\feesvsquotas

Landing Fees vs. Harvest Quotas with Uncertain Fish Stocks

Abstract

The paper analyzes the relative performance of two market-based fisheries management instruments in the presence of a stochastic stock-recruitment relation. Regulators are forced to choose either a *fee* per fish landed or a *quota* on the total fish harvest – at a time when they are uncertain what will be the stock of fish recruits that will actually materialize during the next fishing period. With such "ecological" or "environmental" uncertainty being the predominant random variable in the fishery, some striking regulatory conclusions emerge, which go strongly against conventional wisdom.

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Comments Appreciated

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Introduction

The model of this paper has its origins in some actual experiences of current Icelandic fisheries. Iceland today relies upon a relatively sophisticated *ITQ* (Individual Transferable Quota) fisheries management system to sub-allocate by tradeable permits the *TAC* (Total Allowable Catch). The *TAC* itself is administratively set on an annual basis for all major fish species found within the 200-mile offshore zone.

Currently, there is some inkling of a national mood of discontent about at least one aspect of the system. The major problem that the Icelandic public seems to be having now with the *ITQ* system is not its perceived inefficiency relative to any alternatives, which is the subject of this paper, but rather its perceived unfairness. To make a long story short, the original allocation of *ITQ*'s was given free to vessel owners in proportion to their historical catch record over the 1981-83 period – at a time in the recent past when everyone in Iceland was concerned with doing something about the then-existing bad state of over-fishing, and no one was much concerned with hypothetical future windfall rents from handing out then, for free, potentially valuable quota-harvesting rights. By now, of course, the rents have shot up just as predicted by basic economic theory, in the form of increased quota prices. Furthermore, as might have also been expected for Iceland, which has over ten-times more fisheries income per capita than the second largest such fishing-industry-dominated nation in the world (and which additionally has a super-Scandinavian-style work ethic), the windfall fishery rents are perceived as having caused an unjust and disturbingly-large government-engineered alteration of income distribution.

Thus, in Iceland today, there has arisen a sometimes-heated national debate concerning what to do, or not to do, about spreading the existing quota wealth around more fairly. The key issue is whether some mechanism should be institutionalized for taxing automatically the fishing rents and transferring some of the proceeds to benefit the rest of the population, who was left out of the original quota allocation even though the relevant law begins by declaring that "(t)he exploitable marine stocks of the Icelandic fishing banks are the common property of the Icelandic nation." The Icelandic Parliament appointed a special Natural Resource Committee, whose charge is "...to consider various aspects regarding the utilization of natural resources, especially arrangements for optimal utilization and the advisability of taxation."

An outside economist asked to look in on all this could perhaps be forgiven for believing that now might be a propitious time to try, at least as a kind of mental exercise, thinking through again from first principles why a country or society that seems so concerned with distribution does not just "tax the catch" – since, at least in principle, Pigouvian-style taxes on rents would appear to be the ideal distortion-free instrument for such tax-and-transfer purposes, all the while promoting simultaneously full economic efficiency in the fisheries.

I think it represents a fair generalization to say that the conventional wisdom among fisheries economists is that, for this specific application of regulating the fishing industry, "prices" are an inferior instrument to "quantities." The argument is grounded not so much in anything having to do with equity or unearned-rent transfers, but is based more on the idea that regulating fisheries with prices is *less efficient* than regulating with quantities – in part because of the potential problems associated with highly-uncertain randomly-fluctuating fish stocks.[1]

My own instinct on the issue of "prices vs. quantities" here was quite the opposite from the prevailing wisdom. I tried to make the arguments heuristically, but was myself dissatisfied with the resultant hand waving involved. This paper, then, represents my best attempt to capture and to formalize the major part of that heuristic intuition in the simple standard dynamic fishery model – augmented here by a fairly general stochastic specification of "ecological" or "environmental" fish-stock uncertainty.

