mathrm{I}}\Delta \boldsymbol{R} = r'(K_R)K_R(N_R\nabla k_R + k_R\nabla N_R)\cdot \Delta \boldsymbol{R}. \tag{11}$$

Input suppliers benefit from regulations that increase K_R (i.e., increase either or both of N_R and k_R) and are unaffected otherwise. Thus, input suppliers' interests are in conflict with those of fishing captains. From (11), the slope of the input suppliers' iso-welfare curves is

$$\left.\frac{dN}{dk}\right|_{dW_{\mathrm{I}}=0} = -\left(\frac{N}{k}\right) < 0.$$

Since the partial derivative of $W_{\mathrm{I}}(\boldsymbol{R})$ with respect to either N or k is positive, the directional gradient of increasing welfare $\nabla W_{\mathrm{I}}(\boldsymbol{R})$ is increasing in N and k in Fig. 3. Thus, input suppliers, unlike harvesters, prefer an equilibrium with free entry rather than an equilibrium that maximizes the season length.

Proposition 3.2. *Input suppliers prefer regulations on the* $\pi^N \geqslant 0$ *constraint that* (i) *increase* k *and decrease* N, *or*, (ii) *if* $w + w'N$ *is small*, *regulations that decrease* k *so much such that* $h/k < h'$.

It is the latter of these choices that input suppliers prefer, since the only regulations that increase k are those that restrict entry, and, adversely to input suppliers, these cause the $\pi^N \geqslant 0$ constraint to not bind.

The gross welfare to consumers is the consumer's surplus they earn over the course of the season:

$$W_{\mathrm{C}}(\boldsymbol{R}) = T\left(\int_0^H p(s)\,ds - p(H)H\right). \tag{12}$$

Using (1) to express T as $T = Q/H$, the effect of a regulation change on consumers is

$$\nabla W_{\mathrm{C}}\cdot \Delta \boldsymbol{R} = -\left(\frac{T}{H}\right)\left(\int_0^{H_R} p(s)\,ds - p(H_R)H_R - \frac{p(H_R)H_R}{|\eta|}\right)\nabla H_R \cdot \Delta \boldsymbol{R}, \tag{13}$$

where η is the own-price demand elasticity. When the demand is perfectly elastic, the last term in brackets vanishes, implying that the consumers are worse off by increased harvest rates. As fish products are price elastic, it is assumed that consumers prefer regulations that *decrease* the harvest rate over the relevant range.[11] From (13), the slope of the consumer's iso-welfare curves is

$$\left.\frac{dN}{dk}\right|_{dW_{\mathrm{C}}=0} = -\left(\frac{Nh'}{h}\right) < 0 \quad \text{for } k < \tilde{k}.$$

Thus, the shape of consumer's indifference curves and directional gradient is identical to the shape and directional gradient of the season length constraint. This implies the following:

Proposition 3.3. *Consumers prefer regulatory regimes such that* $T = \bar{T}$, *and are indifferent to any regulatory regime along the* $T = \bar{T}$ *constraint.*

[11] To cite one example, Barten and Bettendorf find estimates of price flexibilities (inverse own-price elasticities) ranging from –0.09 to −0.37 for Belgian white fish (sole, cod, etc.) over the period 1974–1987, indicating own-price demand elasticities on the order of –2.5 to −11.

3.2. The regulator's preferences and policy choice

Suppose the net welfare of the regulator is the weighted sum of the welfare of the interest groups:

$$V_R(\boldsymbol{R}) = \alpha_F W_F(\boldsymbol{R}) + \alpha_I W_I(\boldsymbol{R}) + \alpha_C W_C(\boldsymbol{R}). \tag{14}$$

The parameter $\alpha_g \geqslant 0$, $g = \mathrm{F, I, C}$, measures the marginal utility to the regulator of a dollar of surplus to each group g. As α_g increases, the regulator's marginal valuation of a dollar of surplus to group g increases.

A utility function such as (14) can be obtained as the equilibrium to a common agency game in which the fishing captains, input suppliers and consumers each attempt to influence the regulator [3,7,13,19].[12,13] This is in contrast to Karpoff [16,17], Johnson and Libecap [15], and others, who assume that form of regulations are determined entirely by the preferences of fishermen.

In choosing $\boldsymbol{R}$, the regulator faces behavior constraints by the fishing captains and input suppliers, and the regulator faces the boundary constraints (6) and (7). Recalling Fig. 2, if $\alpha_F = \alpha_I = \alpha_C$, then the social optimum occurs at the point SO, implying that the gradient of the regulator's objective function is decreasing in both N and k. Conversely, if regulator chooses the regulated open access equilibrium ROA, the gradient of the regulator's objective function is increasing in both N and k. Implicitly differentiating $V_R(\boldsymbol{R})$ with respect to N and k yields the slope of the regulator's indifference curves:

$$\left.\frac{dN}{dk}\right|_{dV_R=0} = \left(\frac{\alpha_F(Qp'Nh' - rN) - \alpha_C(Q/H^2)[\int_0^H dP - pH - pH/\eta]Nh' + (\alpha_I - \alpha_F)r'N^2k}{\alpha_F(Qp'h - rk - w) - \alpha_C(Q/H^2)[\int_0^H dP - pH - pH/\eta]h + (\alpha_I - \alpha_F)r'Nk^2}\right). \tag{15}$$

[12] In a common agency model, each interest group g attempts to influence the regulator's actions by offering a contingency payment $B_g(\boldsymbol{R})$ based on the regulations $\boldsymbol{R}$. Following [7,19], let the *net* welfare of each interest group be its gross welfare less its cost of influencing the outcome:

$$V_g(\boldsymbol{R}) = W_g(\boldsymbol{R}) - B_g(\boldsymbol{R})/\beta_g, \quad g = \mathrm{F, I, C}.$$

The parameter $\beta_g \in (0,1]$ measures the transactions costs to group g of raising $B_g(\boldsymbol{R})$. As $\beta_g \to 0$, the costs of raising $B_g(\boldsymbol{R})$ become prohibitively large. Thus as β_g increases, the group's ability to lobby the regulator increases. Similarly, let $\gamma_g > 0$ denote the regulator's valuation of a dollar of surplus to group g. Then the regulator maximizes:

$$\hat{V}_R(\boldsymbol{R}) = (\boldsymbol{R})\Sigma_g \gamma_g W_g(\boldsymbol{R}) + \Sigma_g B_g(\boldsymbol{R}).$$

The common agency equilibrium $(\boldsymbol{R}^0, B_F^0(\boldsymbol{R}^0), B_I^0(\boldsymbol{R}^0), B_C^0(\boldsymbol{R}^0))$ satisfies [4,7,13,19]:

$$(\beta_F + \gamma_F)\nabla W_F(\boldsymbol{R}^0) + \beta_I + \gamma_I)\nabla W_I(\boldsymbol{R}^0) + (\beta_C + \gamma_C)\nabla W_C(\boldsymbol{R}^0) = 0.$$

Thus in (14), $\alpha_g \equiv \beta_g + \gamma_g$ is the sum of parameters reflecting the group's electoral importance and lobbying ability.

