Schools of Fishermen:

A Theory of Information Sharing in Spatial Search

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I. Introduction

> *"I was off the coast of Colombia where we were seeing good signs, the water temperature was right, and it was the crew's general impression that we were in a good 'area' when our skipper heard over the radio that one boat had made a fairly good set some 500 miles to the north. To the surprise of the crew we immediately headed north at full speed … We arrived a day-and-a-half later to find that only one boat had made only one good set, and we were forced to begin a new search in our new – and as it turned out, less desirable – location. … Actions like this are not uncommon."*[1]

Fishermen who compete for a resource in an open access setting generally do not share information amongst each other about where stocks are located. On the other hand, in fisheries where there are established property rights or fishing cooperatives, fishermen tend to share information with each other. The failure to share information when agents have to make decisions under uncertainty may lead to informational externalities referred to in the economics literature as "informational cascades" (Bikchandani *et al*., 1992) or "herd behavior" (Banerjee, 1992). Similar theory and evidence exists in the ecology literature (see Stamps, 1988; Kiester and Slatkin, 1974; Pomiankowski, 1990). Previous work in developing spatial models of fishermen search and behavior has generally ignored the effect that sharing information about where stocks are located can have. Mangel and Clark (1983) compare a competitive fishing fleet with a cooperative fishing fleet but assume that information on total catch, which

[1] Orbach (1977) p78-79.

fishermen Bayesian update on, is identical in both the competitive and cooperative simulations. Sanchirico and Wilen (1999, 2001) do not compare open access with a property rights setting but implicitly assume that agents in an open access setting are perfectly aware of the stock levels at every location in the fishery.

That information sharing and the theory of informational cascades has received little attention from natural resource economists is surprising given that many natural resources are extracted from spatially discrete locations by competing agents under conditions of uncertainty.[2] In this paper we demonstrate how information sharing, or a lack thereof, alters common predictions about how property rights affect the extraction of an open access resource. In particular, we stress how changes in institutions alter the incentives to share information; these alterations may lead to outcomes that were never the original intention of the institutional changes.

The paper is organized as follows. Sections II and III describe the specifics of the model and explain the importance of informational cascades when fishermen do not share spatial information. We define a new parameter, information-dependent catchability, which captures the degree to which information sharing improves the efficiency of spatial search. Section IV nests the information-sharing model within a standard Gordon-Schaefer model. We derive the

[2] One notable exception is an empirical study of deforestation in Costa Rica by Robalino and Pfaff (2005).

conditions under which closing access to a fishery would have such a drastic impact on the incentives to share information (and hence, the efficiency of search) that total effort in the fishery will be unaffected by restricting access. We derive the equivalent conditions for steady state harvest and stock levels. We make an important distinction between Property Rights Rents and Information Sharing Rents (economic rents that can be attributed solely to changes in information-sharing) before highlighting how a fishery manager that ignores the impact of information sharing will always set quotas incorrectly. The ideal field observations to test the predictions of the theory would consist of an information-sharing fleet and a non-information-sharing fleet fishing in the same fishery, under identical environmental conditions with the same gear type. Surprisingly, such a fishery exists. Section V describes the *shiroebi* shrimp fishery in Shinminato, Japan and how it provides a perfect natural experiment for demonstrating the effect that information sharing can have on a fishery. The fishery is harvested by two groups: one group exchanges information about stock locations by radio whilst another group actively takes measures to conceal information from each other about favorable fishing spots. In terms of their fishing effectiveness, information-sharers tend to catch more than non-sharers. There appears to be strong field evidence in support of the existence of Information Sharing Rents.

II. The Importance of Information Sharing

A. A Simple Spatial Model

For the sake of exposition, let us start our analysis with a relatively simple setting. There is a valuable resource that can be extracted from two locations: the *known* location and the *unknown* location. The payoff to extracting from the known location is known by all fishermen and is equal to 1. The payoff to extracting from the unknown location is uncertain: if the state of the world is *Good*, then the payoff is 2 but if the state of the world is *Bad*, then the payoff is zero. The state of the world is fixed. All fishermen start with the same prior belief that each payoff is equally likely. Consequently, all fishermen start out indifferent between the two locations.

Each fisherman receives a conditionally independent and identically distributed signal about the status of the unknown location. Signals can take two forms: "Good" or "Bad". A signal of "Good" is observed with probability $p>1/2$ if the true payoff to the unknown location is 2 and with probability $1-p$ if the true payoff is zero. Fishermen move sequentially by deciding whether to go to the known or unknown location. The expected value of going to the unknown location is given by:

$$E(\pi) = (1-q)\cdot 0 + q\cdot 2,$$

where q is the posterior probability that the payoff to the unknown location is 2. We assume that fishermen are rational Bayesian updaters. The cost of going to either location is zero. If fishermen are indifferent between the two locations, we assume that they toss a coin to decide. The sequence of individuals is fixed and known by all fishermen.

B. Informational Cascades

One of the key phenomena driving the results of this paper is that, under certain conditions, informational cascades may occur. An informational cascade occurs in the above example when it is optimal for a fisherman to imitate the decision of the fisherman that came before him, irrespective of what his private information is telling him to do. Once caught in a cascade, the value of the information provided by a fisherman's signal is zero. To demonstrate this effect, consider a situation in which fishermen do not share their signals with other fishermen: only the actions of fishermen that have already made decisions are observed. Furthermore, assume that the state of the world is *Good* but that the first two signals are "Bad" and all subsequent signals are "Good". The first fisherman to move decides to go to the known location since his signal is "Bad". All subsequent fishermen can perfectly infer the first fisherman's private signal from his action. The second fisherman also decides to go to the known location since he has received a "Bad" signal and he infers that the first fisherman also received a "Bad" signal.

An informational cascade has now started. The third fisherman infers that the first fisherman received a "Bad" signal and he further infers that the second fisherman either received a "Bad" signal or received a "Good" signal and tossed a coin. Even though the third fisherman receives a "Good" signal, his posterior probability that the true payoff to the unknown location is zero is greater than ½.[3] The expected payoff to the unknown location is therefore less than 1 and the third fisherman copies the decision of the first and second fishermen. The fourth fisherman cannot infer anything from the decision of the third fisherman because he knows that, irrespective of the third fisherman's signal, the third fisherman will always decide to go to the known location. The fourth fisherman essentially faces the same decision as the third fisherman and decides to go to the known location; his signal is worthless in terms of the information it provides to him. The fifth fisherman faces the same decision as does the sixth and so on and so on. Thus, a failure to share information can cause all fishermen to take the "wrong" action, in a Pareto dominated sense.