There is a huge theoretical literature on the economics of the fishery. While most of this literature deals with the deterministic case, stochastic models also appear. Perhaps the model in the literature closest technically to the model of this paper is the outstanding contribution of Reed [1979]. In Reed's model there is multiplicative uncertainty about the *future* stock-

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[1] Actually, I would have to go much further in saying that I was shocked at learning the degree to which the regulatory agenda in this area had already been captured by some fisheries economists with an extreme "property rights" interpretation of harvesting quotas, which essentially precludes a serious consideration of Pigouvian-style landing fees from being placed on the discussion table. A reader interested in checking whether my interpretation is fair might begin by consulting recent comprehensive accounts, such as Arnason and Gissurarson (1999) or National Research Council (1999), then followed up by checking out some of the many references to the fisheries literature contained in these two books.

recruitment relation, but the fisheries regulators are allowed to know the *current* recruitment at the time that the *current* harvest decision is made. Unfortunately, as Clark [1990, page 349] notes, "in many fisheries the exact magnitude of the current stock is unknown at the time that quotas are specified." Since it is commonly accepted that "the central problem facing fishery scientists and fishery managers is to understand and deal with recruitment variability,"[2] in such a spirit it seems somewhat self-defeating to postulate for a stochastic fisheries model that the regulators know beforehand what will be the next period's recruitment level.

The aim of this paper is create and to analyze a stochastic fisheries model where regulatory decisions must be made when the pertinent recruitment stocks are unknown. So far as I am aware, the model of this paper is the first to examine analytically the regulatory issue of instrument choice when there are such severe informational constraints about an uncertain fisheries environment being placed upon the managers at the time they must make their regulatory decisions.

The paper works with a model whose informational timing forces the regulatory instruments to be set when the size of the relevant resource stock is unknown, primarily because of significant environmental or ecological uncertainty concerning the stock-recruitment relation. The model is describing a situation where the regulators must be prepared to live with the consequences of stock uncertainty, at least during that part of the next regulatory cycle where the fishermen are reacting to lagged instrument values – throughout the pending fishing period – which are different from what prevailed at the time when the instruments were set.

It is within this general kind of informational and institutional context that the question of "fees vs. quotas" is being posed and analyzed in the paper. Offhand, the usual tradeoff would appear to be present: harvest quotas have the advantage of fixing the total quantity of fish being caught, but suffer from the drawback of being unable to control the possibly-excessive effort being exerted to fish down a stock that, it may just so happen by the laws of chance, is coincidentally experiencing a low recruitment throughout this fishing period; landing fees, on the

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[2] Sissenwine [1984], from an article in *Marine Resource Economics* entitled "the uncertain environment of fishery scientists and managers."

other hand, are (relatively) better able to control the (marginal) fishing effort (or cost), but suffer the drawback of being unable to prevent over-fishing in a situation where, again by the laws of chance, the stock recruitment happens already to be low.

The stochastic part of the simple fisheries model of this paper is sharply and almost exclusively focused on what might be called "ecological" or "environmental" uncertainty. The novel feature of this model is that instrument values are being chosen in a regulatory world where "the central problem facing fishery scientists and fishery managers is to understand and deal with recruitment variability" – in the form of a currently-uncertain stock recruitment. Even with the stochastic component being limited to such ecological or environmental uncertainty, the fee-vs-quota argument is sufficiently complicated that it may, quite reasonably, be unclear beforehand which verdict the formal model will render. Therefore, I would say, the striking affirmation by this simple model of the generic superiority of landing fees over harvest quotas in the presence of stock uncertainties comes as somewhat of a surprise, which perhaps should merit a serious reconsideration in fisheries economics of this entire set of issues.

The Model: Specifications and Assumptions

The basic framework is a discrete-time metered model. Only a difference-equation set up, with its inherent delay effects, can aspire to capture the measurement errors, informational uncertainties, too-late observations, and lagged response features, which form such a critical part of the actual fisheries management scene.

Throughout the paper, the positive integer $t\ (=1,2,...)$ will index a particular *fishing period*. Let S_t represent the *escapement* (from capture) in period t. "Escapement" is a fisheries-biology term for the stock of potential parent fish remaining alive at the *end* of the fishing period. It should be noted throughout the paper that nothing in the technical construction of the model prevents the interpretation that S_t represents the *estimated escapement* (in period *t*), as opposed to the *actual escapement*.

