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The Efficiency Gains from Fully Delineating Rights in an ITQ Fishery

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Abstract

ITQ regulation relies on a decentralized market mechanism and a single price to allocate access to a stock of fish. The resulting allocation will not be fully efficient if the stock being allocated is heterogeneous or if there are potential gains from centralized coordination of harvesting effort. If stocks are heterogeneous in their density, location, or unit value during the season, harvesters governed by an ITQ policy will not be indifferent to when or where they exercise their quotas. Stocks that are relatively dense and/or close to port will be preferred to those less dense or more remote. Because an ITQ policy assigns the same opportunity cost for each unit harvested, individual harvesters have an incentive to compete for higher valued units and such competition may dissipate part of the fishery's potential rent. A similar phenomenon arises when stock densities vary in an unknown way over space or time, so harvesters must engage in costly search. Individual harvesters governed by an ITQ policy have no incentive to share information on stock locations, which can lead to redundant search effort. We demonstrate that both sources of inefficiency can be eliminated either by defining ITQ rights more precisely or by an agreement among harvesters to coordinate their effort. We develop models that illustrate these effects and identify the factors that determine their likely size. Anecdotal evidence on practices adopted by fishery cooperatives is presented to illustrate the practical relevance of the issues we raise.

1 Introduction

The *race to fish* is an allegory for rent-seeking economic behavior by fishermen, such as overinvesting in physical capital to out-race one's opponents

in the quest for high-valued harvest. It is often claimed that by assigning secure individual rights to particular units of harvest, an individual transferable quota (ITQ) will end the race to fish which plagues open access fisheries. Boyce (1992) has argued that the market price for ITQs will not fully reflect production externalities, and hence fishermen will not internalize these effects in their effort decisions. Thus, he argues that ITQs will not fully eliminate cost-increasing behavior when stock and/or congestion externalities are present and implicitly indicates that centralized coordination could lead to efficiency gains.

We advance this argument along two dimensions. First, we argue that even with homogeneous fishermen, no stock externalities, and no congestion externalities, property rights assigned to harvest (ITQs) may not secure all rents in a fishery, though they are unabiguously superior to an open access situation. The outcome, we argue, depends on whether the stock in question is composed of economically homogeneous, or heterogeneous, components. We find that economically heterogeneous fisheries managed with ITQs can generally benefit from a more refined assignment of property rights or from a degree of centralized coordination that ITQ policies do not achieve. We then describe the magnitude of that benefit as a function of bioeconomic characteristics and offer a simple rule-of-thumb indicating whether the benefits from such ITQ refinements are likely to be large or small. Second, we note that uncertainty over the locations of stocks can lead to inefficient search in an ITQ fishery. Once again, this inefficiency can be eliminated either by delineating harvest rights more precisely or by coordinating effort. We formulate a simple search model to illustrate these gains.[1]

Other researchers have addressed similar questions. Boyce (1992) provides an elegant analysis of within-season effort decisions, comparing the social planner's optimum to the outcome with ITQ regulation in a case where each firm's effort interferes with others in the industry. The interference caused by one firm's fishing effort may be of two sorts: (i) it may congest the fishing grounds, or (ii) the firm's catch may raise the catch costs of others by reducing the stock. Boyce finds that an ITQ policy, which imposes a scarcity price on each unit of the stock, necessarily improves on open access. He concludes that it does not cause firms to internalize the costs caused by their mutual interference, however, and thus is not fully efficient when congestion is present. This point was also noted by Clark (1980). Clark and

[1]We do not address the costs of reaching agreement on coordinated actions. On this question, see Johnson and Libecap (1982)

Boyce disagree over whether an ITQ policy will be fully efficient at allocating within-season effort when congestion effects are absent, but catch costs still depend on stock. Wilson (1990) addresses the phenomenon of search in fisheries where the movements of stocks are generally unknown. He examines incentives for the creation, sharing and distortion of knowledge on stock locations in rule of capture fisheries and points out the obvious tendency toward under-provision of knowledge in the absence of some coordinating institution. He also describes the circumstances under which precise, timely information on stock locations will be particularly valuable. He does not link his analysis to specific management regimes, however.

A few preliminary remarks on the way we characterize competition for heterogeneous stocks are in order. The context for our analysis is a static, one-shot game. Each harvester is assigned a number of ITQ units and chooses how to allocate this quota to various fishing dates and portions of the stock. We introduce heterogeneity by partitioning the stock into sub-stocks, each of which contains members that have identical economic value. Those who are *first* to fish a particular sub-stock experience higher unit profits than those who come later, and the resulting competition to be first tends to exhaust the inframarginal rents on superior sub-stocks. We focus on symmetric Nash equilibria, which is natural since we assume all harvesters are equally efficient and receive identical quota allocations. Because harvesters are identical there is no trade in harvest quotas. (Quota allocations still have a positive value, however.) Unit values for sub-stocks are assumed to vary over time within a single season. This would arise if sub-stocks migrate over the fishing grounds causing variations in harvest costs, if sub-stocks become more or less dense (easy to find) at different times during the fishing season, if the unit value of unharvested individuals grows during the season, e.g., due to seasonal variations in quality, or if the price of harvested fish varies over the season. Within-season discounting is ignored for analytical convenience.

