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A Model of Fishery Harvests with a Voluntary Co-op

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Abstract

We present a preliminary model of the within-season behavior of a fishery regulated by a total allowable catch constraint and season closure. An individual's catch depends on where he/she deploys effort and on the effort deployment decisions of other harvesters such that catch per unit effort is greater when effort is deployed before others have contacted the stock. Individual harvesters are allowed, voluntarily, to join a profit sharing co-operative that is allocated a share of the TAC commensurate with its effort capacity. The co-op centrally allocates the effort deployment decisions of all members. Non-joiners fish independently. We find that the co-op will coordinate effort in order to: fish the maximum amount of time the stock is available, concentrate effort among its most efficient members and harvest at the closest feasible distance to port. All independent harvesters will deploy effort at the maximum feasible rate until its TAC share is filled and will deploy effort at the maximum distance that yields positive profit. Harvesters joining the co-op will be the least efficient operators in the fishery.

Keywords: fishery regulation, fishery co-operatives, Nash equilibrium
JEL classifications: Q22, Q20, Q28

1 Preliminary discussion

We begin with an intuitive description of the situation specified by the model developed

in this paper. A stock of fish of size Z becomes available during the year. A regulator

seeks to attain a percentage escapement target for the stock, $(1-\alpha)Z$, and does so by

imposing a fishery closure at an appropriate time. The stock migrates toward the port and

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the cost of catching it falls as the distance to port shrinks. There is a discrete set of fishing zones and the stock spends 1 unit of time in each zone. An individual fisherman can harvest from only one zone. Harvesters differ in two respects: they have different skill levels, which cause differences in cost per unit effort, and they differ in the rate at which they can apply effort. The effort rate is called fishing efficiency. Both of these differences are represented by parameters specific to individual harvesters. For a given harvester, the total effort applied is the product of the effort rate and time spent fishing. The individual harvester's catch is determined by his total effort and the effort of others.

Each harvester can determine whether or not to join a co-op. The regulator partitions the fishery between the co-op and the independent fleet by assigning each group rights to fish a portion of the stock—with the objective of attaining a division that is 'fair' in some sense. We assume that the portion of Z assigned to a given group is proportional to the numbers of vessels weighted by their efficiency. Those who do not join the co-op choose the distance at which to fish and time spent fishing individually, subject to what the regulator does. The regulator closes the fishery to a particular group when the escapement target for that group's portion of the stock has been met. (We assume that each group's harvest capacity is more than sufficient to harvest the TAC for a given stock while the stock is in a single distance zone, i.e., during 1 unit of time. Effectively, each group is assumed to be over-capitalized.) Assuming a condition on the distribution of effort parameters and the maximum outside distance, derived in the text, is satisfied, each non-joiner will fish at the maximum distance and for the maximum amount of time permitted by the regulator. Assuming the fishery is over-capitalized, the

regulator will close the fishery 'early', i.e., before the 1 unit of time the stock spends in the zone being fished, to meet the TAC constraint.

For the group that does join the co-op, distance and effort levels are chosen by the co-op to minimize the co-op's total cost for catching its TAC. The co-op also deploys its effort as close to port as possible. Also, the co-op stretches the time spent fishing out as long as possible, i.e., to 1 unit of time, in order to concentrate effort among its most efficient harvesters. This is true despite the co-op's fleets over-capitalization. Under certain circumstances spelled out in the analysis of the decision to join the co-op, the co-op consists of vessels with the highest cost parameters among licensed harvesters.

2   Model

A stock of fish of size Z becomes available during the year; its size is independent of prior harvests. K harvesters, indexed by the subscript i, are licensed to harvest this stock.[1] Harvesters differ in the rate at which they are able to apply effort; the rate at which i can apply effort is denoted γ_i and is called i's fishing efficiency. The product of γ_i and the time i spends fishing, T_i, equals the total effort harvester i applies toward harvesting the stock.