Not only can informational cascades happen easily, they can occur with high frequency. For example, with p=2/3 there is a 22% chance that a cascade on the wrong action will occur after only two fishermen. With p=0.51, there is a 37% chance. This simple example should hopefully demonstrate that the difference between a group of fishermen that share information and a group that does not is a lot more complicated than simply assuming that the group that does not share information simple receives less signals to update their prior beliefs on. The realistic assumption that fishermen update their beliefs about abundance based on the spatial actions of fishermen and not the information that motivated those spatial actions can lead to extremely inefficient location choices.

[3] For example, with a p=2/3, the posterior probability would be 5/9.

III. Information-sharing and the catchability coefficient

A natural way to incorporate information sharing as a parameter in standard fisheries models is through the catchability coefficient, q. In a comprehensive review of the biological and ecological literature on catchability, Arreguín-Sánchez (1996) concludes that the catchability coefficient is determined by five factors: (i) the size of the fish, (ii) the structure of the population, (iii) differences among fishing fleets, (iv) population density and (v) the amount of fishing. It is the third factor that we are most interested in: differences in information-sharing amongst fleets will create a divergence in catchability between these fleets. In particular, we make an important distinction between the standard catchability coefficient used in most fisheries models, which we call baseline catchability, q_{base}, and information-dependent catchability, q_{info}. Baseline catchability in a fishery with spatially discrete locations is defined as:

$$H_{it} = q_{base} E_{it} X_{it}$$

$$q_{base} = \frac{H_{it}}{E_{it} X_{it}}$$

where H_{it} is harvest in location i in period t, q_{base} is baseline catchability, E_{it} is the effort exerted in location i in period t and X_{it} is the stock abundance at location i in period t. Baseline catchability can be interpreted as similar to technical catchability: upon arriving at a particular fishing ground, it is the fraction of the physical stock present at a location that a fisherman can expect to catch for each unit of effort exerted. information-dependent catchability, on the other hand, is the fraction of the entire stock in the fishery that a fleet can expect to catch based on the strength of the information that the fleet has about where stocks are located. Therefore, aggregate harvest in a fishery with m fishermen and n locations is given by:

$$\sum_{i=1}^{n} H_{it} = q_{info} \sum_{i=1}^{n} E_t \sum_{i=1}^{n} X_t \; .$$

Solving for information-dependent catchability gives:

$$q_{info} = \frac{\sum_{i=1}^{n} H_{it}}{\sum_{i=1}^{n} E_t \sum_{i=1}^{n} X_t}$$

$$q_{info} = \frac{\sum_{i=1}^{n} H_{it}}{\sum_{i=1}^{n} \sum_{j=1}^{m} E_{ijt} \sum_{i=1}^{n} X_{it}}$$

$$q_{info} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} q_{base} E_{ijt} X_{it}}{\sum_{i=1}^{n} \sum_{j=1}^{m} E_{ijt} \sum_{i=1}^{n} X_{it}}$$

Having defined information-dependent catchability, let us now examine how it differs for two fleets: one that has no information whatsoever about the location of fish (this fleet applies effort uniformly across all locations) and a second fleet that has perfect information about where stocks are located. The first fleet is similar to the fleet in a standard Gordon-Schaefer model, which assumes uniformly distributed effort. information-dependent catchability for this uniformly distributed fleet is given by:

$$q_{info}^{U} = \frac{\sum_{i=1}^{n} H_{it}}{\sum_{i=1}^{n}\sum_{j=1}^{m} E_{ijt} \sum_{i=1}^{n} X_{it}}$$

$$q_{info}^{U} = \frac{\sum_{i=1}^{n} q_{base}\left(\frac{1}{n}\sum_{j=1}^{m} E_{jt}\right) X_{it}}{\sum_{j=1}^{m} E_{jt} \sum_{i=1}^{n} X_{it}}$$

since effort is uniformly distributed.

$$q_{info}^{U} = \left(\frac{1}{n}\right) \frac{q_{base} \sum_{j=1}^{m} E_{jt} \sum_{i=1}^{n} X_{it}}{\sum_{j=1}^{m} E_{jt} \sum_{i=1}^{n} X_{it}}$$

$$q_{info}^{U} = \frac{q_{base}}{n}$$

On the other hand, when the fleet has perfect information about where stocks are located, information-dependent catchability is given by:

$$q_{info}^{PI} = \frac{\sum_{i=1}^{n} H_{it}}{\sum_{i=1}^{n}\sum_{j=1}^{m} E_{ijt} \sum_{i=1}^{n} X_{it}}$$

Define $X_{it}{}^{*}$ as the stock abundance at the location with the maximum amount of fish in period t:

$$X_{it}^{*} \geq X_{jt} \;\forall\; j \neq i \,.$$

The fleet will then direct all of its effort on this stock:

$$q_{info}^{PI} = \frac{q_{base}\left(\sum_{j=1}^{m} E_{jt}\right) X_{it}^{*}}{\sum_{j=1}^{m} E_{jt} \sum_{i=1}^{n} X_{it}}$$

$$q_{info}^{PI} = q_{base} \frac{X_{it}^{*}}{\sum_{i=1}^{n} X_{it}}$$

Therefore, the ratio of information-dependent catchability with perfect information to information-dependent catchability with no information is a function of what fraction of the total stock is congregated in one particular location and how many locations there are:

$$\frac{q_{info}^{PI}}{q_{info}^{U}} = n\frac{X_{it}^{*}}{\sum_{i=1}^{n} X_{it}}.$$

The more locations there are and the greater the population concentration in one location, the larger the divergence between q_{info} under perfect information and no information. Obviously, if fish stocks are distributed uniformly across space then information-dependent catchability will be identical under both settings. More importantly, if stocks are distributed across space in any way other than uniformly, then information-dependent catchability is greater for a perfectly informed fleet than an uninformed fleet.