2 Competition for a heterogeneous stock

A stock of fish is composed of N sub-stocks, indexed $n = 1, 2, ..., N$, each of which contains 1 unit of stock before fishing begins. While the stock is biologically homogeneous, different members of the stock may have different economic value depending on their location and other factors. We define a sub-stock as a collection of individual fish that all return the same profit from harvest. A total of J fishermen compete in harvest. The exogenously

determined total allowable catch (TAC) is k, where $k < N$. Thus k is the maximum number of sub-stocks that can be caught in full, given the TAC.

Harvest profitability may vary across sub-stocks at a point in time, and across time for a given sub-stock. For sub-stock n, the profit from harvesting a unit on date s when the sub-stock has not been previously fished is $V_n(s)$. There is a penalty for not being the first to harvest any sub-stock, however. This penalty could arise from lower stock densities, and hence higher costs, for those who do not deploy their gear first. Alternatively, a late arriver might find that a given sub-stock has been entirely harvested by others, forcing the individual to divert effort elsewhere. Marginal profit from harvesting sub-stock n at date s', when others fished the same stock at an earlier date s is

$$V_n(s) - L_n(s' - s) \tag{1}$$

where L_n is continuous and $L_n(s' - s) > 0$ for $s' > s$ and $L_n(s' - s) = 0$ for $s' \leq s$. Harvest dates are constrained by the length of the fishing season, τ, hence $s \in [0, \tau]$. We adopt the following assumptions:

Assumption 1. *All agents have full, symmetric information; there is no uncertainty*

Assumption 2. *$V_n(s)$ is continuous over the interval $[0, \tau]$.*

Assumption 3. *$V_n(s)$ attains a positive maximum at the unique date $s_n^* \in (0, \tau]$ and these maxima are different for each sub-stock.*

Let the indexing for n be chosen so that sub-stocks are ordered in decreasing order of the maximal profit attainable from harvesting them, i.e., $V_1(s_1^*) \geq V_2(s_2^*) \geq ... \geq V_N(s_N^*)$, where s_n^* is defined in Assumption 3. We require one final assumption guaranteeing that it is not optimal to immediately harvest all sub-stocks at the opening of the season and that the k^{th} sub-stock is strictly more profitable (at its maximum) than the $k + 1^{st}$.

Assumption 4. *$V_{n'}(0) < V_k(s_k^*) > V_{k+1}(s_{k+1}^*)$ for all $n' < k$.*

2.1 Case 1: Full assignment of property rights

We characterize a full assignment of property rights as an allocation in which a single maximizing agent is given the right to harvest a single sub-stock. If $J \leq k$ each fisherman is assigned the exclusive right to harvest all of one or more sub-stocks. If $J > k$, the J fishermen are combined into k competitive firms and each firm is assigned the exclusive right to harvest one sub-stock. If firm j' is assigned the right to harvest sub-stock n', its strategy variable is $t_{j'n'}$, the date on which it harvests its assigned stock.

Proposition 1. *A profile of strategies in which the k firms or J fishermen harvest each sub-stock entirely at date* $s_n^* = argmax\{V_n(s)\}$ *is a Nash equilibrium. That is, firm j's best response is the strategy* $t_{jn} = s_n^*$ *for the stock it harvests. If the regulator assigns quota allocations only for stocks* $n = 1, ..., k$*, this Nash equilibrium maximizes the sum of profits (rents) from harvesting a TAC equal to k.*

Proof. Suppose firm j' is allocated the right to harvest sub-stock n'. The profit firm j' realizes from its choice of $t_{j'n'}$ is independent of the choices of other firms, since j' owns the entire allocation for this sub-stock. Therefore, whatever choices the other firms may make, j' can do no better than to harvest n' at date $s_{n'}^*$. □

When each firm plays a best response, and assuming the regulator has assigned quotas only for the first k stocks, the result is efficient in the sense of Proposition 1.

This full assignment outcome depends on each firm receiving an allocation for a single, economically homogeneous stock and on the regulator's choice of stocks $n = 1, ..., k$ as targets for harvest. If an ITQ regime does not meet these conditions the result will not be efficient, as we demonstrate next.

2.2 Case 2: Incomplete assignment of property rights

In this case each fisherman or firm has the right to catch Q fish in total, but is not assigned rights to members of specific sub-stocks. This is the sense in which property rights are incomplete. If more than 1 harvester targets the same sub-stock, those who arrive later in time are penalized according to equation 1. This penalty may be due to diminished abundance and hence higher harvest costs, or it may arise from other sources. As before we assume a TAC equal to k.

Because sub-stocks are not exclusively assigned to fishermen, the choice of which sub-stocks to harvest is now part of each fisherman's strategy. Accordingly, each fisherman announces a strategy that consists of harvest dates and quota allocations for each sub-stock. Harvester j's announcement for stock n is denoted $\{\alpha_{jn}, t_{jn}\}$, where α_{jn} denotes the quota share that j allocates to stock n and t_{jn} denotes the date at which j will harvest it. As before, harvest dates are constrained by the length of the season, hence $t_{jn} \in [0, \tau]$. Fisherman j's quota allocations to individual sub-stocks are constrained by $\sum_{n=1}^{N} \alpha_{jn} = 1$. Assumptions 1-4 continue to hold.