During the season the stock migrates toward a port where fishing vessels are based and processing facilities are located and becomes more concentrated as it comes nearer. Distances are lumped into zones and the stock is assumed to spend 1 unit of time in each zone. For any harvester, the cost of applying a unit of effort falls as the stock approaches port due to reduced costs for travel and search. Harvesters' costs also depend

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[1] Throughout, we treat the number of fishermen as continuous.

on individual skill, which varies among harvesters. Cost per unit effort thus depends on two determinants, skill and distance zone, and their influence is assumed to be additive. Firm i's total cost is written

$$c_i = (\alpha_i + d_i)\gamma_i T_i. \qquad (1)$$

The parameter α_i is a direct measure of cost (an inverse measure of skill); d_i is the distance zone in which i fishes, which also indicates the distance-related cost. By convention, firms are indexed by order of the cost parameter α_i, with $i=1$ being the lowest cost harvester, and so forth. We assume the cost of fishing in the closest feasible zone is 0 and the cost of fishing in the farthest distance zone is $\overline{d}$. The feasible distance zones are enumerated as $\{0, d^1,...,\overline{d}\}$. The price of fish is normalized to unity.

Applying 1 unit of effort (e.g., $\gamma_i T_i = 1$ for 1 harvester) captures the fraction $\theta > 0$ of the available stock and the fraction $(1-\theta)$ escapes. The fraction of the initial stock escaping if E units of effort are applied is therefore $(1-\theta)^E$ and the fraction that is caught equals $1 - (1-\theta)^E$. The regulator seeks to achieve an escapement target of $(1-\alpha)Z$ for the total stock, implying that the TAC equals αZ. The regulator achieves this target by closing the fishery.

Because the stock migrates toward port, those who deploy their gear further from port encounter larger stocks. Given the effort deployment choices of others, a given harvester's catch is therefore greater if he/she deploys effort at greater distances from

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port. If more than 1 unit of effort is deployed at the same distance, each effort unit is assumed catch an equal number of fish.[2]

Before fishing starts harvesters are allowed to join a co-operative organization that will coordinate their effort during the season, as specified below. Joining the co-op is voluntary. The sets of non-joiners and joiners, which are determined endogenously, are denoted I (independent) and J (joiners), respectively, and $I + J = K$. The regulator assigns separate portions of the stock and specifies separate TACs for each group. The partitioning is 'fair' in the sense that each group is assigned a portion of the stock that is proportional to the group's aggregate effort capacity. Aggregate effort capacities are denoted $E_I = \sum_{j \in I} \gamma_j$ for group I and $E_J = \sum_{j \in J} \gamma_j$ for group J. The sub-stocks assigned to groups I and J are of size $Z_I = \dfrac{E_I}{E_I + E_J} Z$ and $Z_J = \dfrac{E_J}{E_I + E_J} Z$, respectively, and their TACs are αZ_I and αZ_J.

Those who join the co-op share profits equally. The co-op decides by majority rule the distance at which each member will deploy effort and the time each member will spend fishing. These decisions are binding on all who join. Those who do not join the co-op choose distance and time spent fishing for each run independently, taking as given the decisions of other non-joiners. Regardless of which group is fishing, the regulator allows fishing to proceed until the group's TAC is filled and then closes the fishery. We assume each group's effort capacity is sufficient to harvest its TAC while the stock is in a single

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[2] For species that do not migrate, the model can be interpreted to capture the effect of competition with respect to the date of fishing. With or without migration, the available stock, which is Z at the beginning of the season, diminishes as harvests take place. Accordingly, the harvest obtained from a unit of effort, which equals θ times the available stock, is greater if it is applied before other harvesters apply their effort. Since racing to fish in this case amounts to harvesting too early, the variable d can be interpreted as capturing the corresponding cost (Costello and Deacon 2007.)

distance zone if all of the group's members fish. To ensure that no harvester will find it infeasible to join a co-op, we assume all harvesters' costs are sufficiently low that each could earn positive profit by joining a co-op and fishing at distance 0. Fig. 1 describes the sequence of decisions for each harvester.
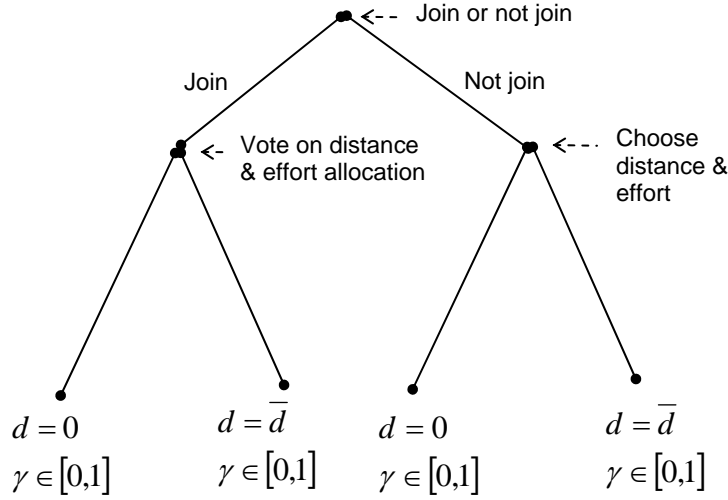