The *recruitment* of fish stock that actually shows up *during* period *t* is denoted R_t. Let $\boldsymbol{\varepsilon}_t$ represent the *state of the fishery environment* during period *t*. The fundamental *stock-*

recruitment relation is given by the stochastic equation

$$R_t = F(S_{t-1}|\varepsilon_t) \quad , \tag{1}$$

where the $\{\varepsilon_t\}$ are independent identically distributed (i.i.d.) random variables with a known given probability density function. It is assumed that for all values of ε having positive probability measure,

$$F_1(0|\varepsilon) > 0 \quad , \tag{2}$$

and, for all values of $S \geq 0$,

$$F_{11}(S|\varepsilon) \leq 0 \quad . \tag{3}$$

It is important to be very clear about the timing and informational sequence being modeled here. The fisheries *regulators* first observe (or estimate) escapement S_{t-1} at the end of period t-1. Then, operating in time on the thin border line between the end of period t-1 and the beginning of period t, and *before* anyone can observe what will be the realization of the state of the environment ε_t, the regulators assign a "best value" to their management instrument, which is here either a landing fee or a harvest quota. Finally, the *fishermen react* to the value of the management instrument *during* the period t, in effect choosing their most economical level of fishing effort, via the harvest they take, *after* they have observed the realization of the state of the environment ε_t – from the decks of their boats so to speak – in the form of $R_t = F(S_{t-1}|\varepsilon_t)$. The subsequent value of S_t is then the result of profit-maximizing fish-harvesting behavior, given the imposed regulatory instrument value and the actual realization of ε_t.

The *harvest* of fish taken during period t is denoted H_t. The following formula must then hold for all periods t:

$$S_t = R_t - H_t \ . \tag{4}$$

Let the *unit or marginal profitability* when the fish stock is x be denoted $\pi(x)$. If a total of H fish are harvested during the period, starting from recruitment level R at the beginning of the period, then the corresponding total fishing profit for the period is

$$\int_{R-H}^{R} \pi(x)\ dx \ . \tag{5}$$

In the standard fisheries model, $\pi(x)$ is typically assumed to be of the form

$$\pi(x) = p - c(x) \ , \tag{6}$$

where p is the unit price of fish, while $c(x)$ represents the unit cost of harvesting (at fish population x) – but there is no reason to be so restrictive. The only critical assumption being made here is that

$$\pi'(x) > 0 \tag{7}$$

for all $x \geq 0$, which corresponds to the standard assumption $c'(x) < 0$.

Loosely speaking, the fisheries managers are trying to pick instruments in such a way as to induce harvest levels that will attain as high a level as can be achieved of an -expected-present-discounted-profits expression having the general form

$$\mathrm{E}[\sum_{t=1}^{\infty} \alpha^{t-1} \int_{R_t-H_t}^{R_t} \pi(x)\ dx] \ , \tag{8}$$

subject to (1), (4) and some initial conditions. The operator notation $\mathrm{E}[\bullet]$ here stands for the expected value of whatever is contained within the square brackets, taken over all relevant realizations of $\{\varepsilon_t\}$, while

$$\alpha \equiv \frac{1}{1+r} \quad , \tag{9}$$

represents the relevant discount factor when r is the one-period discount rate.

The reduced-form core uncertainty in this model concerns the overall relationship between last period's estimated fish escapement stock and next period's actual recruitment. Let us call this kind of stochastic reduced-form relationship e*cological uncertainty*. It comes about in this model by a compounding of two stochastic effects – (1) uncertainty about the actual escapement; (2) uncertainty about the stock-recruitment relationship. Such kind of reduced-form "ecological uncertainty" represents, arguably, the largest single source of fluctuations in the fishing industry and the largest single kind of variability in the fishery regulatory process – but there are many other important sources of uncertainty in fisheries management. (Actually, the fishery seem to represent one of the most difficult industries in the world to regulate well, in part because everywhere the regulators look they see uncertainty.)

So, while I believe there are some very useful, and perhaps even important, insights that will come out of this way of modeling fisheries management, there is no way I want to argue that this model represents the final word or that the conclusions could not be undone by another model constructed differently. The actual regulation of fisheries is more than a match for any model. The model of this paper merely overlays just one type of uncertainty – ecological uncertainty about fish stocks – on top of the standard bare-bones deterministic model, which is itself the simplest meaningful dynamic model of the fishery. The most we can hope to accomplish with such an approach is to develop a slightly better intuition about the direction of the pure effect of the single extra feature being added (in this case the pure effect of ecological uncertainty on the choice of regulatory instrument between fee or quota), when the rest of the model is isolated away from all other forms of fisheries uncertainty.

The Optimal Regulatory Quota Under Ecological Uncertainty

In this section of the paper we assume a market-based *ITQ* (Individual Transferable Quota) management system is in place, within which sub-allocations of the *TAC* (Total Allowable Catch) are automatically determined via competitively traded permits. The task of the regulators here is to determine the optimal *TAC* in the presence of ecological uncertainty.