[13] A referee has pointed out that in order to have the weights $\alpha_C \neq \alpha_F \neq \alpha_I$, that transactions costs must be sufficiently high so that groups cannot arrange for extra-regulatory transfers between themselves. A regulated open access equilibrium is itself evidence that both intra- and inter-group transactions costs are sufficiently high to prevent a Coase theorem result to occur. Regulations such as limited entry and ITQs lower intra-group transactions costs for fishing captains, but do nothing to alleviate inter-group transactions costs between fishing captains and consumers or input suppliers. Regulations such as input restrictions or regulated open access actually increase intra-group transactions costs, because the free entry aspect of these regulations means that any potential entrant needs to be included in a between group transfer.

The first and second terms in the numerator and denominator are each negative. The third term is positive or negative as the expression $\alpha_I - \alpha_F$ is positive or negative. Thus, a necessary condition for the regulator's welfare to be increasing in N or k is that α_I is strictly greater than α_F.

Proposition 3.4. *The regulator chooses a policy in which free entry drives the marginal fishing captain's profits to zero only if* $\alpha_I \gg \alpha_F$ *and the weight on consumers is not too large*, *relative to* α_I.

The indifference curves for the regulator are depicted in Fig. 3. This proposition shows that the regulated open access outcome is the result of a regulator with strong preferences for the welfare of input suppliers. A regulator with relatively strong preferences for the welfare of fishing captains and consumers chooses a set of instruments such that the equilibrium occurs on the $T = \bar{T}$ boundary constraint.

While Proposition 3.4 describes the effect of *large* changes in the regulator's preferences, the next propositions describe the effect of *small* changes in the weights of the regulator's utility function on the equilibrium number of vessels (the effect on variable inputs is opposite).

Proposition 3.5. *When the profit constraint* (7) *is binding*, (i) $\partial N/\partial \alpha_F \gtrless 0$ *as* $w' \gtrless 0$, (ii) $\partial N/\partial \alpha_I < 0$ *when* $h/k > h'$ *and* $\partial N/\partial \alpha_I > 0$ *only when* $h/k < h'$ *and* $w + w'N$ *is small*, *and* (iii) $\partial N/\partial \alpha_C > 0$ *for* $h/k < h'$ *and* $\partial N/\partial \alpha_C < 0$ *only when* $h/k > h'$ *and* $w + w'N$ *is small.*

With unrestricted entry, fishing captains prefer regulations that increase the number of vessels only when there is heterogeneity. Input suppliers prefer regulations that increase the number of vessels only when variable inputs are severely restricted (i.e., only when $k < \hat{k}$) and when the opportunity cost of fishing captains is both low and relatively elastic. In contrast, consumers prefer regulations that increase the number of vessels only when the input restriction is not significant.

Proposition 3.6. *When the season length constraint* (6) *is binding*, (i) $\partial N/\partial \alpha_F < 0$ *for* $h/k < h'$, (ii) $\partial N/\partial \alpha_I > 0$ *when* $h/k < h'$, *and* (iii) $\partial N/\partial \alpha_C = 0$.

When the season length constraint binds, the regulator's choice of the number of vessels is decreasing in the weight on harvesters, increasing in the weight on input suppliers, and independent of the weight on consumers. Fig. 4 illustrates this result. In contrast to the case where the zero profit constraint is binding, the interests of harvesters and input suppliers are opposed when the season length constraint binds.

The next proposition shows which source of rents is most important in determining whether regulations allowing free entry are adopted.

Proposition 3.7. *For the regulator to choose regulations on the zero-profit constraint* (3), *it is necessary that the supply of inputs is positive sloped, but it is not necessary that fishing captains are heterogeneous, nor is it required that demand be downward sloping.*

Thus, it is the infra-marginal rents to input suppliers not the infra-marginal rents to heterogeneous fishing captains or surplus to consumers that causes inefficient instruments to be chosen in a fishery.

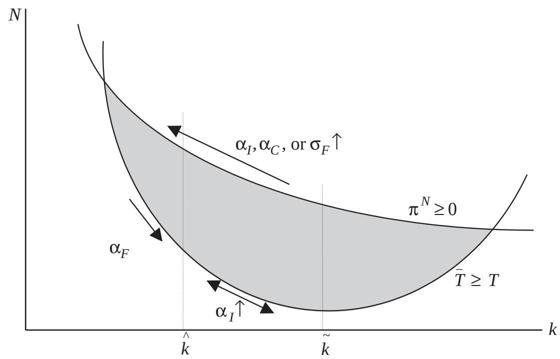

Fig. 4. Effects of small changes in the preferences of the regulator.

4. Effects of regulatory instruments

Next, let us consider the effects of policy instruments such as input restrictions, entry restrictions and ITQs, when each is used alone or in combination.