Fig. 1 Effort Deployment with Voluntary Co-op

Choice of distance and effort by co-op joiners

We proceed by backward induction and first consider the payoffs for the second stage choices of distance and effort levels. For those who join the co-op this is a voting decision.

The profit individual joiner *i* earns depends on the co-op's effort allocation and choice of distance as follows:

$$\pi_i\left(d_j, T_j, j \in J\right) = (1/J)\left\{ Z_J\left(1 - (1-\theta)^{\sum_{j \in J} \gamma_j T_j}\right) - \sum_{j \in J}\left(\alpha_j + d_j\right)\gamma_j T_j \right\}. \qquad (2)$$

In (2) J indicates both the set of joiners and the number of joiners, d_j is the distance at which member j fishes and T_j is the time j spends fishing. The regulator's TAC target constrains the co-op's total catch, the first term inside the brackets, to equal αZ_J. The co-op's profit maximizing allocation can therefore be found by solving

$$\min_{d_j, T_j} \sum_{j \in J} (\alpha_j + d_j) \gamma_j T_j \tag{3}$$

subject to the TAC constraint $1 - (1-\theta)^{\sum_{j \in J} \gamma_j T_j} = \alpha$, which can be written

$$\sum_{j \in J} \gamma_j T_j = \ln(1-\alpha) / \ln(1-\theta) \equiv \kappa. \tag{4}$$

The solution also must satisfy $d_j \in \{0, d^1, ..., \overline{d}\}$ and $0 \le T_j \le 1$ for all j. The policy that solves this problem requires setting $d_j = 0$ for each member. It also assigns positive harvest times to members with the lowest cost parameters a_j and each of these members fishes the entire 1 unit of time that the stock is available; other co-op members do not fish at all.[3] Because all members share profits, this choice is optimal for all members regardless of their skill or effort capacity. This choice is therefore unanimous and obtains a majority. The co-op's policy is described as follows:

Result 1 The co-op's policy requires that all members fish as close to port as possible, only the most efficient members apply effort and these efficient members fish the entire 1 unit of time the stock is available in zone 0.

Proof This follows from the first-order Kuhn Tucker conditions for minimizing (3) with respect to d_j and T_j, subject to (4), $d_j \in \{0, d^1, ..., \overline{d}\}$ and $0 \le T_j \le 1$ for all j.

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[3] The co-op's allocation is described by the Kuhn-Tucker conditions for minimizing (3) subject to (4) and to the conditions $d_j \in \{0, d^1, ..., \overline{d}\}$ and $1 \ge T_j \ge 0$.

Choice of distance and effort by non-joiners

We begin with a preliminary assumption: all non-joiners can earn positive profit per unit effort by fishing at the maximum distance if all other non-joiners do likewise. If this condition were not met, fishing competitively would not be the right choice at stage 1.

Suppose all non-joiners fish *outside*. To meet the non-joiners' TAC allocation the regulator must close the season when non-joiners have collectively applied $\sum_{j \in I} \gamma_j T_j = \ln(1-\alpha)/\ln(1-\theta) \equiv \kappa$ units of effort. Regardless of where non-joiner i fishes, the catch obtained is proportional to the amount of time i spends fishing. Fisherman i's cost is also proportional to T_i, by (1). Therefore i's profit is proportional to T_i and i, because profit per unit time is necessarily positive, each non-joiner will fish the entire time the fishery remains open. All non-joiners will fish for a common amount of time, T_I, determined by the regulator as a consequence of a season closure. Non-joiner i's catch is $\dfrac{\gamma_i T_I}{\kappa} Z_I \left(1 - (1-\theta)^\kappa\right)$ and i's transportation cost is $\overline{d} \gamma_i T_I$.