The profit per fish that j receives from playing strategy $\{\alpha_{jn}, t_{jn}\}$ depends on the strategies of all others. This per fish payoff is expressed as follows:

$$\Pi_{jn}\left(\{\alpha_{jn}, t_{jn}\}; \{\alpha_{j'n}, t_{j'n}\}, j' \neq j\right) =$$
$$\begin{cases} V_n(t_{jn}) & \text{if } t_{jn} \leq t_{j'n} \text{ for all } j' \neq j, n = 1, ..., N \\ V_n(t_{j'n}) - L_n(t_{jn} - t_{j'n}) & \text{if } t_{jn} > t_{j'n} \text{ for some } j' \neq j, n = 1, ..., N. \end{cases} \quad (2)$$

Because $L_n(0) = 0$ and $L_n(t_{jn} - t_{j'n}) > 0$ for $t_{jn} - t_{j'n} > 0$, there is a penalty for being late to the fishing grounds for any sub-stock. Logically, the the size of the penalty j experiences for being late to sub-stock n should depend on the total catch of firms that harvest sub-stock n before j does. We choose not to examine the structure of $L_n(\cdot)$ in any detail; rather, we simply assume that the preceding condition holds for any positive catch by other firms.

Equation (2) gives per fish profits from sub-stock $n = 1, ..., N$ as a function of the timing of fishing effort. In cases where the sum of announced catches for sub-stock n is no greater than 1, which is the size of sub-stock n, each firm achieves its announced share and profits are computed by multiplying the α_{jn} by profit per fish. In cases where the announced catches of individual firms exceed 1, the announced catches of all firms are scaled down proportionately to equal the sub-stock's size and profits are again found by multiplying catch by profit per fish. In such cases the harvesters whose quotas were scaled down will necessarily catch fewer than Q fish over the season, so total catch will be less than the TAC and some fish will escape. This does not happen in the Nash equilibrium we examine shortly, however.

Proposition 2. *The profile of strategies that was a Nash equilibrium under full assignment of property rights is not in general a Nash equilibrium in the present context.*

Proof. In the full assignment case, suppose fisherman 1 was assigned the right to catch sub-stock 1 and fisherman 2 was assigned the right to catch sub-stock 2. From Proposition 1, firm 1 would choose date $t_{11} = s_1^*$ and firm 2 would choose $t_{22} = s_2^*$. Given our indexing convention and Assumption 3, we know $V_1(s_1^*) > V_2(s_2^*)$. Fisherman 2's best response when rights are incompletely assigned is to fish for sub-stock 1 at date $s_1^* - \epsilon$ for small ϵ. By Assumption 2, this guarantees a profit increase for fisherman 2 for ϵ suitably small. Therefore, the strategies that resulted in a Nash equilibrium under full assignment of property rights are not best responses in the present context. □

Proposition 2 points out that when stocks are heterogeneous in value fishermen will not be content to harvest all sub-stocks at dates that are efficient. Anyone harvesting a lower valued stock could gain by switching effort to a higher valued stock and harvesting earlier than is optimal. Under this incomplete assignment of fishing rights, a race to catch the 'best fish' persists. As we point out later, this phenomenon is a consequence of heterogeneity in the maximal value of sub-stocks. Absent such heterogeneity, the optimal harvest dates described in Proposition 1 still constitute a Nash equilibrium profile of strategies.

Proposition 3. *Under Assumptions 1-4, a symmetric strategy profile is a Nash equilibrium if it satisfies the following conditions:*

1. *Each fisherman announces harvest shares of Q/k $(= 1/J)$ for stocks $n = 1, ..., k$;*
2. *Each fisherman announces a harvest date of $s_k^* = argmax\{V_k(s)\}$ for sub-stock k;*
3. *Each fisherman announces the unique harvest date $\hat{s}_n = \min\left\{V_n^{-1}(V_k(s_k^*))\right\}$ for sub-stocks $n < k$.*

The Nash equilibrium described in Proposition 3 has several policy-relevant features. First, only the sub-stocks with greatest maximal profit are harvested. Second, noting that sub-stock n may attain a given level of profit on several dates, part 3 of Proposition 3 indicates that the Nash equilibrium harvest date in such cases is the earliest of these dates. Third, combining the preceding result with Assumption 4 ensures that the profit $V_n(s)$ for $n < k$ is increasing in s at the Nash equilibrium. We make use of this fact in the proof that follows. Finally, the Nash equilibrium profit earned from harvesting each sub-stock equals the maximal profit from harvesting the least profitable sub-stock, $V_k(s_k^*)$.

Proof. Assume all firms announce dates and quantities described in parts 1-3. We consider whether firm j could do better by choosing a different strategy given the play of others.

First, could j gain by announcing a positive harvest quantity and any harvest date for some sub-stock $\tilde{n} > k$? Because j's allocation is exactly exhausted in the original strategy profile, this deviation would cause an equal reduction in j's catch for some sub-stock $n \leq k$. This switch would necessarily reduce j's profit because the maximal profit j can earn from any sub-stock sub-stock $\tilde{n} > k$ is necessarily lower than the profit j can earn

from harvesting sub-stock k at date s_k^* and sub-stocks $n = 1, ..., k-1$ at dates $\hat{s}_n$. Accordingly, this deviation cannot be part of a best response.