4.1. Effect of input restrictions in a regulated open access fishery[14]

If an input restriction is binding, but entry is free, fishing captains enter until profits are driven to zero for the marginal entrant. Thus, the input restricted equilibrium $\{T_k, N_k, k_k\}$ satisfies:

$$k_k = \bar{k} < k_{\rm O}, \quad T_k H_k = Q, \quad \text{and} \quad T_{kp}(H_k)h(\bar{k}) - r(K_k)\bar{k} - w(N_k) = 0, \tag{16}$$

where $H_k \equiv N_k h(\bar{k})$ and $K_k \equiv N_k \bar{k}$. The next proposition summarizes the effects of input restrictions:

Proposition 4.1. *An input-restricted fishery is characterized by*: (i) $N_k > N_{\rm O}$; (ii) $T_k > T_{\rm O}$, *implying that* $H_k < H_{\rm O}$ *and* $W_{\rm C}(\{\bar{k},\cdot,\cdot\}) > W_{\rm C}(\{\cdot,\cdot,\cdot\})$, *when* $\bar{k} < \hat{k}$; (iii) $K_k > K_{\rm O}$ *and* $W_{\rm I}(\{\bar{k},\cdot,\cdot\}) > W_{\rm I}(\{\cdot,\cdot,\cdot\})$ *when* $\bar{k} < \hat{k}$, $p' < 0$, *and* $w + w'N$ *small*; *and* (iv) $W_{\rm F}(\{\bar{k},\cdot,\cdot\}) \geqslant W_{\rm F}(\{\cdot,\cdot,\cdot\})$ *only if* $w' \geqslant 0$.

The input restricted free entry equilibrium is depicted as the point KT on the $\pi^N = 0$ constraint in Fig. 5. Result (i) of the proposition implies that capital restrictions increase N. This is in contrast to Karpoff [16, Proposition 1, p. 188]. The difference arises because Karpoff assumes that input restrictions decrease the season harvest quota, while here the harvest quota is exogenous. More importantly, there exist conditions ($w' > 0$, $p' < 0$ and $w + w'N$ small) such that relative to open access, input restrictions increase the welfare of fishing captains, input suppliers and consumers. However, to do so the restriction must be *significant* in the sense that $\Delta k \equiv k_{\rm O} - \bar{k}$ is large enough so that $\bar{k} < \hat{k}$. If these conditions are met, it provides a powerful incentive to the regulator to adopt such regulations. An example of a significant input restriction occurred in the post second world war regulation in the Bristol Bay, Alaska, salmon fishery, which prohibited

[14] While some input restrictions—e.g., mesh size restrictions—are designed for stock preservation purposes, others appear to exist for purely for reasons of economic transfer. See [21] for examples.

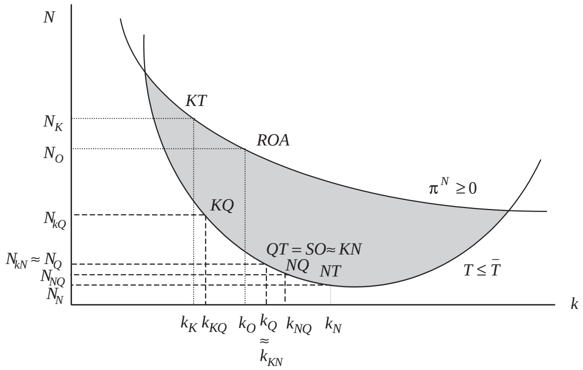

Fig. 5. Instrument choice in a fishery.

motor powered vessels and winches. Fishing captains could only use sailing vessels and were forced to pull the nets in by hand. Such a regulation is hardly for conservation purposes.

4.2. Entry restrictions in a regulated open access fishery[15]

The effect of an entry restriction in a regulated open access fishery is to restrict the number of fishing captains to $N \leqslant \bar{N}$.[16] Fishing captains choose k, and the season length depends upon $\bar{N}$ and k via (1). Profits in excess of the opportunity cost of the marginal fishing captain become capitalized into the value of the limited entry permits l. Thus, the limited entry equilibrium $\{T_N, N_N, k_N, l_N\}$ satisfies:

$$N_N = \bar{N},\ \ T_N H_N = Q,\ \ T_N p(H_N) h'(k_N) = r(K_N),\ \text{ and}$$
$$l_N = T_N p(H_N) h(k_N) - r(K_N) k_N - w(\bar{N}), \tag{17}$$

where $H_N = \bar{N} h(k_N)$ and $K_N = \bar{N} k_N$. The effect of entry restrictions are as follows:

Proposition 4.2. *An entry-restricted fishery is characterized by*: (i) $k_N > k_\text{O}$; (ii) $T_N > T_\text{O}$, *implying that* $H_K < H_\text{O}$ *and* $W_\text{C}(\{\cdot, \bar{N}, \cdot\}) > W_\text{C}(\{\cdot, \cdot, \cdot\})$; *and for* $\bar{N}$ *significantly less than* N_O; (iii) $K_N < K_\text{O}$, *implying* $W_\text{I}(\{\cdot, \bar{N}, \cdot\}) < W_\text{I}(\{\cdot, \cdot, \cdot\})$; *and* (iv) $l_N > 0$ *and* $W_\text{F}(\{\cdot, \bar{N}, \cdot\}) > W_\text{F}(\{\cdot, \cdot, \cdot\})$.

Because both k and T increase, limiting entry moves the equilibrium off the zero profit constraint. As a necessary—though not sufficient—condition for regulator to adopt limited

[15] The salmon and herring roe fisheries in western Canada and Alaska, the Australian prawn and abalone fisheries, and the Norwegian purse-seine herring fishery have all adopted limited entry. See [10,21,23].

[16] Entry is usually limited by prohibiting *future* entrants, i.e., $\bar{N} = N_\text{O}$, although to be effective, $\bar{N} < N_\text{O}$. In the Alaska salmon fishery, a hatchery program increased the annual harvest quota generating rents to license holders. In the British Columbia fisheries, the government reduced N by buying permits [21]. Thus, those who exited were also compensated. This feature is crucial to the acceptance of a limited entry program, since without it, fishing captains have no incentive to support the program. (See *n*.9, *supra*.).

entry is that $\alpha_I < \alpha_F$, by Proposition 3.5, the limited entry equilibrium must occur on the $T = \bar{T}$ boundary at point such as NT in Fig. 5. A limited entry program transfers rents to fishermen in the form of limited entry permit values and to consumers in the form of lower harvest rates. Even though there is "capital stuffing," i.e., $k_N > k_O$ (cf. [21,23]), input suppliers are made worse off relative to open access, because the regulator ensures that the increase in the season length overcomes increases in capital per vessel. Nevertheless, because NT is to the right of other equilibria on the $T = \bar{T}$ boundary, the costs to input suppliers are less than with other instruments (see Proposition 4.6 below). Thus, limited entry can only be an equilibrium choice if the weight on input suppliers is fairly large (though still less than the weight on fishing captains), since fishing captains prefer equilibria to the left of SO while NT is to the right of SO.