As discussed earlier, a surprising number of fisheries economics models adopt one of the above two assumptions: either fishermen apply effort randomly across space or fishermen have perfect information about where stocks are located. We now present the results of some slightly more realistic simulations to demonstrate the importance of information-sharing. There are four vessels in a fleet, each one operated by a single fisherman. There are four fishing locations: the first has a population of fish equal to 100 units, the second has a population of 50, the third has a population of 25 and the final location has a population of 15. The fishermen do not know the true underlying populations at each location; they have beliefs about where stocks are located and make decisions based on those beliefs. We are interested in comparing information-dependent catchability between a fleet that shares information about stock abundance at different spatial locations and one that does not. Making comparisons of catchability in a dynamic setting with stock depletion is not an "apples to apples" comparison. After two time periods, a perfectly informed fleet and an uninformed fleet will essentially be in different fisheries since they face different stock sizes at the various locations. Therefore, we briefly assume that there is no stock depletion. The search problem now becomes one of simply finding the location with 100 units of fish. Suppose that each member of the group begins with the same prior beliefs over all four locations:

$$B(X_i) \sim N(\mu_i, \sigma^2) \text{ for } i\text{=1, 2, 3, 4.}$$

The mean of the distribution can have one of four initial values: 100, 50, 25 or 15, without replacement. If a fisherman decides to go to a site *i* and fish there, he receives a signal about the true stock abundance at this location of the form:

$$S_i = X_i + \varepsilon$$

where X_i is the true stock abundance at location *i* and $\varepsilon \sim N(0, \sigma_\varepsilon^2)$.

Upon receiving a signal about the stock abundance, the fishermen then updates his belief on abundance at that site using Bayes' theorem (De Groot, 1970):

$$B(X_i)' \sim \left(\frac{S_i\sigma^2 + \mu_i\sigma_\varepsilon^2}{\sigma^2 + \sigma_\varepsilon^2}, \frac{\sigma^2\sigma_\varepsilon^2}{\sigma^2 + \sigma_\varepsilon^2} \right)$$

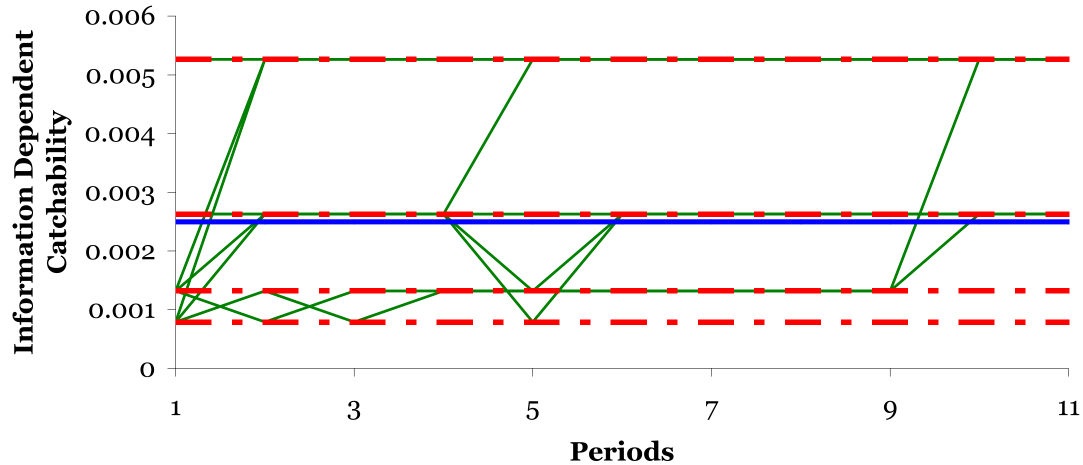
In the next period, the fisherman decides to go to the location that he believes has the highest mean. Upon arriving at that particular location, he receives another signal. We ran a simulation in which we contrasted two fleets of fishermen. One fleet shared information: at the end of each period, each individual Bayesian updated based on all four signals received by all members of the fleet. The other fleet did not share information: at the end of each period they updated based on their own private signal and an inference of what signals the other group members must have received. The simulation ran for a hundred periods. To create a strong informational cascade effect, the inference rule used was that observation of another fishermen at location *i* was equivalent to receiving a signal S_i=100 for that location.[4] The results of the simulations are shown in figure 1. Catchability for the non-information sharing group is shown as a dotted red line. This does not change over time since all fishermen start with the same priors thus these priors are repeatedly reinforced by the other three fishermen. For example, if a fisherman's prior beliefs direct him to the worst location, the patch with 15 units, he will receive a signal that stock abundance is extremely low at this location. However, when he Bayesian updates, his private signal about stock abundance is outweighed by the fact that he observes three other fishermen at the same location and infer that they must be receiving good signals. In other words,

[4] This is perhaps an excessive assumption but it aids the exposition. A weaker assumption would be that fishermen initially update on the actions of other fishermen but then realize that they are caught in a cascade and update solely on their own signals. Ultimately, stock abundances, prior beliefs and the number of fishermen in a fleet can be altered to either guarantee that a cascade will occur or to guarantee that a cascade will not occur. We are interested in fleet dynamics when cascades are possible thus we "rig" our inference rule to guarantee herding behavior.

since there are three other boats at the worst location he thinks that there must be good abundance here and he is simply having bad luck.

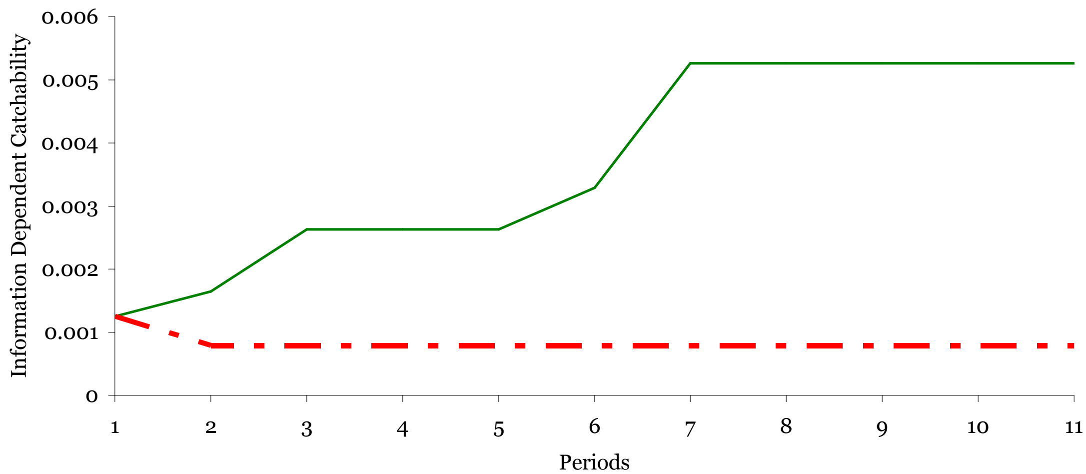
The information sharing group, on the other hand, quickly discovers either the best or the second-best location and stays there. Thus, by the 11^{th} period, their information-dependent catchability is either the highest or the second highest possible. The blue line represents the information-dependent catchability with a Gordon-Schaefer model uniform effort distribution. One of the most interesting observations is that information sharing, after 11 periods, always outperforms randomly distributed effort but that not sharing information can frequently do *worse* than random effort. This is precisely because of the cascade effect: a fisherman's private information from going fishing is essentially swamped by the information he infers from observing other fishermen's actions and he never learns anything about the true stock abundance. This result is obviously sensitive to the initial starting conditions: cascades are more likely when there are many fishermen and one good location combined with many terrible locations but less likely when there are few fishermen and locations are roughly comparable. Nevertheless, allowing for informational cascade or herd behavior amongst rational searchers can lead to effort allocations that are permanently worse than randomly assigned effort.