The "harvest-quota" system works as follows. Given a *TAC* of Q, which is set by the fisheries manager, let the *ITQ*-fishery *harvest response function*

$$H_q(Q;S|\varepsilon) \tag{10}$$

be defined implicitly by the pair of conditions

$$\pi(F(S|\varepsilon)-Q) \geq 0 \quad \Rightarrow \quad H_q(Q;S|\varepsilon) = Q \quad , \tag{11}$$

representing a corner solution where $H=Q$, and

$$\pi(F(S|\varepsilon)-Q) < 0 \quad \Rightarrow \quad \pi(F(S|\varepsilon)-H_q(Q;S|\varepsilon)) = 0 \quad , \tag{12}$$

representing an interior solution where $H<Q$.

Taken together, conditions (11) and (12) mean that the fishermen are expending their optimal effort to attain the profit-maximizing harvest level, given the actual ecological environment, and subject to the total allowable catch being no greater than Q. (In equation (12) we impose the convention that whenever $x<0$, then $\pi(x) \equiv -\infty$.)

The manager's optimal *TAC* is most readily explained in this model by going straight to the dynamic-programming formulation. In the framework of this paper, the fisheries manager contemplating the setting of a total quota for period t takes the previous period's escapement S_{t-1} as the relevant state variable upon which to condition the setting of a *TAC*.

Let

$$V_q(S) \tag{13}$$

be the expected present discounted value from following a optimal *TAC* policy starting from state *S*. The optimizing manager's corresponding dynamic programming equation is:

$$V_q(S) \quad = \quad \max_{Q\geq 0} \; \mathop{E}_{\varepsilon} \; [\int_{F(S|\varepsilon)-H_q(Q;S|\varepsilon)}^{F(S|\varepsilon)} \pi(x)\; dx \quad + \quad \alpha \; V_q(F(S|\varepsilon)-H_q(Q;S|\varepsilon))] \quad , \tag{14}$$

where $H_q(Q;S|\varepsilon)$ is defined by (11) and (12).

Let the value of Q that maximizes the right hand side of (14) be denoted

$$\hat{Q}(S) \quad . \tag{15}$$

In period t the managers just prorate the TAC

$$\hat{Q}(S_{t-1}) \quad . \tag{16}$$

equally per existing quota unit, and then let the market-based *ITQ* system automatically take care of the sub-optimizing cost-minimizing part of the "quota" system. Note that fisheries regulation with quotas seems *relatively* direct and straightforward, at least by comparison with a fees system, to which subject we now turn.

The Optimal Landing Fee Under Ecological Uncertainty

The landing-fee regulatory control system is dual to the quota-based *TAC* system. The two systems are symmetric opposites – in instrument they are controlling, but also on the issue of whether or not relevant within-period new information (available to the fishermen *within* the fishing period) is being utilized by the endogenous profit-maximizing fishing "response." A quota controls directly the *TAC* quantity output but leaves uncertain next period's escapement "response," and is informationally inflexible in not permitting to be utilized some relevant within-period new information. A fee controls marginal profitability (or marginal effort), and is informationally flexible in allowing some use of within-period relevant new information about recruitment levels, but leaves uncertain the harvested catch "response."

The "landing-fee" system works as follows. Given a landing fee of Φ per unit of fish, which is set by the fisheries manager, let the landing-fee-fishery *harvest response function*

$$H_\phi(\Phi; S|\varepsilon) \tag{17}$$

be defined implicitly by the pair of conditions

$$\pi(F(S|\varepsilon)) > \Phi \quad \Rightarrow \quad \pi(F(S|\varepsilon) - H_\phi(\Phi; S|\varepsilon)) = \Phi \quad , \tag{18}$$

representing an interior solution where $\pi = \Phi$, and

$$\pi(F(S|\varepsilon)) \leq \Phi \quad \Rightarrow \quad H_\phi(\Phi; S|\varepsilon) = 0 \quad , \tag{19}$$

representing a corner solution where the profit from catching the first fish is less than the landing fee. Taken together, conditions (18), (19) mean that the fishermen are expending their optimal effort to attain the level of harvesting which maximizes their profits, given the environment and subject to the fee Φ being imposed on each unit of their landings.