4.3. Effect of combining input and entry restrictions

Limited entry programs often also restrict inputs.[17] This is consistent with the claim in Proposition 4.2 that limited entry programs are designed to transfer rents to fishing captains and to consumers. In general, the input- and entry-restricted equilibrium $\{T_{kN}, l_{kN}\}$ must satisfy the following:

$$T_{kN}\bar{N}h(\bar{k}) = Q, \quad \text{and} \quad l_{kN} = T_{kNp}[\bar{N}h(\bar{k})]h(\bar{k}) - r(\bar{N}\bar{k})\bar{k} - w(\bar{N}). \tag{18}$$

However, a regulator who limits entry has an incentive to utilize the full season, since limited entry only occurs if $\alpha_F > \alpha_I$. Thus, the combination of $\bar{N}$ and $\bar{k}$ the regulator chooses will be on the $T = \bar{T}$ constraint:

Proposition 4.3. *An input- and entry-restricted fishery is characterized by*: (i) $T_{kN} = \bar{T} = T_N > T_k$, *implying that* $W_C(\{\bar{k}, \bar{N}, \cdot\}) = W_C(\{\cdot, \bar{N}, \cdot\}) > W_C(\{\bar{k}, \cdot, \cdot\})$; (ii) $l_{kN} > l_N > l_k = 0$, *implying* $W_F(\{\bar{k}, \bar{N}, \cdot\}) > W_F(\{\cdot, \bar{N}, \cdot\}) > W_F(\{\bar{k}, \cdot, \cdot\})$; (iii) $K_{kN} < K_N < K_k$, *implying that* $W_I(\{\bar{k}, \bar{N}, \cdot\}) < W_I(\{\cdot, \bar{N}, \cdot\}) < W_I(\{\bar{k}, \cdot, \cdot\})$.

This equilibrium is depicted as the point KN in Fig. 5. Adding input restrictions to a limited entry program prevents rents from being dissipated at the input margin, and adding entry restrictions to an input-restricted fishery prevents dissipation of rents at the entry margin. Both increase fishing captains' rents. However, combining these two instruments hurts input suppliers relative to using either instrument alone. Thus, limited entry programs include input restrictions, since this benefits the same group (fishing captains and consumers) who benefited from limited entry. However, adding entry restrictions to an input restricted fishery hurts input suppliers, a major beneficiary in the coalition that lobbied to obtain the capital restrictions in the first place. While

[17] The input restrictions preceded entry restrictions in each [21].

most limited entry fisheries restrict inputs, very few input restricted fisheries have adopted entry restrictions.

4.4. Effect introducing ITQs in a regulated open access fishery

Suppose the N_O fishing captains under open access are allocated quota shares q_n, so that $\sum_{n=1}^{N} q_n = Q$.[18] Let $x_n \geqslant -q_n$ denote the quantity of annual quotas purchased ($x_n > 0$) or sold ($x_n < 0$) by the nth fisherman at price m, the seasonal rental price for a quota. The quota price m causes aggregate quota demand to vanish (i.e., $\sum_{n=1}^{N} x_n = Q$). Entry in an ITQ market is determined by having the marginal entrant indifferent between actively fishing and selling his permits at the market price m:

$$T_n p(H)h(k_n) - r(K)k_n - mx_n - w(n) = mq_n \quad \text{for } n = N_Q. \tag{19}$$

Each of the N_Q active fisherman maximizes fishing profits by choosing T_n, k_n, and x_n, subject to the season length constraint (2), and the constraint that his harvest cannot exceed his quotas:

$$T_n h_n \leqslant x_n + q_n, \ \ n = 1, \dots, N_Q. \tag{20}$$

Proposition 4.4. *An ITQ regulated fishery is characterized by*

$$T_Q = \bar{T}, \ \ \bar{T}HQ = Q, \ \ \bar{T}[p(H_Q) - m_Q]h'(k_Q) = r(K_Q), \ \ \textit{and} \ \ \bar{T}[p(H_Q) - m_Q]h(k_Q) = r(K_Q)k_Q + w(N_Q). \tag{21}$$

For $m = \lambda$, the conditions in (21) are identical to those in the social planner's problem (4). Thus, ITQs yield a first-best solution. This equilibrium is depicted as the point QT in Fig. 5. Thus, reversing Proposition 2.2 shows the effects of ITQs relative to the regulated open access equilibrium: ITQs improve the welfare of fishing captains and consumers, and reduce the welfare of input suppliers. Therefore, a regulator who implements ITQs in a regulated open access fishery has preferences $\alpha_F > \alpha_I$.

4.5. Effect of adding input restrictions to ITQs

In an input restricted ITQ fishery, ITQs allow each captain to fish the entire possible season, and entry is determined by (19). Thus, the input-restricted ITQ equilibrium $\{T_{kQ}, N_{kQ}, k_{kQ}, m_{kQ}\}$ includes:

$$k_{kQ} = \bar{k} < k_Q, \ \ T_{kQ} = \bar{T}, \ \ T_{kQ}N_{kQ}h(\bar{k}) = Q \quad \text{and} \quad T_{kQ}[pH_{kQ} - m_{kQ}]h(\bar{k}) = r(K_{kQ})\bar{k} + w(N_{kQ}). \tag{22}$$

[18] When fishing captains are identical $q_n = Q/N_O$, is a simple and obvious way to allocate the quotas. However, if fishing captains are heterogeneous, there may no longer be a simple solution to the initial quota allocation problem. See [15,16] for discussions of this point.

Proposition 4.5. *An input restricted ITQ fishery is characterized by*: (i) $T_{kQ} = T_Q = \bar{T}$, *implying* $H_{kQ} = H_Q$ *and* $W_C(\{\bar{k}, \cdot, \text{ITQs}\}) = W_C(\{\cdot, \cdot, \text{ITQs}\})$; (ii) $N_{kQ} > N_Q$, (iii) *if and only if* $\bar{k} < \hat{k}$, $K_{kQ} > K_Q$, *implying* $W_I(\{\bar{k}, 0, \text{ITQs}\}) > W_I(\{0, 0, \text{ITQs}\})$, *and* (iv) *if and only if* $\bar{k}$ *is sufficiently close to* k_Q, $W_F(\{\bar{k}, \cdot, \text{ITQs}\}) > W_F(\{\cdot, \cdot, \text{ITQs}\})$.