Figure 1: Simulation Results



Consider, finally, a simulation in which the fishermen start with different priors. Suppose that three fishermen start with the worst possible prior beliefs: they all believe that the worst location is actually the best, the second worst is actually the second best and so on. The remaining fisherman has more accurate prior beliefs but they are not ideal: he correctly believes that the two worst locations are in fact the two worst locations but he incorrectly believes that the second-best location is the best location. Is his better prior information enough to drag his three blissfully ignorant colleagues to the better fishing grounds? Results are shown in figure 2 where again green represents the information-sharing group's q_{info} over time and the red dashed line represents the non-information sharing group. The simulation was run for a hundred periods but we show the first 11 as nothing changes after period 7.

Figure 2: Fishermen have different priors



The two fleets initially start with the same level of information-dependent catchability (since all agents make their first decision based purely on their private information) but a divergence quickly emerges. It's clear to see that when fishermen share information, the better-informed fisherman discovers the best location and quickly leads the herd of three to it. Now, when the fishermen don't share information, the herd of three essentially drags the other fishermen to the worst location and their q_{info} has the lowest value possible. Their effort allocation is highly inefficient and they remain permanently at the worst location.

The take-home message is that the difference between sharing and not sharing spatial information is not that non-sharers receive fewer signals about the state of the world. This is undoubtedly true but the key difference is that, because of informational cascades, non-sharers may get permanently stuck at bad locations whereas sharers will nearly always find the best locations.[5] Defining *m*, the number of fishermen, as the *time-scale of learning* and *n*, the number of periods for which a population remains in the same location, as the *time-scale of movement,* we formulate the following proposition:

Proposition (The Importance of Cascades). *If the* time-scale of learning *is sufficiently large relative to the* time-scale of movement*, the information sharers' priors will almost surely converge on the true stock level for each location they visit. The non-sharers' priors will not almost surely converge on the true stock levels.*

A pair of related examples should illustrate the intuition behind why the non-sharers' ability to converge on the true stock levels depends on the relative time-scales. In both examples, the fishermen do not share information with each other but can observe every action that comes before them, there is one population of fish that randomly moves every *n* periods and there are two possible locations but all fishermen start out indifferent between the two. Each fisherman has the same Bernoulli distributed priors over both locations and each time a fisherman goes fishing, he receives a signal that is binary (absence or presence of fish) and is correct with probability $p>\frac{1}{2}$.

[5] Unless the entire fleet starts with identical and grossly incorrect priors.

Example 1: The *time-scale of learning* is large, $m<\infty$, whilst the *time-scale of movement* is small, $n=2$. In even-numbered periods, the probability that every single fishermen goes to the location with no fish present is equal to:

$$\frac{(p-2)(p-1)}{2}$$

which is simply the probability of an incorrect informational cascade starting on the third fishermen in an even-numbered period.

Notice how the probability of an incorrect informational cascade in Example 1 does not decline over time. The stock is moving so often and the fleet is so large means that fishermen must firstly abandon their privately accumulated information every two periods (since it is worthless) and, secondly, try to infer information from observing their many colleagues. There is not enough time in this setting for a fishermen to accumulate enough private information to overcome an incorrect informational cascade, thus his priors will never almost surely converge on the true distribution of the stock.

Example 2: The *time-scale of learning* is small, $m=1$, whilst the *time-scale of movement* is large, $n=\infty$. The sole fisherman will almost surely find the location with fish.

Since there is only one fisherman, he will never be dragged into an informational cascade. Furthermore, the stock does not move. As the number of signals received tends to infinity, his priors will converge on the true distribution of the stock. Hopefully it is now clear that sharing information is important and, *ceteris paribus*, information-dependent catchability will be higher if fishermen share information. This will become an important assumption later on in the paper.

IV. Nesting information-sharing within a Gordon-Schaefer Model

A. The Tragedy of the Commons

The standard "tragedy of the commons" (see Gordon, 1954 and Hardin, 1968) occurs in fisheries where fishermen, acting in their own self interest, continue to enter the fishery or expand effort as long as average revenues are greater than the marginal cost of expanding effort. To demonstrate, we define Total Revenue as the price of each fish, p, multiplied by the quantity of fish harvested, H, then, assuming homogeneity in fish quality, Total Revenue in period t is given by:

$$TR_t = pH_t .$$

In the Gordon-Schaefer model, harvest is defined as the catchability coefficient, q, multiplied by the effort exerted by the fishing fleet, E, multiplied but the fish stock, X. Therefore, Total Revenue in period t can be reformulated as:

$$TR_t = p(qE_t X_t).$$

This system will come to a long-run steady-state or equilibrium when the growth rate of the population is zero. One of the simplest and best known growth functions is the logistic growth function:

$$F(X_t) = rX_t\left(1 - \frac{X_t}{K}\right)$$

where *r* is the intrinsic growth rate and *K* is the environmental carrying capacity. Long run steady-state occurs at the point where the natural growth rate of the population equals the mortality rate from fishing, in other words, when harvest equals growth:

$$H = rX\left(1 - \frac{X}{K}\right)$$

We have removed the time subscripts to indicate that we are now in steady state. Solving for the steady state fish population size gives:

$$qEX = rX\left(1 - \frac{X}{K}\right)$$

$$X = \left(1 - \frac{qE}{r}\right)K .$$

Therefore, steady state Total Revenue is given by:

$$TR = pqE\left(1-\frac{qE}{r}\right)K = pqEK - \frac{pq^2E^2K}{r}$$

Without loss of generality, set p=1. Average Revenue is then given by Total Revenue divided by Effort:

$$AR = qK - \frac{q^2EK}{r}.$$

Effort will continue to expand until Marginal Cost, which is assumed to be a constant, c, equals Average Revenue:

$$MC = AR$$

$$c = qK - \frac{q^2EK}{r}$$

$$q - q^2\frac{E}{r} = \frac{c}{K}$$

which gives us the steady-state effort level under Open Access (OA):

$$E_{OA} = \frac{r}{q^2}\left(q - \frac{c}{K}\right)$$

On the other hand, the optimal steady-state effort level, from a rents-seeking perspective, is at the point where Marginal Revenue equals Marginal Cost. In the fisheries literature this policy is often referred to as the "Sole Owner" outcome, implying that a property right has been established over the fishery and a benevolent sole owner is optimally directing the fishing fleet. Sole ownership is not a necessary condition for the optimal policy; it could also be achieved by cooperation amongst the existing fleet through enforceable contracts, entry barriers or pooling harvest. Irrespective, the optimal steady-state effort level is derived as follows:

$$MR = \frac{\partial TR}{\partial E} = qK - \frac{2q^2 EK}{r}$$

Setting Marginal Revenue equal to Marginal Cost:

$$qK - \frac{2q^2 EK}{r} = c$$

Solving in terms of E gives the steady-state effort level under a fishing cooperative or Sole Owner setting (SO):

$$E_{SO} = \frac{1}{2}\frac{r}{q^2}\left(q - \frac{c}{K}\right)$$

As can be seen, the Gordon-Schaefer model predicts that if a property right is established over a fishery, the optimal rent-maximizing policy will be to significantly reduce fishing effort. In fact, with the functional forms used in this example, effort is twice as large under open access. Within this framework, the rents associated with establishing property rights over an open access resource are all derived from a reduction in effort.

B. The Nested Model

We now nest the earlier results on information-dependent catchability within a standard Gordon-Schaefer model. This nested model allows for fishermen to share or withhold information from each other, dependent on the incentive structure. At one extreme of the spectrum of information-sharing would be a competitive open access fishery where stocks are sedentary but their location is stochastic and difficult to observe (examples from the field would include most invertebrate species such as urchins, sea cucumbers and lobsters as well as sessile benthic species like most species of rockfish). Fishermen in these fisheries have no incentive to share information but high incentives to observe the spatial behavior of other fishermen. At the other extreme is fishery over which a fleet has established a property right and the fleet itself is highly cooperative, sharing information freely.

Assumption 1. *The* time-scale of learning *is large relative to the* time scale of movement.

Assumption 2. *Fishermen in a fishery with established property rights have an institutional incentive to share information. Fishermen in an open access fishery do not. Thus,*

$$q_{info}^{SO} \equiv q_{SO} > q_{info}^{OA} \equiv q_{OA}.$$

We replace the standard catchability coefficient with our newly defined information-dependent catchability to reflect the differences in catchability between a fleet that shares information and one that does not. Steady-state effort under the two settings is now defined as:

$$E_{OA} = \frac{r}{q_{OA}^2}\left(q_{OA} - \frac{c}{K}\right)$$

$$E_{SO} = \frac{1}{2}\frac{r}{q_{SO}^2}\left(q_{SO} - \frac{c}{K}\right)$$

Incorporating information-sharing in this relatively straightforward fashion leads to a number of interesting predictions. The first prediction is that establishing a property right over a fishery may have no effect on steady-state effort levels.

Proposition (Equal or Greater Effort). *When catchability under open access and sole owner are related as follows:*

$$2(q_{SO})^2\left(q_{OA}-\frac{c}{K}\right)\le (q_{OA})^2\left(q_{SO}-\frac{c}{K}\right)$$

$$\text{where } q_{OA}\le \frac{2c}{K} \text{ and } q_{SO} > q_{OA} > 0$$

then the long run effort level under a Sole Owner setting will be greater than or equal to the long run effort level under Open Access.

It is therefore possible that total effort in a fishery will be unaffected by establishing a property right over the fishery. In thinking of a story to explain this result, think of a species that is hard to find and extremely costly to harvest. Yellowfin tuna is a fairly good example. A fleet that does not share information is so inefficient in searching that the average revenue it can extract from an additional unit of effort rapidly falls below the Marginal Cost of that effort. The information-sharing fleet, on the other hand, is so efficient at searching that even though it pursues the optimal policy, the marginal revenue of its effort is so much higher that it maintains effort at or above the level of the non-sharing fleet.
Another interesting prediction concerns total harvest levels:

Proposition (Equal Harvest). *When catchability under open access and sole owner are related as follows:*

$$4q_{OA}q_{SO}^{2}\left(q_{OA}-\frac{c}{K}\right)-4q_{SO}^{2}\left(q_{OA}-\frac{c}{K}\right)^{2}=2q_{OA}^{2}q_{SO}\left(q_{SO}-\frac{c}{K}\right)-q_{OA}^{2}\left(q_{SO}-\frac{c}{K}\right)^{2}$$

where $q_{SO}>q_{OA}>0$

then the long run harvest level will be unaffected by establishing a property right over a fishing ground.

The motivation behind this result is that the Open Access fleet exerts significantly more effort but their searching is so inefficient and hence their information-dependent catchability is so low that they end up harvesting the same amount as the Sole Owner fleet.

If we are concerned with the conservation of natural resources, it may be pertinent to know if the information-sharing effect could ever be so strong that establishing a property right over a fishery makes no difference to the steady-state population levels.

Proposition (Equal or Smaller Steady State Stock). *When catchability under open access and sole owner are related as follows:*

$$2(q_{SO})\left(q_{OA}-\frac{c}{K}\right)\leq(q_{OA})\left(q_{SO}-\frac{c}{K}\right)$$

$$\textit{where } q_{OA} \leq \frac{2c}{K}$$

then the long run stock level under a Sole Owner setting will be less than or equal to the long run stock level under Open Access.

In essence what is driving this surprising result is that sustainable cost is so much higher under open access that the fishermen essentially give up fishing at an equilibrium effort level that is below the maximum sustainable yield level. Information-sharing, induced by the change in management, significantly reduces that cost through improved search efficiency. The sole owner fleet can now afford to expand effort whilst still maximizing rents and it is this expansion in fishing effort that drives the equilibrium stock level down. From a stock conservation perspective, there is no benefit to establishing a property right over the fishery.