Second, consider a deviation in j's announced date for some sub-stock $n' < k$. Announcing an earlier date would reduce j's profit per fish because $V_{n'}$ is upward sloping when condition 3 is satisfied. Announcing a later date, $t_{jn'} > \hat{s}_{n'}$, would cause a loss of $L_{n'}(t_{jn'} - \hat{s}_{n'})$ in profit per fish. Regarding sub-stock k, announcing a harvest date either earlier or later than s_k^* would cause a loss since s_k^* maximizes profit per fish. The harvest dates specified in parts 2 and 3 of Proposition 3 are therefore best responses.

Finally, given the announced dates $\hat{s}_n$ and s_k^*, can j gain by deviating from harvests of Q/k for sub-stocks $1, ..., k$? In the allocation satisfying conditions 1-3, j is earning $V_k(s_k^*)$ per fish for stocks $n = 1, ..., k$. Announcing a catch larger than Q/k for some stock $n' < k$ would require that j announce a commensurately smaller catch for some other stock. Since all stocks yield the same profit per fish this cannot yield a gain in profit, so announcing Q/k for each sub-stock harvested is a best response. □

Proposition 3 described the salient features of one Nash equilibrium in this setting, but did not rule out the possibility of other Nash equilibria. In fact, in most cases it can be shown that multiple Nash equilibria exist. However, we can show that of all the possible Nash equilibria in this problem, the one described in Proposition 3 returns maximal profit. This is a powerful result because it will ultimately allow us to place an upper bound on the fishery rents under an incomplete assignment of rights (i.e. an ITQ), and thus to place a lower bound on potential gains from fully assigning property rights in the fishery. To prove this result requires the following lemma:

Lemma 1. *A Nash equilibrium requires that all harvested sub-stocks return equal profit.*

Proof. We will proceed by contradiction. Assume a set of strategies yields a Nash equilibrium. Suppose that some sub-stock, n', returns higher profit in equilibrium than the other harvested sub-stocks. Any agent spending less than his full allocation of harvest on sub-stock n' will benefit from reallocating towards sub-stock n' at a slightly earlier time, thus ensuring his full capture of the profitable stock. Thus the assumed strategies cannot be a Nash equilibrium, and have proven the result by contradiction. □

This lemma allows us to show that while our previously described Nash equilibrium is not unique, it returns maximal profit.

Corollary 1. *Of all the possible Nash equilibria, the one characterized in Proposition 3 returns maximal profit.*

Proof. The equilibrium in Proposition 3 returns $V_k(s_k^*)$ for each harvested sub-stock. First, observe that by Lemma 1 and the fact that the total quota is k sub-stocks, there exists no Nash equilibrium that returns $> V_k(s_k^*)$ for each harvested stock. If the return was $> V_k(s_k^*)$, the full quota would not be used (because $V_k(s_k^*)$ is the maximal profit for the k^{th} sub-stock), and any individual could increase his profit by harvesting his full quota at an earlier date. Second, observe (again by Lemma 1) that any Nash equilibrium that returns $< V_k(s_k^*)$ per harvested stock would necessarily return lower aggregate rents than does the Nash equilibrium described in Proposition 3. This follows directly from the fact that in both cases the entire allocation (k sub-stocks) is harvested. □

Figure 1 illustrates an example with $N = 4$ sub-stocks, each with a different time profile of profitability and different optimal harvest date, and a TAC of $k = 3$. If rights were fully assigned, harvest of each sub-stock would take place at its respective peak, s_1^*, s_2^*, and s_3^*, yielding profits of $V_1(s_1^*)$, $V_2(s_2^*)$, and $V_3(s_3^*)$. When rights are not fully assigned, Corollary 1 shows that the rent-maximizing Nash equilibrium (see Proposition 3) implies that each sub-stock is harvested on the date when its profit equals the maximum profit from harvesting the k^{th} least profitable sub-stock. These times are given by $\hat{s}_1$, $\hat{s}_2$, and $\hat{s}_3$ respectively. The least profitable sub-stock, sub-stock 4, is left unharvested in this example.

A useful result can be established for the special case where the first k stocks each attain the same maximal profit. Importantly, the profit profiles need not be identical, nor do they need to attain their maxima on the same date. This special case is defined below:

Definition 1. *Sub-stocks* $\{1, 2, ..., k\}$ *are said to have* **equa-maximal-profit** *if* $V_1(s_1^*) = V_2(s_2^*) = ... = V_k(s_k^*)$.

Corollary 2. *Under Assumptions 1-4, the Nash equilibrium stragety profile in Proposition 3 maximizes profits from harvesting a TAC of k units if and only if sub-stocks* $\{1, 2, ..., k\}$ *have equa-maximal-profit.*

Proof. Sufficiency is a direct consequence of Proposition 3. To prove necessity, suppose the condition did not hold. By the ordering of profits, that would imply $V_1(s_1^*) > V_k(s_k^*)$. According to Proposition 3, sub-stock 1 would be harvested at time $\hat{s}_1 < s_1^*$ yielding a payoff lower than that achieved under complete property rights assignment. □