This equilibrium is depicted as the point *KQ* in Fig. 5. Imposing relatively minor input restrictions helps fishing captains, hurts input suppliers, and has no effect on consumers. Imposing major input restrictions has the opposite effect on fishing captains and input suppliers. In the Pacific halibut ITQ fishery, the input restrictions were retained from the regulatory regime when only input and season closures were used. This suggests that this was an effort by the regulator to reduce the damages from ITQs on input suppliers.

4.6. Effect of adding entry restrictions to ITQs

An entry-restricted ITQ equilibrium $\{T_{NQ}, N_{NQ}, k_{NQ}, m_{NQ}, l_{NQ}\}$ satisfies:

$$N_{NQ} = \bar{N} < N_Q,\ \ T_{NQ} = \bar{T},\ \ T_{NQ}\bar{N}h(k_{NQ}) = Q,\quad T_{NQ}[p(H_{NQ}) - m_{NQ}]h'(k_{NQ}) = r(K_{NQ}),$$
$$\text{and}\quad l_{NQ} = T_{NQ}[p(H_{NQ}) - m_{NQ}]h(k_{NQ}) - r(K_{NQ})k_{NQ} - w(\bar{N}). \tag{23}$$

Even though entry is restricted, ITQs allow fishing captains to choose how long to fish, and each again utilizes the entire season. The third expression in (23) yields the input demand by each fishing captain, and the last two conditions define the license value l_{NQ} and the quota value m_{NQ}. Thus, we have:

Proposition 4.6. *An entry-restricted ITQ fishery is characterized by*: (i) $T_{NQ} = T_Q$, *implying* $W_C(\{\cdot, \bar{N}, \text{ITQs}\}) = W_C(\{\cdot, \cdot, \text{ITQs}\})$; (ii) $k_{NQ} > k_Q$; (iii) $K_{NQ} > K_Q$, *implying* $W_I(\{\cdot, \bar{N}, \text{ITQs}\}) > W_I(\{\cdot, \cdot, \text{ITQs}\})$; *and* (iv) $W_F(\{\cdot, \bar{N}, \text{ITQs}\}) < W_F(\{\cdot, \cdot, \text{ITQs}\})$.

This equilibrium occurs at a point such as *NQ* in Fig. 5. Adding entry restrictions to an ITQ fishery benefits input suppliers, but causes fishing captains to be worse off. Thus, in contrast to the regulated open access case, fishing captains will not support a limited entry program when ITQs are in place. This is consistent with there being no ITQ programs to my knowledge that also limit entry.

4.7. Effect of adding ITQs to an input-restricted fishery

Suppose ITQs are adopted in a fishery that currently is regulated only with an input restriction. If the input restriction is maintained, this moves the equilibrium to *KQ* from *KT* in Fig. 5. This unlikely to occur, since a regulator that has adopted input restrictions has strong preferences favoring input suppliers over fishing captains (i.e., $\alpha_I \gg \alpha_F$). An ITQ system benefits fishing captains and consumers at the expense of input suppliers. Thus, this could only occur with a large change in the regulator's preferences.

4.8. Effect of adding ITQs to an entry-restricted fishery

Finally, consider adding ITQs to a limited entry fishery, without altering the entry restriction. This reduces the advantage of adopting ITQs, since the limited entry program already fully captures the surplus for consumers (since $T_N = T_{NQ} = \bar{T}$) and some of the surplus for fishing captains. Therefore, the gain from doing adopting ITQs is relatively meager.

5. Conclusions

This paper examined a model of regulatory choice in a fishery in which fishing captains, input suppliers, and consumers each obtain surplus in equilibrium. The question the paper addresses is why are inefficient regulations adopted? If one accepts Johnson and Libecap's [15] argument that inefficient regulations such as input restrictions result from heterogeneous fishing captains protecting infra-marginal rents, then why do they choose such an inefficient way to generate surplus? Similarly, if one accepts Karpoff's [16] argument that inefficient fishermen obtain input restrictions to keep out the efficient fishermen, then the inefficient fishermen would benefit more by obtaining ITQs and earning the transitional gains. Thus, each of these arguments falls apart in the same way—too much is left on the table if inefficient regulations are designed to benefit only fishing captains. This paper argues that it is the surplus of input suppliers, not the heterogeneity of fishing captains, that is the primary determinant of whether or not inefficient regulations will occur.

Acknowledgments

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Appendix A

Proof of Proposition 2.1. Let τ be the Kuhn–Tucker multiplier for the season length constraint (2). The first-order conditions for the social planner's problem include (1) and the following:

$$\partial V/\partial T = \int_0^H p(s)\,ds - \lambda H - \tau = 0, \tag{A.1}$$

$$\partial V/\partial N = T[p(H) - \lambda]h(k) - r(K)k - w(N) = 0, \tag{A.2}$$

$$\partial V/\partial k_l = T[p(H) - \lambda]h'(k) - r(K) = 0, \tag{A.3}$$

$$\tau \geqslant 0, \bar{T} \geqslant T, \tau(\bar{T} - T) = 0. \tag{A.4}$$

$T = \bar{T}$ follows from (A.1), (A.2), and (A.4). Eq. (4) then follows from (1), (A.2), (A.3), and (A.4). □

Proof of Proposition 2.2. The total differential of the system of equations describing the equilibrium $\{k,N,T\}$ is

$$\begin{pmatrix} T(p-\lambda)h'' + Tp'Nh'^2 - r'N & Tp'hh' - r'k & (p-\lambda)h' \\ Tp'Nhh' - r'Nk & Tp'h^2 - r'k^2 & (p-\lambda)h \\ -TNh' & -Th & -Nh \end{pmatrix} \begin{pmatrix} dk \\ dN \\ dT \end{pmatrix} = \begin{pmatrix} Th' \\ Th \\ 0 \end{pmatrix} d\lambda. \tag{A.5}$$

Let $|J|$ be the determinant of the Jacobian matrix of second derivatives on the left-hand side of (A.5):

$$\begin{aligned} |J| &= T(p-\lambda)h''[T(p-\lambda)h^2 - Tp'Nh^3 + r'Nhk^2] \\ &\quad + [Tp'r'Nh - Tr'(p-\lambda)N](h - h'k)^2 + Tp'r'N^2h^3 < 0. \end{aligned}$$