The manager's optimal landing fee is most readily explained in this model by going straight to the dynamic-programming formulation. In such a framework, the fishery manager contemplating the setting of a landing fee for period t takes the previous end-of-period's estimated escapement S_{t-1} as the relevant state variable upon which to condition the setting of the landing fee.

Let

$$V_\phi(S) \tag{20}$$

be the expected present discounted value of following a optimal-landing-fee policy starting from state S. The corresponding dynamic programming equation for the optimizing fishery manager is:

$$V_\phi(S) \quad = \quad \max_{\Phi \geq 0} \; \underset{\epsilon}{\mathrm{E}} \; [\int_{F(S|\varepsilon) - H_\phi(\Phi;S|\varepsilon)}^{F(S|\varepsilon)} \pi(x) \; dx \quad + \quad \alpha \;\; V_\phi(F(S|\varepsilon) - H_\phi(\Phi;S|\varepsilon))] \; , \qquad \textbf{(21)}$$

where $H_\phi(\Phi;S|\varepsilon)$ is defined by (18) and (19).

Let the value of Φ that maximizes the right hand side of (19) be denoted

$$\hat{\Phi}(S) \quad . \qquad \textbf{(22)}$$

For period t, the fisheries manager selects the fee

$$\hat{\Phi}(S_{t-1}) \qquad \textbf{(23)}$$

to be charged per unit of fish landed in period t. Thereafter, self-interested decentralized profit maximization by the fishermen determines the level of fishing effort during the period.

Compared with the relatively-more-straightforward quota system, fishery regulation with a landing fee seems somewhat indirect and difficult to explain, or, for that matter, may even be difficult to understand. It is no wonder, perhaps, that the direct quota system is typically preferred to the indirect fee system in most of the fisheries economics literature. As we shall see, however, exactly the opposite conclusion is warranted, at least for the case treated here of pure ecological uncertainty.

The "As-If-Omniscient" First-Best Fishery Policy

At this point we are almost ready to compare the relative performance of landing fees with harvest quotas under ecological uncertainty. But first we briefly make here a seeming digression to characterize, as a benchmark reference point, the hypothetical "perfect-information" solution of the stochastic fishery problem when it is known beforehand what will be the environment one period ahead.

In this section of the paper, but *only* in this section, we assume that an *as-if-omniscient* fishery manager can "see" *before setting the regulatory-instrument values* the complete resolution of the ecological uncertainty of the next fishing period. In all other sections of the paper we make the more realistic assumption that only the fishermen themselves can observe the realization of ecological uncertainty, as it unfolds around them in the ocean, and while they are reacting to the quasi-fixed regulatory instruments that have already been imposed upon them. More technically, we are assuming in this section of the paper, *but only in this section of the paper*, the following highly unrealistic timing sequence concerning what the regulators know.

In this section of the paper, it is assumed that the omniscient fishery manager, operating in time on the thin border line between the end of period $t-1$ and the beginning of period *t*, can observe not only the variable S_{t-1} at the end of period $t-1$, but here (in this section of the paper only) *knows beforehand also the yet-to-be-realized value of* $\boldsymbol{\varepsilon}_t$. The omniscient fishery manager then conditions regulations on *both S and* $\boldsymbol{\varepsilon}$, with corresponding dynamic programming problem

$$V^*(S;\varepsilon) \;=\; \max_{Q\geq 0}\ \{ \int_{F(S|\varepsilon)-Q}^{F(S|\varepsilon)} \pi(x)\ dx \;+\; \alpha\ \tilde{\mathbf{E}}[(V^*((F(S|\varepsilon)-Q);\tilde{\varepsilon})]\}\ , \qquad \textbf{(24)}$$

where the operator notation $\tilde{\mathbf{E}}[\bullet]$ stands for the expected value of whatever is contained within the square brackets, being taken over all relevant realizations of the dummy random variable $\tilde{\boldsymbol{\varepsilon}}$.

Let the solution of the problem on the right hand side of (24) be denoted

$$Q^*(S;\varepsilon)\quad . \qquad \textbf{(25)}$$

Now, at last, we are ready for the main result of the paper.

The Basic Result

Define the *immediate-harvest-value* function

$$\Pi(Y) \equiv \int_A^Y \pi(x)\ dx \quad , \tag{26}$$

where A is an arbitrarily-fixed lower bound, defined, for example, by the free-access zero-profit condition

$$\pi(A) = 0 \quad . \tag{27}$$

Next, assume that for all possible states of the environment the immediate-harvest-value function always shows non-increasing-returns to escapement levels. This is the analogue in the fisheries context of assuming a reduced-form convex production structure.