C. Information Sharing Rents

Allowing for differences in catchability based on information sharing introduces the concepts of *Information Sharing Rents* and *Property Rights Rents*.

Definition (Information Sharing Rents). *Information Sharing Rents are defined in the nested Gordon-Schaefer model as the difference between Total*

Revenue when rents are being maximized and information is shared and Total Revenue when rents are being maximized and information is not shared:

$$ISR = TR_{SO}^{MR=MC} - TR_{OA}^{MR=MC}$$

which is equivalent to:

$$ISR = \frac{c^2}{4K^2}\left((q_{OA})^{-2} - (q_{SO})^{-2}\right).$$

Definition (Property Rights Rents). *Property Rights Rents are defined in the nested Gordon-Schaefer model as the difference between Total Revenue when rents are being maximized and information is not shared and Total Revenue when there is open access to the fishery and information is not shared:*

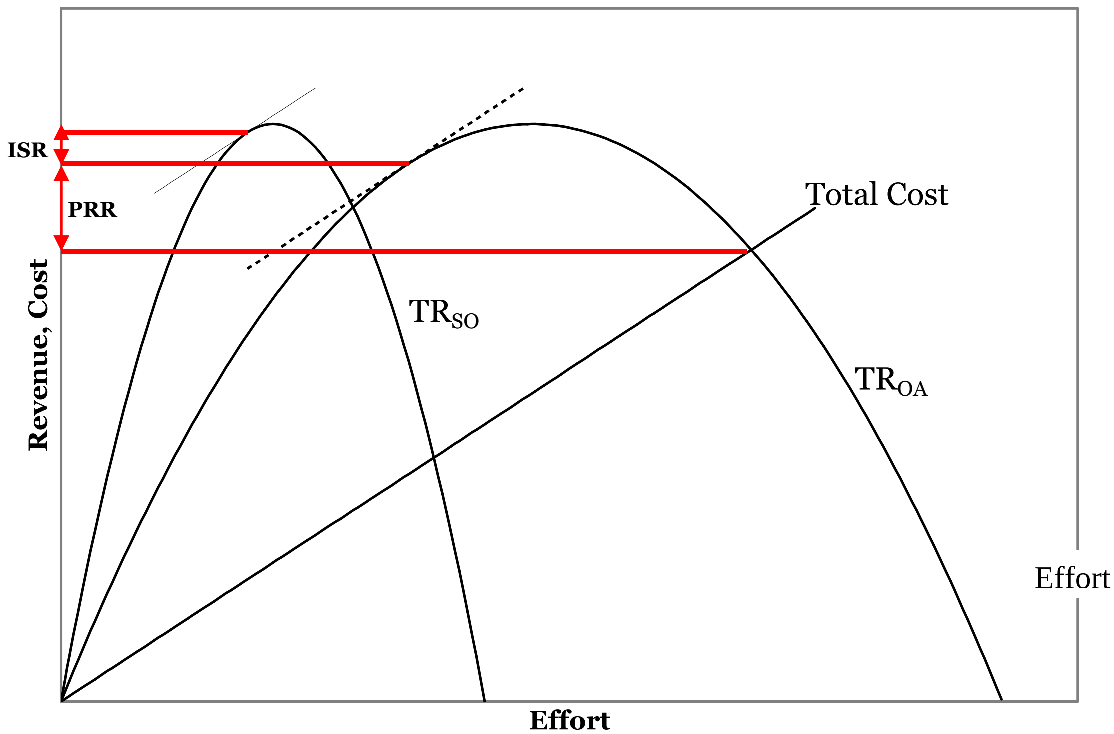
$$PRR = TR_{OA}^{MR=MC} - TR_{OA}^{AR=MC}$$

which is equivalent to:

$$PRR = \frac{1}{4} - \frac{c}{K}(q_{OA})^{-1} + \frac{3c^2}{4K^2}(q_{OA})^{-2}.$$

These two concepts are demonstrated in figure 3, where ISR represents the Information Sharing Rents and PRR denotes the Property Rights Rents.

Figure 3. Information Sharing Rents vs. Property Right Rents



Information Sharing Rents can be thought of as the rents that result from creating incentives to share information by establishing a property right over a common property resource. Property Rights Rents are the standard rents found in the natural resource economics literature; they are the rents accruing from agents coordinating to set Marginal Revenue equal to Marginal Cost instead of Average Revenue equal to Marginal Cost.

Proposition (Concavity of ISR). *Information Sharing Rents (ISR) will be present in any fishery in which information-dependent catchability is improved* *by sharing information. Furthermore, these rents will be a concave function of the Sole Owner's information-dependent catchability,* ceteris paribus.

Figure 4. Concavity of Information Sharing Rents

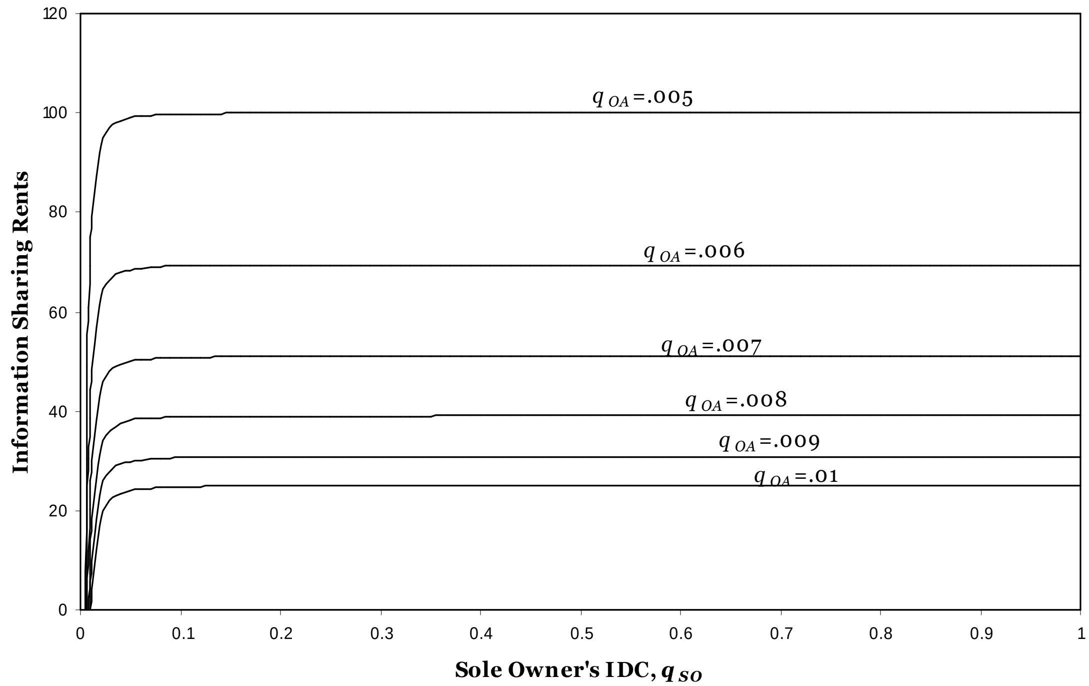


Figure 4 is drawn with c=10 and K=100.