If non-joiner i switched to fishing *inside* at distance 0, i's catch would be $Z_I (1-(1-\theta)^{\gamma_i T_I})(1-\theta)^{\kappa - \gamma_i T_I}$ and the transportation cost would be eliminated. Substituting the approximation $(1 - (1-\theta)^{\gamma_i T_I}) \cong \gamma_i T_I \theta$, which is close when θ is small, the strategy profile in which all non-joiners fish outside at $\overline{d}$ and fish for time T_I is a Nash equilibrium if the following condition is met:

$$\max_{\gamma_i} \left\{ \frac{\left(1-(1-\theta)^\kappa\right)}{\kappa} - \theta(1-\theta)^{\kappa-\gamma_i T_I} \right\} \geq \frac{\overline{d}}{Z_I} \cdot^4 \qquad (5)$$

The bracketed term on left-hand side of (5) is proportional to the average catch per unit effort i would experience by fishing outside (and sharing the catch of all non-joiners in proportion to the effort i applies) minus the marginal catch per unit effort i would experience if he/she were to fish inside while all other non-joiners fish outside. The difference in these two quantities, average catch and marginal catch, is largest for the most effective (highest γ_i) non-joiner, which accounts for the 'max' term in (5). Condition (5) will tend to be satisfied when the non-joining group's aggregate effort is large relative to the effort of a single individual and the outside distance is relatively small. Further, if (5) is satisfied then fishing outside will also yield higher profit than fishing at any distance between 0 and $\overline{d}$.[5] We can now state:

Result 2 In the location subgame in which non-joiners can choose to fish outside at distance $\overline{d}$ or at any distance closer to port, the strategy profile in which all non-joiners fish outside and apply effort until the fishery is closed is a Nash equilibrium if (5) is satisfied.

Proof From the way condition (5) was derived, this result is true by construction.

Can the strategy profile in which all non-joiners fish inside at distance 0 ever be a Nash equilibrium? By fishing inside when all other non-joiners do the same, i realizes a catch of $\frac{\gamma_i T_I}{\kappa} Z_I\left(1-(1-\theta)^\kappa\right)$ and a transportation cost of 0. By fishing outside when all

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[4] In deriving condition (5) the cost parameter α_i, which is incurred regardless of the location fished, was cancelled from both sides of the profit comparison.
[5] This is true because fishing at an intermediate distance when all others fish outside will lead to the same reduction in catch, but will yield a smaller transportation cost saving.

others fish inside, i would realize a catch of $\gamma_i T_I Z_I \theta$ and transportation cost of $\bar{d}\gamma_i T_I$.

Fishing outside at $\bar{d}$ would yield a profit gain for i if and only if

$$\gamma_i T_I \left[\theta - \frac{\left(1 - (1-\theta)^{\kappa}\right)}{\kappa} \right] \geq \frac{\bar{d}}{Z_I}. \tag{6}$$

The strategy profile in which all non-joiners fish inside at distance 0 cannot be a Nash equilibrium to the location choice subgame if (6) is satisfied for a *single* non-joiner. Accordingly, the condition

$$\max_{\gamma_i} \gamma_i T_I Z \left\{ \theta - \frac{\left(1 - (1-\theta)^{\kappa}\right)}{\kappa} \right\} \geq \bar{d} \tag{7}$$

rules out the existence of a Nash equilibrium in which all non-joiners fish inside at distance 0. It can be shown that condition (5) implies condition (7) for $\kappa > 1$, so (5) implies that the strategy profile in which all non-joiners fish inside at distance 0 cannot be a Nash Equilibrium.[6] The same is true with greater force for any inside distance greater than 0 since moving outside results in a smaller increase in transport cost, so a strategy profile in which all independent harvesters deploy effort at any distance less than $\bar{d}$ cannot be a Nash equilibrium.

Suppose independent harvesters deploy effort at different, distinct distances. In this case, the harvester who fishes at the smallest distance, denoted d_0, will obtain a catch equal to what he/she would obtain if all others fished outside. For this minimum distance harvester, the gain in catch from moving to location $\bar{d}$ will be at least as great as the gain that would result if all other independent harvesters fished at distance $\bar{d}$ and the cost increase will be the same. Accordingly, fishing distance d_0 cannot be a best response for

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[6] This result, that (5) implies (7), has only been demonstrated numerically by grid search over values of the relevant parameters.