Assumption: *For all possible values of* ε*, the function*

$$\Pi(F(S|\varepsilon)) \tag{28}$$

is concave in S.

The following proposition shows that, with ecological uncertainty, the optimal landing fee attains the "as-if-omniscient" first-best fishery policy, and therefore is always superior to a *TAC* quota system.

Theorem: *Under the assumptions of the model, for all possible values of* ε *and of S,*

$$H_\phi(\hat{\Phi}(S);S|\varepsilon) = Q^*(S;\varepsilon) \quad , \tag{29}$$

and for all S (in every case except the singular deterministic case)

$$V_q(S) < V_\phi(S) \ . \tag{30}$$

Proof: Define by induction for each positive integer n the function

$$V_n(S|\varepsilon) \;=\; \underset{X \le F(S|\varepsilon)}{maximum} \;\{ \int_X^{F(S|\varepsilon)} \pi(x)\; dx \;+\; \alpha \underset{\varepsilon}{\mathrm{E}} \,[V_{n-1}(X|\varepsilon)]\} \;, \tag{31}$$

where $V_0(S|\varepsilon) \equiv 0$. Making the substitution $X = F(S|\varepsilon) - Q$, it is readily confirmed by inspection that if the function sequence $\{V_n(S|\varepsilon)\}$ defined by (31) converges, then the limiting function must obey equation (24).

Next, define the function

$$W_n(X) \;=\; -\Pi(X) \;+\; \alpha \underset{\varepsilon}{\mathrm{E}} \,[V_{n-1}(X|\varepsilon)] \;. \tag{32}$$

Using definitions (26) and (32), rewrite equation (31) as

$$V_n(S|\varepsilon) \;=\; \underset{X \le F(S|\varepsilon)}{maximum} \;\{\Pi(F(S|\varepsilon)) \;+\; W_n(X)\} \;. \tag{33}$$

We now prove by induction that for all *n* (and for all possible ε), the function $V_n(S|\varepsilon)$ is concave in *S*. It is clearly true for $n=0$, because $V_0(S|\varepsilon) \equiv 0$. Suppose the concavity assumption is true for $n-1$. It then follows, making use of (7) and the fact that a convex combination of concave functions is concave, that $W_n(X)$ defined by (32) is concave in *X*.

For any possible value of ε, choose any S_1 and S_2. Let the corresponding values of *X* that maximize the right hand side of expression (33) be denoted, respectively, X_1 and X_2. Thus,

$$V_n(S_1|\varepsilon) \;=\; \Pi(F(S_1|\varepsilon)) \;+\; W_n(X_1) \tag{34}$$

and

$$V_n(S_2|\varepsilon) \;=\; \Pi(F(S_2|\varepsilon)) \;+\; W_n(X_2) \;. \tag{35}$$

Also, from feasibility, $X_1 \le F(S_1|\varepsilon)$ and $X_2 \le F(S_2|\varepsilon)$, implying from the concavity assumption (3) that

$$\lambda X_1 + (1-\lambda)X_2 \;\le\; F(\lambda S_1 + (1-\lambda)S_2|\varepsilon) \tag{36}$$

for $0 \le \lambda \le 1$. Thus, the policy $X \equiv \lambda X_1 + (1-\lambda)X_2$ is *feasible* for $S \equiv \lambda S_1 + (1-\lambda)S_2$. Therefore, from the maximum part of the equation (31), it follows that,

$$V_n(\lambda S_1 + (1-\lambda)S_2|\varepsilon) \;\ge\; \Pi(F(\lambda S_1 + (1-\lambda)S_2)|\varepsilon)) \;+\; W_n(\lambda X_1 + (1-\lambda)X_2) \;\; . \tag{37}$$

From concavity of (28) and (32), it follows directly that

$$\Pi(F(\lambda S_1 + (1-\lambda)S_2|\varepsilon)) \;\ge\; \lambda\Pi(F(S_1|\varepsilon)) \;+\; (1-\lambda)\Pi(F(S_2|\varepsilon)) \tag{38}$$

and

$$W_n(\lambda X_1 + (1-\lambda)X_2) \;\ge\; \lambda W_n(X_1) \;+\; (1-\lambda)W_n(X_2) \;\; . \tag{39}$$