Thus, we expect Information Sharing Rents to be large in fisheries where sharing information significantly improves the efficiency of search and small in fisheries where sharing information is not that helpful. Some examples of oceanographic and biological characteristics that might influence the size of Information Sharing Rents are presented in table 1.

Table 1: Oceanographic and Biological Determinants of ISR

Larval dispersal	***Adult Life History***	***Environmental Variability***	***Relative Magnitude of Information Sharing Rents***
Stochastic	-	-	Large
Density-dependent	-	-	Small
Sink-Source			Small
-	*Pelagic*	-	Large
	Benthic		Small
-	*Sessile*	-	Small
-	-	*Interannual*	Small
-	-	*Seasonal*	Large

D. The Importance of Information Sharing For Fisheries Management

Suppose that a fishery manager decides to use a Total Allowable Catch or Individual Transferable Quota (ITQ) policy in a fishery to overcome the tragedy of the commons. The natural way to do this is to work out the steady harvest that maximizes rents in the fishery and then either declare that harvest as the Total Allowable Catch or divide it up in to ITQs that are then distributed amongst fishermen. A pertinent question to ask is what happens if the change in management induces fishermen to share information but the manager does not take this effect into account?

Proposition (Quotas). *A manager that ignores the impact of a quotas policy on incentives to share information will always set quotas too low.*

The intuition behind this result is that the optimal steady state harvest level is strictly increasing in information-dependent catchability. Thus, any quota policy that induces an increase in information-dependent catchability but ignores this effect could actually increase rents even further by raising the quota.

V. An example of Information Sharing Rents: the Shinminato *Shiroebi* shrimp fishery

The ideal field observations to test the predictions of the theory presented in this paper would have information sharing and no information sharing occurring in the same fishery, under identical environmental conditions with the same gear type. Surprisingly, such a fishery exists in Japan. *Shiroebi* shrimp fishing in Shinminato, Japan provides an ideal microcosm for demonstrating the effect that information sharing can have on a fishery.

The fishermen who catch *shiroebi* in the bay near Shinminato are organized into two groups. The members of the two groups live in Shinminato, belong to the same local Fishery Cooperative Association, use the exact same harbor facilities and operate in the same fishery. However, there are four major differences between these groups: their history in *shiroebi* fishing, whether or not they pool their catch, whether or not they share information about the location of shrimp and their social preferences for cooperation. One group, the "sharers", has been fishing *shiroebi* for generations, they pool their catch and gear expenses, share information amongst each other about where stocks are located and exhibit social preferences for cooperation. The second group, the "non-sharers", began *shiroebi* fishing in 1992, they do not pool their catch or expenses, they do not share information and they do not exhibit social preferences for cooperation (Carpenter and Seki, 2005).

For thirty years, the sharers were the only *shiroebi* fishermen operating in Shinminato. Declining stocks and markets in other fisheries led to the entry of the non-sharers in 1992. An arrangement was agreed to under which the non-sharers were allowed to fish *shiroebi* on Tuesdays, Thursdays and Saturdays during the main season while the poolers limited themselves to fishing on Mondays, Wednesdays and Fridays. When a boat in the information sharing group identifies a promising area, this information is exchanged by radio with all the other boats in the group. There is no such cooperation among the non-information sharing boats who actually take measures to conceal information about favorable fishing spots (Carpenter and Seki, 2005).

The sharers' coordination and information exchange seems to yield productivity gains. In terms of their fishing effectiveness, sharers tend to catch more than non-sharers. This difference was first recognized in Platteau and Seki (1998) and was confirmed almost five years later in Carpenter and Seki (2005).

Interestingly, there is no indication that sharers exert less effort, in fact they exert slightly more as can be seen in table 2. This higher effort level accords with Proposition (Equal or Greater Effort) and would be hard to explain under a Gordon-Schaefer model that ignored the impact of information-sharing. An important caveat is that the standard incentive to reduce effort is weaker than if the cooperative group had a complete property right over the fishery since it has to share the fishing grounds with the non-sharers.

Table 2: Effort in the *Shiroebi* Fishery

Average Number of Hauls per fishing day		
	Sharers	**Non-Sharers**
Boat 1	3.83	3.36
Boat 2	3.78	3.38
Boat 3	3.78	3.36
Boat 4	3.78	3.23
Boat 5	3.83	3.70
Boat 6	3.78	-
Boat 7	3.57	-

Source: Platteau and Seki, 2000

Previous research (Carpenter and Seki, 2005) provides a compelling test of both Proposition (Equal or Greater Effort) and Proposition (Concavity of ISR): if effort levels are roughly equal between a cooperative fishing fleet that shares information and one that does not then the rents accruing to the cooperative fleet are largely composed of Information Sharing Rents. In a Tobit regression of a boat's harvest on skipper experience, crew experience, boat speed and a dummy variable for whether or not that boat is a member of the information-sharing group, the results in table 3 are obtained.[6]

Table 3. Information Sharing and Harvest

Dependent variable is standardized number of kilos caught per trip	
Skipper's Experience	0.973 [0.438]**
Skipper Experience^2	-0.830 [0.455]*
Crew experience	0.138 [0.119]
Boat Horse Power	0.384 [0.144]***
Catch and Information Sharing Dummy Variable	0.404 [0.151]***
Observations	115

Results are coefficients from a Tobit regression with fishing week fixed effects. Standardized regression coefficients reported in parentheses. *** indicates statistically significant at 1%, ** at 5% and * at 10%.

Source: Carpenter and Seki, 2005.