The results of the proposition are applications of Cramer's rule, using (A.5) and $|J|$:

$$\frac{\partial k}{\partial \lambda} = \frac{Tr'Nhk^2(h' - h/k)}{|J|} > 0 \quad \text{for } h' < h/k,$$

$$\frac{\partial N}{\partial \lambda} = \frac{-T^2Nh^2(p-\lambda)h'' + Tr'N^2hk(h' - h/k)}{|J|} < 0, \quad \text{for } h' < h/k,$$

$$\frac{\partial T}{\partial \lambda} = \frac{T^2[Th^2(p-\lambda)h'' - Nr'k^2(h' - h/k)]}{|J|} < 0 \quad \text{for } h' < h/k,$$

$$\frac{\partial K}{\partial \lambda} = N\left(\frac{\partial k}{\partial \lambda}\right) + \left(\frac{\partial N}{\partial \lambda}\right) = \frac{-T^2h^2Nk(p-\lambda)h''}{|J|} < 0. \qquad \square$$

Proof of Proposition 3.1. In both the social optimum and the fishing captains' welfare maximizing equilibria, $H = Q/\bar{T}$, so there is no output price effect of moving along this constraint. Using this fact and the relationship that $dN/dk = -Nh'/h$ along the $T = \bar{T}$ locus, the $\{k_F^*, N_F^*\}$ combination that maximizes fishing captain's welfare satisfies

$$w(N_{\mathrm{F}}^*) = \left(\frac{h}{k_{\mathrm{F}}^*} - h'\right)\left(\frac{k_{\mathrm{F}}^*(r + r'K_{\mathrm{F}}^*)}{h'}\right). \tag{A.6}$$

In the social optimum, the combination $\{k^*,N^*\}$ on the $T = \bar{T}$ locus that maximizes social welfare satisfies

$$w(N^*) = \left(\frac{h}{k^*} - h'\right)\left(\frac{k^*r}{h'}\right).$$

Thus, using the implicit Function Theorem on (A.6), the differential $dk/d(r'K)$ is

$$\frac{dk}{d(r'K)} = -\left(\frac{h}{h'} - k\right)^{-1}\left\{-w'\left(\frac{dN}{dk}\right) - \left(\frac{hh''}{h'^2}\right)(r + r'K) + \left(\frac{h}{h'} - k\right)(2r' + r''K)\left(\frac{dK}{dk}\right)\right\} < 0.$$

To sign this expression, note that $dN/dk = -Nh'/h < 0$ along the $T = \bar{T}$ locus and $dK/dk = \left(\frac{K}{h}\right)\left(\frac{h}{h'} - k\right) > 0$, and assume that $2r' + r''K > 0$. Thus, when $r'K > 0$, fishing captains prefer $k_{\mathrm{F}}^* < k^*$ and $N_{\mathrm{F}}^* > N^*$. □

Proof of Proposition 3.2. An increase in k along the $\pi^N = 0$ locus as the effect on input suppliers that

$$\left.\frac{\partial W_I}{\partial k}\right|_{\pi^N=0} = r'K\left(\left.\frac{dK}{dk}\right|_{\pi^N=0}\right) = r'K\left(\frac{Qp'(h - h'k) - w - w'N}{Q(p'H - p)/N^2 - r'k^2 - w'}\right).$$

The term in brackets on the right-hand side is positive unless $h/k - k < 0$ and $w + w'N$ is small. □

Proof of Proposition 3.5. When the zero profit constraint (3) binds, the regulator chooses N and k such that

$$\Sigma_g \alpha_g W_N^g + \lambda_\pi \pi_N = 0 \quad \text{and} \quad \Sigma_g \alpha_g W_k^g + \lambda_\pi \pi_k = 0, \tag{A.7}$$

where $W_k^g = \partial W_g/\partial k$, $W_N^g = \partial W_g/\partial N$, $\lambda_\pi \geqslant 0$ is the Lagrange multiplier for the constraint (3), $\pi_k = \partial \pi^N/\partial k$, and $\pi_N = \partial \pi^N/\partial N$. Totally differentiating (A.7) and (3) yields:

$$\begin{pmatrix} \Sigma_g \alpha_g W_{NN}^g + \lambda_\pi \pi_{NN} & \Sigma_g \alpha_g W_{Nk}^g + \lambda_\pi \pi_{Nk} & \pi_N \\ \Sigma_g \alpha_g W_{Nk}^g + \lambda_\pi \pi_{Nk} & \Sigma_g \alpha_g W_{kk}^g + \lambda_\pi \pi_{kk} & \pi_k \\ \pi_N & \pi_k & 0 \end{pmatrix}\begin{pmatrix} dN_R \\ dk_R \\ d\lambda_\pi \end{pmatrix}$$
$$= -\begin{pmatrix} W_N^{\mathrm{F}} \\ W_k^{\mathrm{F}} \\ 0 \end{pmatrix} d\hat{\alpha}_{\mathrm{F}} - \begin{pmatrix} W_N^{\mathrm{I}} \\ W_k^{\mathrm{I}} \\ 0 \end{pmatrix} d\hat{\alpha}_{\mathrm{I}}. \tag{A.8}$$

Maximization implies a positive determinant $|J_{R\pi}|$. The results follows by applying Crammer's Rule to (A.8):

$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{F}}} = \frac{-\pi_k}{|J_{R\pi}|}[\pi_N W_k^{\mathrm{F}} - \pi_k W_N^{\mathrm{F}}] = \frac{\pi_k^2 w'N}{|J_{R\pi}|} \gtrless 0 \ \text{ as } \ w' \gtrless 0,$$

$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{I}}} = \frac{\pi_k}{|J_{R\pi}|}[\pi_k W_N^{\mathrm{I}} - \pi_N W_k^{\mathrm{I}}] = \frac{\pi_k r'K}{|J_{R\pi}|}[Qp'k(h' - h/k) + w + w'N] < 0 \ \text{ for } \ h' < h/k,$$