Combining (38) and (39) with (37), and rearranging terms in the latter expression, we have

$$V_n(\lambda S_1 + (1-\lambda)S_2|\varepsilon) \;\ge\; \lambda[\Pi(F(S_1|\varepsilon)) + W_n(X_1)] \;+\; (1-\lambda)[\Pi(F(S_2|\varepsilon)) + W_n(X_2)] \;\; . \tag{40}$$

Finally, substituting (34) and (35) into (40) yields the desired induction conclusion

$$V_n(\lambda S_1 + (1-\lambda)S_2|\varepsilon) \;\ge\; \lambda V_n(S_1|\varepsilon) \;+\; (1-\lambda)V_n(S_2|\varepsilon) \;\; . \tag{41}$$

From the general theory of dynamic programming, we know that the successive approximation (31) converges to the unique solution of (24). (Any standard mathematical textbook on dynamic programming will contain this contraction-mapping result.) The concavity condition (41) then proves that the function

$$V^*(S;\varepsilon) \quad = \quad \lim_{n\to\infty} V_n(S|\varepsilon) \quad , \tag{42}$$

which uniquely satisfies (24), is concave in S. In its turn, this implies that the function

$$W^*(X) \quad \equiv \quad -\Pi(X) \quad + \quad \alpha \mathop{\mathrm{E}}_{\varepsilon} [V^*(X|\varepsilon)] \quad . \tag{43}$$

is concave in X.

Thus, we have proved that $W^*(X)$ is a concave function defined on the extended real line $[0,\infty)$. Let the maximum value of $W^*(X)$ be attained at the point $X{=}S^*$, meaning that for all values of $X\geq 0$,

$$W^*(X) \;\leq\; W^*(S^*) \quad . \tag{44}$$

Now rewrite (24) in the equivalent form

$$V^*(S;\varepsilon) \quad = \quad \mathop{maximum}_{X\leq F(S|\varepsilon)} \;\{\Pi(F(S|\varepsilon)) \;+\; W^*(X)\} \quad . \tag{45}$$

The argmax solution of the right hand side of (45) is just the function

$$X^*(S;\varepsilon) \;=\; \min\{F(S|\epsilon),\; S^*\} \quad . \tag{46}$$

In other words, equation (46) means that the "as-if-omniscient" optimal fisheries policy is a most-rapid-approach to the constant escapement level S^* defined by (44). The remainder of the proof consists of confirming from the harvest reaction functions (18) and (19) that a most-rapid-approach to the "as-if-omniscient" escapement level S^* is automatically induced from *any possible* values of S and ε by imposing the constant landing fee

$$\Phi^* \equiv \pi(S^*) \quad , \tag{47}$$

while it is impossible for any quota system to attain this same "as-if-omniscient" first-best solution unless $\boldsymbol{\varepsilon}$ essentially has a degenerate distribution with all probability mass effectively concentrated at one singular point. ■

Discussion

The result that a landing fee is able to attain the "as-if-omniscient" first-best fishery policy seems so striking that it cries out for elucidation. How does the landing fee "know" before period t what will be the realization of the state-of-the-environment random variable $\boldsymbol{\varepsilon}_t$?

The answer here is yet another example of the powerful general theme of economics that a "price signal" can compress into a simple reduced form all relevant information for inducing correct decentralized decisions. The point is that by using the instrument of a landing fee, the fishery manager obviates or shunts aside the need to know the actual recruitment of fish stocks.

After all, the only use to the fishery manager of knowing recruitment in this model is to be able to set accurately the harvesting quota that will attain the desired escapement level. The knowledge of recruitment stocks and the setting of harvesting quotas are just the two *means* to the single reduced-form *end* of hitting accurately an escapement target. The "as-if-omniscient" first-best policy in this model is a most rapid approach to the (constant) escapement level S^* defined by (44). By casting the regulatory problem into the mold of the dual price side, in the form of an optimal landing fee Φ^* defined by (47), the fishery manager can automatically induce the fishermen to attain most rapidly the escapement level S^* *irrespective of the actual recruitment level*.

Such economizing on information is the hallmark of a price system. All that the current fishermen need to know, really, is the expected marginal efficiency cost to future fishing of their landing one more current fish – i.e., the optimal landing fee Φ^*. Decentralized self-interested profit maximization will take care of all the rest.