[6] A Tobit regression is used since some boats return to port without any fish. The Tobit regression also included week fixed effects to control for weather and market demand effects.

This estimation suggests that sharers typically catch 0.4 standard deviations (30 kilograms) more per trip than non-sharers and this difference is significant at the 1% level. This is fairly strong evidence that the rents associated with cooperation and coordination are, at least partially, a consequence of information-sharing. Granted, this is not as clean a test as might be hoped for but the direction and strength of the information sharing effect should go some way in highlighting the importance that it can play in a pelagic species fishery.[7]

In summary, the sharing group has institutionalized the pooling of their harvest. This institutional structure creates strong incentives to share information. The sharing of information at least partially explains the extra rents accruing to the sharers for the same effort as the non-sharers.

VI. Discussion

The point of this paper is that information sharing matters. It matters especially for common property resources with uncertainty about where the resource is located spatially. We have demonstrated that allowing for information sharing can substantially alter the predictions of the most well-known fisheries economics model. The purpose was not to critique the Gordon-Schaefer model but to highlight the importance of thinking about information-sharing when

[7] It should be noted that when Carpenter and Seki (2005) include variables for the social preferences of each boat that the direct effect of each social preference they examine is significant and the interactions of social preference and pooling soak up some of the variance in productivity that is attributed to the sharing indicator in Table 3.

considering optimal policies for managing a natural resource whose location is not known with certainty. Institutions change the incentives to share information. Information sharing changes outcomes. This knock-on effect is rarely considered in the debate over institutional change in fisheries management, but it should be (for a global meta-analysis of institutions and incentives in fisheries management see Hilborn et al., 2005). The Shinminato *shiroebi* fishery was used as an example to demonstrate how a model that incorporates information sharing better predicts outcomes in this fishery and to validate the existence of Information Sharing Rents. We have focused on a fishery in this paper but the results could be generalized to many renewable resources and possibly non-renewable resources whose spatial location is uncertain.

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Appendix

A. Proof of Proposition (The Importance of Cascades)

Proof. Let there be two fleets of Bayesian updaters, the sharers and the non-sharers, with identical numbers of agents in each.

Definition. *All agents in the two groups start with the same normally distributed prior,* $X \sim N(\mu_x, \sigma_x^2)$.

Let $S_1, \ldots, S_n$ be a sequence of independently and identically normally distributed signals drawn from a distribution with mean μ_s and variance σ_s^2. Each agent in both fleets is sequentially numbered and receives a signal from the sequence according to his or her number. For example, if there are five agents in a fleet there will be one agent numbered 1, one agent numbered two and so on. Agent i will receive signals $S_i, S_{i+5}, S_{i+10}, \ldots, S_{i+5j}, \ldots, S_n^i$

Definition. *The* time-scale of movement *is n, which is the total number of signals received before a stock randomly moves to a new location.*

Definition. *One season is the length of time it takes to receive n signals.*

Definition. *The time-scale of learning is m, which is the number of fishermen in the fleet.*

Signals take the form:

$$S_i = X_k + \varepsilon, \qquad \varepsilon \sim N(0, \sigma_s^2)$$

where X_k is the true stock abundance.

X_k changes each season such that $\mathrm{Cov}(X_k, X_{k+j})=0$ for all j.

Assumption. *m is greater than the square root of n.*

Assumption. For each n the variance of S_n is finite and

$$\sum_{n=1}^{\infty} \frac{Var(S_n)}{n^2} < \infty .$$

The sharers update on all signals. By Kolmogorov's Strong Law of Large Numbers (Feller, 1968), the sample mean of the sharers' signals almost surely converges on the true mean as the number of signals within a season approaches infinity:

$$P\left(\lim_{n\to\infty} \overline{S}_n = X_k\right) = 1 .$$

Thus, the sample mean of all signals for all agents in the sharer fleet almost surely converges on the true mean signal.

Now allow for the possibility of incorrect informational cascades. There is a small but positive probability that all fishermen will get caught in a cascade on a belief that is bounded away from the true population mean. Define S^* as identical to the previous sequence $S_1, \ldots, S_n$ except that for all S after S_j, $S_i = S_i^*$ where S_i^* is the signal that an agent receives once they are caught in an incorrect cascade. S_i^* is bounded away from X_k such that:

$$E(S_i^*) = X_k^* \neq X_k .$$

For any S^* in which a cascade occurs and is permanent, i.e. $j<n<m^2$:

$$P\left(\lim_{n\to\infty} \overline{S}_n = X_k\right) < 1.$$

Thus, the sample mean of all signals for all agents in the non-sharer fleet will not almost surely converge on the true mean signal.

Q.E.D.

B. Proof of Proposition (Concavity of ISR).

Proof. The first sentence in the proposition is trivial to prove. Let $q_{SO}=kq_{OA}$ where $k>1$ and substitute appropriately. For the second sentence, ISR are defined to be Total Revenue under the Sole Owner outcome and information sharing minus Total Revenue under the Sole Owner outcome and no information sharing:

$$ISR \equiv \frac{1}{2q_{SO}}\left(q_{SO} - \frac{c}{K}\right)\left[1 - \frac{1}{2q_{SO}}\left(q_{SO} - \frac{c}{K}\right)\right] - \frac{1}{2q_{OA}}\left(q_{OA} - \frac{c}{K}\right)\left[1 - \frac{1}{2q_{OA}}\left(q_{OA} - \frac{c}{K}\right)\right]$$

$$\frac{\partial ISR}{\partial q_{SO}} = \frac{c^2}{2K^2} q_{SO}^{-3} > 0$$

$$\frac{\partial^2 ISR}{\partial q_{SO}^2} = -\frac{3c^2}{2K^2} q_{SO}^{-4} < 0$$

Q. E. D.

C. Proof of Proposition (Quotas).

Proof. Define H* as the rent-maximizing steady state harvest level. This is equivalent to the rent maximizing total quota. Define E* and X* as the corresponding Effort and Stock levels.

$$H^* \equiv qE^* X^*$$

Substitution yields:

$$H^* = \frac{1}{4} - \frac{c^2}{4q^2K^2}$$

Since

$$\frac{\partial H^*}{\partial q} = \frac{c^2}{2q^3K^2} > 0$$

the optimal quota level is always increasing in q. Therefore, any quota policy that induces information-sharing (interpreted as an increase in q) but ignores the possibility of this effect will be below the true rent-maximizing quota level.

Q. E. D.