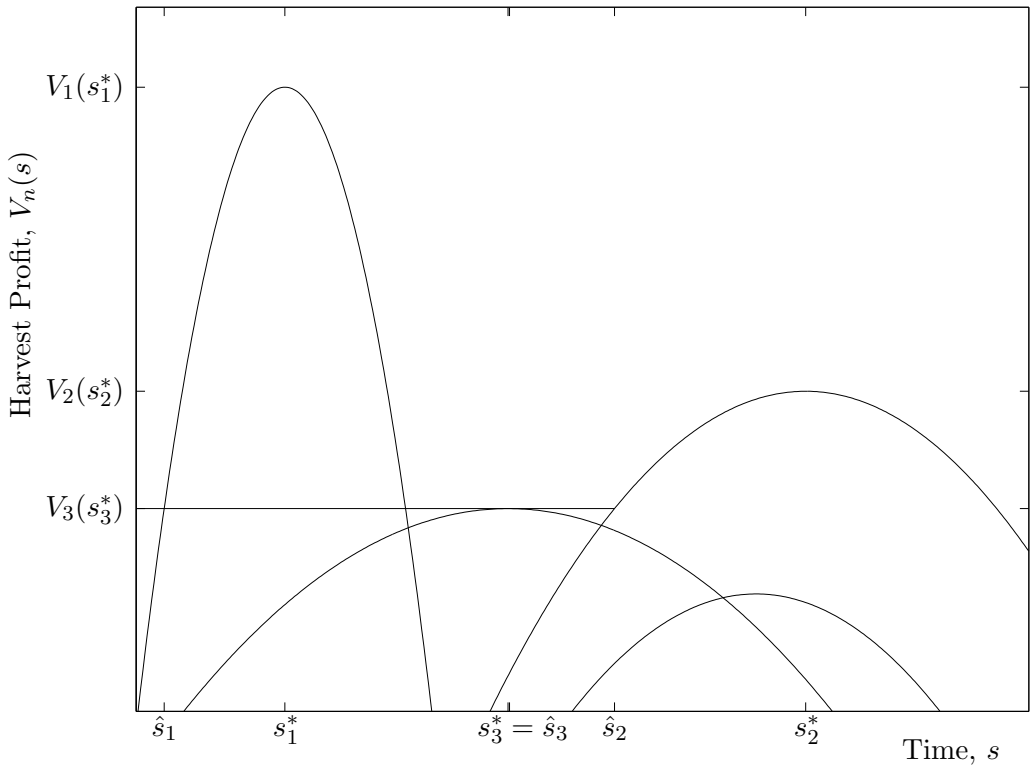

Figure 1: Incomplete assignment of harvest rights: Harvest dates and profits for $N = 4$ sub-stocks, with a TAC of $k = 3$ sub-stocks.

Proposition 3 and Corollary 2 suggest that total rent could go from a large positive value, as when the sub-stocks harvested have identical maximal profits, to near zero, as when $V_k(s_k^*) = \epsilon$ (for small ϵ), simply by changing the profit from harvesting sub-stock k. The degree of systemic rent dissipation under an incomplete assignment of rights, therefore, hinges critically upon the heterogeneity of maximal profits across sub-stocks.

What dissipates rents when property rights are imperfectly assigned is competition for the highest valued sub-stocks. In our model this competition takes the form of premature harvest, which necessarily reduces profitability. In other contexts the actions firms take may be different. For example, a firm might deploy set nets or traps around a highly profitable site even if the gear catches nothing, so long as it forestalls catch by others. Because these actions can only diminish the net value of the harvest, they are socially wasteful. A full assignment of rights, i.e., separate catch quotas for all sub-stocks that have different maximal values, would eliminate this waste.

If a complete delineation of rights is infeasible, the same end might be reached by augmenting a simple ITQ regime with a set of formal rules or informal conventions that coordinate effort in order to reduce wasteful competition. In terms of Figure 1, a set of separate season openings for each sub-stock, with sub-stock 1 opening on s_1^* and sub-stock 2 opening on s_2^*, would accomplish this.[2] If the time profiles of profitability are driven by spatial movements, as when sub-stocks migrate toward ports, rules that prohibit fishing in specified locations would accomplish the same end. In a later section we examine evidence that this kind of coordination is often attempted in actual fisheries.

3 Gains from more efficient search

The preceding section showed that rent capture in an ITQ fishery can be enhanced by defining rights precisely in cases where stocks are economically heterogeneous. There may also be efficiency gains from defining rights precisely in cases where sub-stocks are economically identical. The key requirement is that the locations of sub-stocks are uncertain, so harvesters must search to find them. Under a simple ITQ policy, harvesters will generally engage in duplicative search, which reduces rents. When this occurs,

[2]Such a rule would raise profits for the affected sub-stocks relative to other sub-stocks, creating an incentive for harvesters to find other ways to compete for them. To avoid inefficiency, the rule must also ration access to the sub-stocks that are rendered more valuable.

gains can be realized by assigning rights to harvest in specific areas, which amounts to a more complete assignment of rights.