$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{C}}} = \frac{\pi_k}{|J_{R\pi}|}[\pi_k W_N^{\mathrm{C}} - \pi_N W_k^{\mathrm{C}}] = \frac{\pi_k W_H^{\mathrm{C}}}{|J_{R\pi}|}[k(r + r'K)(h' - h/k) + (w + w'N)h'] > 0 \ \text{ for } \ h' < h/k. \qquad \square$$

Proof of Proposition 3.6. If the season harvest constraint (2) is binding, then the regulator's problem is to choose N and k such that

$$\Sigma_g \alpha_g W_N^g - \lambda_T T_N = 0, \quad \text{and} \quad \Sigma_g \alpha_g W_k^g - \lambda_T T_k = 0, \tag{A.9}$$

where $\lambda_T \geq 0$ is the multiplier for (2), $T_k = \partial T/\partial k$, and $T_N = \partial T/\partial N$. Totally differentiating (A.9) and (2) yields:

$$\begin{pmatrix} \Sigma_g \alpha_g W_{NN}^g - \lambda_T T_{NN} & \Sigma_g \alpha_g W_{Nk}^g - \lambda_T T_{Nk} & -T_N \\ \Sigma_g \alpha_g W_{Nk}^g - \lambda_T T_{Nk} & \Sigma_g \alpha_g W_{kk}^g - \lambda_T T_{kk} & -T_k \\ -T_N & -T_k & 0 \end{pmatrix} \begin{pmatrix} dN_R \\ dk_R \\ d\lambda_\pi \end{pmatrix}$$
$$= -\begin{pmatrix} W_N^{\mathrm{F}} \\ W_k^{\mathrm{F}} \\ 0 \end{pmatrix} d\hat{\alpha}_{\mathrm{F}} - \begin{pmatrix} W_N^{\mathrm{C}} \\ W_k^{\mathrm{C}} \\ 0 \end{pmatrix} d\hat{\alpha}_{\mathrm{C}} - \begin{pmatrix} W_N^{\mathrm{I}} \\ W_k^{\mathrm{I}} \\ 0 \end{pmatrix} d\hat{\alpha}_{\mathrm{I}}. \tag{A.11}$$

Again, the determinant $|J_{RT}|$ is positive. The results follow by applying Crammer's Ruler to (A.12):

$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{F}}} = \frac{-T_k}{|J_{RT}|}[T_k W_N^{\mathrm{F}} - T_N W_k^{\mathrm{F}}] = \frac{-Q^2[h'w + k(h' - h/k)(r + r'K)]}{(Nh)^4 |J_{RT}|} < 0 \text{ for } h' > h/k,$$
$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{I}}} = \frac{-T_k}{|J_{RT}|}[T_k W_N^{\mathrm{I}} - T_N W_k^{\mathrm{I}}] = \frac{Q^2 N h' k^2 r'(h' - h/k)}{|J_{RT}|} < 0 \text{ for } h' > h/k,$$
$$\frac{dN_R}{d\hat{\alpha}_{\mathrm{I}}} = \frac{-T_k}{|J_{RT}|}[T_k W_H^{\mathrm{C}} h - T_N W_H^{\mathrm{C}} N h'] = 0. \qquad \square$$

Proof of Proposition 3.7. To prove necessity of $r' > 0$, suppose that $\alpha_{\mathrm{I}} \gg \alpha_{\mathrm{F}}$, but $r' = 0$. Then the expression (15) is identical to the weighted sum of fishing captains' and consumers welfare, and we saw above the each prefer policies that decrease N and k. In contrast, the denominator of (15) is unaffected by whether or not w' is positive or zero. If $w' > 0$, then w is increasing in N, but an increase in w makes it more unlikely that the regulator will choose a policy on the zero profit constraint for a given set of policy weights. $\square$

Proof of Proposition 4.1. The system of equations (16) describing the input restricted equilibrium includes the endogenous variables T_K and N_K, with $\bar{k}$ exogenous. Total differentiating this system of equations yields:

$$\begin{pmatrix} Tp'h^2 - k^2 r' - w' & ph \\ Th & Nh \end{pmatrix} \begin{pmatrix} dN \\ dT \end{pmatrix} = -\begin{pmatrix} Th'(p + p'Nh) - r - r'Nk \\ TNh' \end{pmatrix} d\bar{k}. \tag{A.12}$$

Let $|J_k|$ denote the determinant of the Jacobian matrix on the left-hand side of this equation. Then

$$|J_K| = -Th^2(p - p'H) - N(r'k^2 + w') < 0. \tag{A.13}$$

The results follow from Crammer's Rule applied to (A.12), using (A.13):

$$\frac{dN_K}{d\bar{k}} = \frac{H(-Tp'Hh' + r + r'K)}{|J_K|} < 0,$$
$$\frac{dT_K}{d\bar{k}} = \frac{T[k(h' - h/k)(r + r'K) + w + w'N]}{|J_K|} < 0, \quad \text{when } h' > h/k,$$
$$\frac{dK_K}{d\bar{k}} = \frac{Nh[THp'k(h/k - h') - w - w'N]}{|J_K|} < 0, \quad \text{only if } h' > h/k, p' < 0, \text{ and } w + w'N \text{ small.}$$

To see the effect on W_F, note that with free entry, W_F may be written as $W_F = w(N)N - \int_0^N w(s)\,ds$. Thus, the effect of a capital restriction on fishing captains' welfare is given by

$$\frac{\partial W_F}{\partial \bar{k}} = w'(N_K)N_K\left(\frac{\partial N_K}{\partial \bar{k}}\right) < 0. \qquad \square$$

Proof of Proposition 4.2. The system of equations (17) describing the entry-restricted equilibrium include the endogenous variables k_N, T_N, and l_N. Totally differentiating this system in $\bar{N}, k_N, T_N$, and l_N yields:

$$\begin{pmatrix} TNhp'h' - r'kN & ph & -1 \\ TNp'h'^2 - r'N + Tph'' & ph' & 0 \\ NTh' & Nh & 0 \end{pmatrix}\begin{pmatrix} dk_N \\ dT_N \\ dl_N \end{pmatrix} = -\begin{pmatrix} Tp'h^2 - r'N - w' \\ Tp'hh' - r'k \\ Th \end{pmatrix} d\bar{N}. \tag{A.14}$$