To intuit more vividly why prices systematically outperform quantities here, imagine that fishing is done by a kind of floating "suction machine," whose operation is analogous to that of a vacuum cleaner. In this analogy, there are two natural candidates for regulation: either (1) the power (i.e., effort) setting at which the floating vacuum cleaner is operated; or (2) the number of fish actually "siphoned up" by the machine.

A harvest quota corresponds to a restriction on how many fish can be "siphoned up" by the machine. When recruitment is higher than anticipated and fish are relatively abundant, the fishermen operators will most profitably attain their quotas by running their suction machines at lower power settings, thereby saving on power (i.e., effort) costs. But if fish recruitment levels are lower than was expected by the managers, and fish are unexpectedly relatively hard to find or catch, then the profit-maximizing operators will attempt to meet their quotas by revving the suction machines up to higher power settings, thereby drawing down fish escapement stocks to undesirably low levels. It is not control of the harvest that is socially desirable *per se*, but control of the escapement. Setting the harvest quota gives the fisheries regulators the *sensation* of being in direct control of an important quantity, but this is essentially an illusion because they are unable to control the really important quantity, which is escapement.

I think the model is trying to tell us that with ecological uncertainty in fish recruitment, it is a better policy to effectively set an upper limit on the power at which the fish vacuum cleaners may be run than to attempt to regulate directly the total volume of fish that the suction machines are allowed to ingest. In the presence of such basic stock uncertainty, it is far better to control marginal fishing *effort*, which is what the price/fee accomplishes indirectly, than to control *directly* the quantity/harvest level. The fact that fish stocks are highly variable is *not*, in and of itself, a valid argument for the preferment of harvest quotas to landing fees. Just exactly the opposite is true. Pure ecological uncertainty, in and of itself, constitutes a powerful generic argument for the superiority of landing fees, as a regulatory instrument, over harvest quotas.

Of course, such conclusions come only from a model. In this model there is just one source of variability – the fluctuations in fish stocks, which we are here calling "ecological uncertainty." What happens to these conclusions where there are also present other sources of uncertainty, namely "economic uncertainty" about the $\pi(x)$ profit function? Which regulatory instrument – landing fee or harvest quota – is then superior?

A formal analysis of exactly how "ecological uncertainty" and "economic uncertainty" interact to determine the optimal choice of fishery regulatory instruments involves a complicated tradeoff that is properly the subject of another paper. Nevertheless, the outlines of a tentative answer seem intuitively clear and can be indicated roughly here. As this paper has shown, pure ecological uncertainty unambiguously favors fees over quotas. By contrast, pure economic uncertainty is a typical "prices-vs-quantities-type" mixed situation where the answer can go either way depending, among other things, on the relative slope of the marginal profit function. A relatively flat marginal profit function by itself tends to favor quotas. In order to end up favoring harvesting quotas to landing fees overall, then, it should be the case *both* that ecological uncertainty is relatively less significant than economic uncertainty, *and* that the marginal profit function $\pi(x)$ is relatively unresponsive to fish stock levels x.

It is a useful task for future theoretical research to develop rigorously the mathematical formulas that may show exactly how the comparative advantage of landing fees over harvesting quotas depends quantitatively upon the various relevant specific features of the problem – including economic and ecological uncertainty. And it will be a useful applied problem of fisheries economics to attempt to categorize, however crudely, which types of fisheries are more likely to be better managed by landing fees and which types of fisheries are more likely to be better regulated by harvest quotas. The current paper may then perhaps be seen as a first tentative step in the direction of such a research program.

Conclusion

The implicit point of departure for this paper has been the familiar prototype fisheries model where a fictitious sole owner harvests a fish population to maximize present discounted profits. In the deterministic case, it does not matter whether the fishing externality is corrected by a market-based quantity instrument, in the form of a total harvest quota, or a market-based price instrument, in the form of a landing fee. What happens to this theoretical equivalence, though, when there is uncertainty?

The most significant form of uncertainty present in the fishing industry is usually held to be the "ecological" uncertainty associated with a stock-recruitment relation that is inherently stochastic and whose realization cannot be observed by the fishery managers at the time when they issue regulations. It seems fair to say that the conventional wisdom in fisheries economics favors harvest quotas over landing fees, often, or even typically, citing as justification the inherently-unknowable randomness of this very stock-recruitment relation. The basic result of the model of this paper shows that such logic is exactly backwards. The primacy of ecological uncertainty tends to make a generic argument in favor of landing fees over harvest quotas – rather than the other way around.

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