Suppose that at the beginning of the fishing season the N sub-stocks of fish are distributed across space, where sub-stock n is located at a unique known location and each sub-stock contains 1 unit of fish. Fish within sub-stocks are assumed to congregate with one another, they do not appreciably change location during the fishing season, and no two sub-stocks occupy the same location. Fisherman j must exert one unit of effort to visit a location. If it contains a sub-stock, j catches it entirely; if the location visited is depleted, j catches nothing and must move to another location to fill his quota. The total cost of fishing is cE where c is a constant and E is the units of effort exerted in a season. What total profit will result from a TAC of $k < N$ in this spatial fishery, and how does this profit depend on information sharing? To simplify we assume that sub-stocks all have the same unit value, normalized here to 1. The industry's total profit from harvesting k sub-stocks is then:

$$\Psi(k) = k - cE \tag{3}$$

3.1 Full assignment of rights

We define a full assignment of rights in the present context as one in which each fisherman is assigned a unique set of fishing locations. With search locations assigned in this way, there will be no wasted or redundant effort because each fisherman knows whether or not a specific location assigned to him has been fished in the past and therefore knows the exact location of each remaining sub-stock in his assigned area. To obtain a total harvest of k therefore requires exactly $E^* = k$ units of effort, yielding profit

$$\Psi^*(k) = k - ck = k(1 - c) \tag{4}$$

3.2 No spatial assignment

What happens when individual fishermen are assigned rights to harvest, but these rights are not spatially explicit? A fisherman visiting a particular location does not know whether or not it has already been searched (and thus depleted) by others. If all fishermen visit several sites sequentially during the season, the first units of effort will be relatively productive because few sites will have been visited earlier. Subsequent effort becomes less efficient as sites are depleted, however, increasing (in expectation) redundant effort on patches already depleted. This result is formalized below:

Proposition 4. *Without spatial harvest assignments, the profit from an expected harvest of $k < N$ is:*

$$\hat{\Psi}(k) = k - c\left[\frac{ln(1-k/N)}{ln(1-1/N)}\right] \tag{5}$$

where N is the number of locations, each containing one sub-stock of population 1 prior to harvest.

Proof. Suppose n locations have already been visited and thus depleted. The probability that the next unit of effort deployed will visit an undepleted location is $\frac{N-n}{N}$ and the probability that it will visit a site already depleted is $\frac{n}{N}$. Let A_m be the expected number of locations depleted after m units of effort have been deployed. We can immediately write down the recursive relation:

$$A_{m+1} = \left(\frac{N-A_m}{N}\right)(A_m+1) + \left(\frac{A_m}{N}\right)A_m = A_m(1-1/N)+1. \tag{6}$$

This recursive relation can be solved, yielding the following closed-form expression for the expected harvest with E units of effort:

$$\text{Expected Harvest} = N\left(1-(1-1/N)^{E+1}\right). \tag{7}$$

Setting 7 equal to k, and solving for E gives the desired expression - the profit from an expected total harvest of k. □

Marginal harvest cost is constant (in k) with full assignment of rights, while it is increasing (in k) in the absence of spatial rights. The consequence of Proposition 4 is that increasing amounts of harvest have increasingly larger marginal costs when rights are not fully assigned, due to the redundancy of effort. This is illustrated in Figure 2, which shows total harvest cost as a function of the quota for both cases (spatial rights and no spatial rights). Comparing equation 4 to equation 5, profit is always larger under the full assignment of rights and the wedge between the two is increasing in the quota, k. Assigning rights to spatial harvest locations captures the fishery's entire rent because no effort is redundant. If spatially assigned rights are infeasible, the same end could be achieved by an industry agreement to share information on which locations have been searched.

4 Anecdotal evidence

The use of ITQ instruments to regulate fisheries has spread around the globe over the last 20 years due to dissatisfaction with earlier management regimes