Let $|J_N|$ denote the determinant of the Jacobian matrix on the left-hand side of (A.14), which equals:

$$|J_N| = NTh'^2(1 + 1/|\eta|) + Nh(Nr' - pTh'') > 0. \tag{A.15}$$

Applying Crammer's Rule to (A.14) yields the results of the proposition:

$$\frac{dk_N}{d\bar{N}} = \frac{-h[Th'(p - p'H) + r'K]}{|J_N|} < 0,$$
$$\frac{dT_N}{d\bar{N}} = \frac{T[r'K(h' - h/k) + Tphh'']}{|J_N|} < 0, \quad \text{since } h' < h/k,$$
$$\frac{dK_N}{d\bar{N}} = \frac{TN[h'k(h' - h/k)(p - p'Nh) - hkph'']}{|J_N|} > 0, \quad \text{as } k_N \to \tilde{k}, \text{which holds for significant restrictions,}$$

$$\frac{dl_N}{d\bar{N}} = \frac{-TNh'^2w'(p - p'H)}{|J_N|} + \frac{ph[Th(p - p'H) + w'N]h''}{|J_N|} + \frac{Hr'[Tph''k^2 - (p - p'H)Th - w'N]}{|J_N|}$$
$$+ \frac{Th'r'K(p - p'Nh)(2h - h'k)}{|J_N|} < 0 \text{ as } k_N \to \tilde{k}, \quad \text{which holds for significant restrictions,}$$

$$\frac{dW_{\text{F}}}{d\bar{N}} = \frac{-TNh'r'K(p-p'H)(2h-h'k)}{|J_N|} + \frac{TNh'l_N(p-p'H)}{|J_N|} + \frac{THhh''(p-p'H)}{|J_N|} - \frac{TN^2r'[h(p-p'H)-pk^2h'']}{|J_N|} < 0 \text{ as } k_N \to \tilde{k}, \text{ which holds for significant restrictions.} \quad \square$$

Proof of Proposition 4.3. Totally differentiating the systems of equations (18) in the endogeneous variables T_{NK} and l_{NK} and the instruments k and $\bar{N}$ yields:

$$\begin{pmatrix} -1 & ph \\ 0 & Nh \end{pmatrix} \begin{pmatrix} dT_{NK} \\ dl_{NK} \end{pmatrix} = -\begin{pmatrix} Th'(p+p'Nh) - r - r'Nk \\ TNh' \end{pmatrix} d\bar{k} - \begin{pmatrix} Tp'h^2 - r'k^2 - w' \\ Th \end{pmatrix} d\bar{N}. \tag{A.16}$$

The determinant $|J_{NK}| = -Nh < 0$. The results follow from applying Crammer's Rule to (A.16):

$$\frac{dT_{NK}}{d\bar{N}} = \frac{Th}{|J_{NK}|} < 0, \qquad \frac{dT_{NK}}{d\bar{k}} = \frac{NTh'}{|J_{NK}|} < 0,$$

$$\frac{dH_{NK}}{d\bar{N}} = h > 0, \qquad \frac{dH_{NK}}{d\bar{k}} = \bar{N}h' > 0,$$

$$\frac{dl_{NK}}{d\bar{N}} = \frac{h[Th(p-p'H) + H(r'K + w')]}{|J_{NK}|} < 0, \qquad \frac{dl_{NK}}{d\bar{k}} = \frac{H(r + r'K - THp'h')}{|J_{NK}|} < 0,$$

$$\frac{dK_{NK}}{d\bar{N}} = \bar{k} > 0, \qquad \frac{dK_{NK}}{d\bar{k}} = \bar{N} > 0,$$

$$\frac{dW_{\text{F}}}{d\bar{N}} = \frac{H(k(r + r'K) + w - THhp')}{|J_{NK}|} < 0, \qquad \frac{dW_{\text{F}}}{d\bar{k}} = \frac{Hh(r + r'K - THp'h')}{|J_{NK}|} < 0. \quad \square$$

Proof of Proposition 4.4. In the ITQ equilibrium, the profit maximizing level of capital and the season length each fishing captain fishes under ITQs must satisfy (20), and

$$\partial\pi_n/\partial T_n = [p(H) - m]h(k_n) - \tau_n = 0, \ \tau_n \geqslant 0, \ T_n < \bar{T}, \text{ and } (\bar{T} - T_n)\tau_n = 0 \quad n = 1, \ldots, N_Q, \tag{A.19}$$

$$\partial\pi_n/\partial k_n = T_n[p(H) - m]h'(k_n) - r(K) = 0, \quad n = 1, \ldots, N_Q, \tag{A.20}$$

$$\partial\pi_n/\partial x_n = -m + \lambda_n = 0, \quad n = 1, \ldots, N_Q, \tag{A.21}$$

where λ_n is the multiplier for constraint (19) and τ_n is the multiplier for constraint (2). In addition, entry continues until profits are driven to zero for the marginal entrant. From (19) and (20), this yields:

$$T_n[p(H) - m]h(k_n) - r(K)k_n - w(n) = 0, \quad n = N_Q. \tag{A.22}$$

Finally, combining (A.19) and (A.22) shows that each active fisherman chooses to fish the entire allowable season, i.e., $T_Q = \bar{T}$. The results in (21) follow from (1), (19), (A.20), and (A.22), with m chosen such that $\sum_{n=1}^{N} x_n = 0$. □

Proof of Proposition 4.5. The input restricted ITQ equilibrium is given by (22), and (1), with $T_{kQ} = \bar{T}$ by the same logic as in Proposition 4.4. This proves result (i). A movement along $T = \bar{T}$ has the effect that $dN/dk = -Nh'/h < 0$, proving result (ii). Thus, $dK_{QK}/d\bar{k} = (h/k - h')Nk/h > 0$, which proves result (iii). Result (iv) follows from Proposition 3.1. □

Proof of Proposition 4.6. In the entry-restricted ITQ equilibrium, the constraint $T_{NQ} = \bar{T}$ is satisfied, because ITQs give fishing captains the chance to fish the whole season, proving (i). $T_{NQ} = \bar{T}$ implies that $dk/d\bar{N} = -h/Nh'$, proving result (ii). This result implies that $dK_{NQ}/d\bar{N} = -(h/k - h')k/h' < 0$, which proves results (iii). Result (iv) follows from result (ii) and Proposition 3.2. □

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