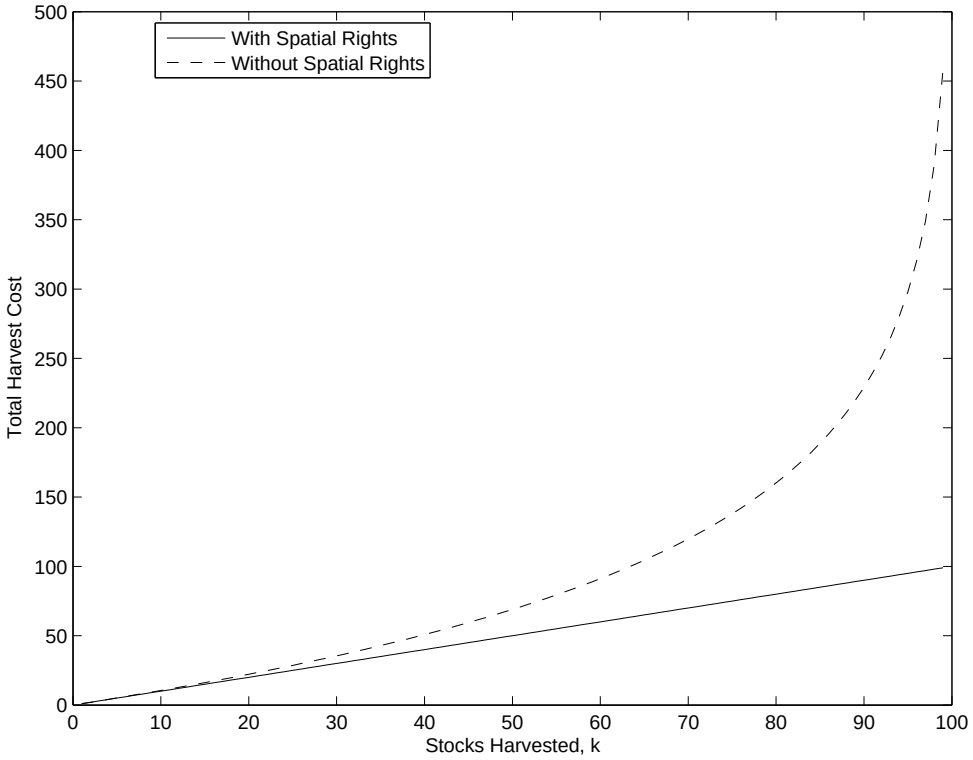

Figure 2: Harvest cost as a function of the number of sub-stocks harvested (k), for a total of $N = 100$ sub-stocks and marginal cost of effort $c = 1$. The solid line is for spatial harvest rights; the dashed line is without spatial rights.

on both economic and ecological grounds. Overall, the experience has been positive. Enhanced rents are directly evident in positive prices for quota allocations and higher unit values for final products. Indirect evidence of improved efficiency is apparent in improved catch per unit effort and longer fishing seasons. Without denying these successes, our analysis indicates that even greater rent capture may be possible if an ITQ policy adopts finer definitions of rights. We have not, however, provided any evidence that the phenomena we examine are significant in practice and we cannot point to any actual ITQ policies that formally delineate rights so precisely.

If the problems we describe are significant we would expect to see ITQ participants, or possibly regulators, taking steps to eliminate them. Examples would be formal restrictions in an ITQ fishery to allocate effort spatially or temporally, or cooperative agreements among harvesters that achieve the same ends by coordinating the effort. In this section we present some suggestive evidence on this point. The examples we report involve cooperatives, whether formally sanctioned or not, that reside within a larger fishery management structure. The larger structure typically defines rules of the game, e.g. quota or effort allocations for individuals or groups, which typically preserve some rents in the fishery. Subject to those constraints, the cooperative then serves as a coordinating body that increases the efficiency of harvest, thus increasing profits to its members. The following examples deal both with coordinating effort to avoid unproductive competition and with the issue of redundant search.

- *Chignik Salmon Cooperative.* Until 2002 the sockeye salmon harvest in the Chignik region of Alaska on the southern side of the Alaskan Peninsula was regulated by limited-entry with an annual, fishery-wide quota. The harvest technology is purse seines and there are about 100 active permits (which are transferable) in any given year. These institutions apparently preserve some rents because about 20 permits change hands in a typical year, at a price of roughly $200,000 (Alaska Board of Fisheries 2003). In 2002 a group of Chignik fishermen petitioned the Alaska Board of Fisheries to form a cooperative, into which 77 of the 100 permit holders elected. The remaining 23 fishermen maintained their independent status. The Board of Fisheries divided the total quota between these two groups, 69% to the coop and 31% to the independent holders, and the two groups fished separate openings (Knapp and Hill 2003). The cooperative structured its harvest and payoffs as follows: 22 of the 77 members were paid to catch the coop's entire quota, while 55 did not fish but shared in the revenues

from catch according to a predetermined formula.[3] During its short life, the coop coordinated effort across space in a sophisticated fashion. One member of the coop was designated the fleet director and was provided real time information on stock concentrations at all locations while the harvest was taking place. This individual then directed effort over the fishing grounds to avoid opportunistic races to catch fish at privately advantageous locations or times. Late in 2002, members of both groups were surveyed. Those in the cooperative reported significant financial advantages from cooperation, from decreased harvest costs and increased product quality. Most coop members expressed an opinion found the fishing experience to be less competitive and more enjoyable.[4]

- *Geoduck Fishery of Washington State.* The Geoduck is the largest bivalve in North America with an average size of 2 pounds, and a maximum size of about 14 pounds. Different patches of Geoducks have different profitability, so an undifferentiated ITQ would not allow the full capture of rents. Partly as an attempt to mitigate this problem, the state of Washington auctions off harvest rights on a bed-by-bed basis. Property rights, therefore, are designated at a very fine spatial scale. The Department of Natural Resources selects the beds to be auctioned and provides information to participants on their respective profitabilities.

- *Fishing Cooperatives of Baja California, Mexico.* Many small, remote fishing communities on the Pacific coast of Baja California, Mexico have secured from the federal government exclusive access to harvest in particular areas of ocean. The most economically important species are small pelagic fish, lobster, and abalone. The cooperatives are responsible for drafting their own fishery management plan, as well as for monitoring and enforcement, all nested within a federal fisheries management framework. Annual quotas have been augmented with a system-wide cooperative effort. For example, the 9 cooperatives of the Vizcaino Peninsula organized into a federation (Fedecoop) to coordinate harvest and processing to increase profits. Within this cooperative, lobster harvesters share information about the locations of fish caught, reducing search costs.

[3] The formula allocated $63,000 to fishing members and $23,000 to non-fishing members.

[4] A subsequent court ruling found this arrangement to be illegal and it was subsequently banned in Alaska. The court ruled that it is illegal for a harvester to profit from a right to fish if the individual does not actually engage in fishing.

- *"Ambushi" Fishermen of Okinawa, Japan.* Stake netting ("Ambushi") fishermen in Japan have a complex community structure that provides for exclusive access to particular fishing grounds, where more senior members have secured access to the most profitable grounds. The coordination problem is solved by an elaborate system where a senior fisherman calls a meeting of all fishermen to discuss use rights, new fishing locations, and the spatial distribution of harvest (Akimichi 1984). Oral histories reveal a complex tenure system meant to internalize spatial and temporal externalities and thereby avoid cost-increasing behavior that would result without coordination (Akimichi 1984).

- *"Shiroebi" Shrimp Fishermen of Toyama Bay, Japan.* Two groups of fishermen harvest *shiroebi* (Japanese glass shrimp) from Toyama Bay under very different institutional structures (Gaspart and Seki 2003). For over 40 years one group, a cooperative, has shared both revenues and costs. Members of a second group, which was granted access to the fishery in 1992, operate independently. The two groups share access to the stock during part of the year by fishing on alternating days of the week. Both groups use the same harbor facilities, fish the same waters and harvest the same species. Members of the cooperative group share information with one another, by radio, on productive fishing locations.[5] The independent harvesters tend to conceal information from one another. The cooperative group also coordinates access among members to productive fishing spots. Controlling for differences in the experience levels of skipper and crew as well as boat size, catch per day is significantly higher for members of the cooperative group than for the other group.

- *New Zealand paua.* The *paua* (abalone) is a univalve shellfish found in the rocky coastal areas of New Zealand. Since 1986 it has been managed under New Zealand's ITQ quota management system. Since 2004 a commercial stakeholder group consisting of harvesters operating near Christchurch has collaborated on a voluntary effort to coordinate effort among harvesters. A key component of the group's harvesting plan for this region is a policy of managing effort spatially, in order

[5]The cooperative group cooperates in other ways as well, by sharing expertise, searching for lost equipment and jointly investigating new fishing methods (Lynham 2006). According to Gaspart and Seki (2003), the cooperative *shiroebi* fishermen escape the free-rider problem one might expect to accompany their financial sharing arrangement because all members place great value on the prestige that comes with being a highly productive harvester.

> to direct effort away from certain highly accessible areas that tend to be over fished and toward less heavily exploited areas. The group also cooperates on sharing information on diving conditions and stocks, on efforts to reseed depleted grounds, and on controlling poaching. In addition, this group has proposed a diver accreditation plan, indended in part to reduce incidental harvesting mortality, and has implemented voluntary size limits in certain areas.[6]

We have also found less detailed evidence for the potential gains from cooperation from descriptions of individual fisheries. Wilen's (2002) account of experience in the Bering Sea pollock fishery after the formation of cooperatives in 1998 points to the presence of potentially important heterogeneity. The roe content of female pollock, and hence their unit value, varies over time during the season and even varies according to position within a migrating mass of fish. Our analysis suggests that a simple ITQ policy would not fully capture the rents from harvesting this species, whereas an agreement to coordinate fishing dates and locations among fishermen might.

Schalger, et al (1994) report on the role that cooperative organizations play around the world in managing fisheries. They report that rules limiting competition for the best fishing spots, e.g., by specifying a strict order in which an area can be fished or time slots during which specific individuals are allowed to use a given spot, are among the most common kinds of agreements reached. Rules governing the size of fish taken and periods during the year when fish can be taken are also common. Hannesson (1988) describes assignment rules in Turkish fisheries that limit competition for use of the best fishing grounds. More generally, he notes that spatial rules apparently serve to mitigate spatial competition and to ration access to spots where fish are easily accessible due to migratory patterns. A policy that simply assigns rights to harvest undifferentiated portions of the stock, e.g., tons of biomass, cannot accomplish the coordination evident in these rules.

Finally, there is extensive anthropological evidence on information sharing among groups of fishermen. Gatewood (1984) reports that small groups of purse seine skippers in inland salmon fisheries in southeast Alaska often meet to negotiate sharing information on stock locations. Each participant searches an agreed upon area a day or two before the opening. The afternoon before before the opening, they meet again to share information. Such groups are often based on kinship ties; members must be relied on to provide honest information and not to leak information to outsiders. These

[6] See http://www.seafood.co.nz/doclibrary/industryorgs/paua.

cooperative efforts are particularly valuable because salmon movements are unpredictable in the short run and only up to the minute information is valuable before openings.

5 Conclusions

Our central message echoes a conclusion from Wilen (2002), that the rents fisheries can generate are complex and their levels are determined by interactions among fishermen along several dimensions. The seminal open access model of Gordon (1954) seemed to suggest, incorrectly, that full rent capture could be achieved by limiting fishing 'effort'. Shifting attention toward pricing the unowned biomass, as with ITQs, has brought enormous gains. As we argue here, however, the biomass itself may be complex and multidimensional, and its economic value may vary across space and time. When this is the case, no single scarcity price or simple assignment of undifferentiated rights to harvest can capture all the rent the resource is capable of generating. Any single price will leave room for individual agents to compete to harvest stocks under the most advantageous circumstances. Accordingly, when a single price policy such as an ITQ is used to manage a multidimensional resource, there will be opportunities to improve on the resulting allocation by adapting the policy to recognize resource heterogeneity. Our analysis suggests that such improvements may come from making more precise delineations of harvest rights or from coordinating effort to avoid wasteful competition and duplication.

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