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any harvester and, by implication, a strategy profile in which independent harvesters deploy effort at different, distinct distances cannot be a Nash equilibrium if condition (5) is satisfied. Therefore, we can state:

Result 3 In the non-joiners' location subgame in which each can choose to fish at any distance in $\{0, d^1, ..., \bar{d}\}$, the strategy profile in which all non-joiners apply effort the entire time the fishery is open and fish outside at $\bar{d}$ is the unique Nash equilibrium if condition (5) is satisfied.[7]

Proof The proof follows from the relationship between conditions (5) and (7).

If effectiveness did not vary, the condition guaranteeing that any fisherman i cannot profit by moving inside would correspond to condition (5) without the 'max' clause. Stating (5) as a requirement on the *most efficient* non-joiner ensures that it will be satisfied for all non-joiners, so fishing outside is always a best response.

The model determines the length of the fishing season for both the co-op and for non-joiners. For the co-op the season length is 1, the maximum amount of time its portion of the stock is available to harvest. If the co-op's fleet is over-capitalized in the sense that $\sum_{j \in J} \gamma_j > \ln(1-\alpha)/\ln(1-\theta)$, then the least effective (lowest γ_i) co-op members will not fish. By contrast, all non-joiners will fish the entire time their season is open, regardless of the fleet's total capacity. If the independent fleet is over-capitalized, so $\sum_{j \in I} \gamma_j > \ln(1-\alpha)/\ln(1-\theta)$, its season must be closed before the stock migrates out of

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[7] Costello and Deacon (forthcoming) obtain a similar result for an ITQ fishery in which the economic value of catch can very over time or space.

zone $\bar{d}$ in order to meet the TAC constraint. In this case the length of its season

is $\left(\ln(1-\alpha)/\ln(1-\theta) \right) \Big/ \sum_{j \in I} \gamma_j$. We can therefore state

Result 4 The co-operative fleet operates during the entire time the stock is available, regardless of its effort capacity (E_J). If the independent fleet is over-capitalized it fishes only a fraction of the time the fish are available and the length of its season is inversely proportional to its effort capacity (E_I).

Proof The argument preceding the result establishes it.

The co-op stretches fishing out as long as possible in order to concentrate the catch among its most efficient boats. In the competitive fishery, all boats fish full time until the competitive group's share of the TAC is filled and the regulator closes the season.

The decision of whether or not to join

A harvester's decision of whether or not to join the co-op is made by comparing maximal profits under either choice. If a set J of harvesters joins, the profit earned by each joiner is

$$\pi_i \left(d_j, T_j, j \in J \right) = (1/J) \left\{ Z_J \left(1 - (1-\theta)^\kappa \right) - \sum_{j \in J_{\min}} \alpha_j \gamma_j \right\} \tag{8}$$

where the summation index $j \in J_{\min}$ means that the individual cost terms are only summed over joiners who have lowest cost, up to κ units of effort. The profit earned by those who do not join is

$$\pi_i (d_j, T_j, j \in I) = \frac{\gamma_i T_I}{\kappa} Z_I \left(1 - (1-\theta)^\kappa \right) - \bar{d} \gamma_i T_I . \tag{9}$$

Harvester i will not join the co-op if

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$$(1/J)\left\{Z_J\left(1-(1-\theta)^\kappa\right)-\sum_{j\in J_{\min}}\alpha_j\gamma_j\right\} < \frac{\gamma_i T_I}{\kappa}\left\{Z_I\left(1-(1-\theta)^\kappa\right)\right\}-(\alpha_i+\overline{d})\gamma_i T_I. \quad (10)$$

The comparison of profits for joiners and non-joiners is complicated by the variation in efficiencies across harvesters, which implies that a harvester's catch will generally be different if he/she joins the co-op versus fishing independently.

We examine the joining decision for the special case where harvester efficiencies, the γ_i, are identical. In this case all harvesters deploy identical effort due to the regulatory constraint that each sector's TAC is proportional to its aggregate effort. Consequently, the revenue component of the profit comparison for joining versus not joining is the same for either decision and the relevant comparison only involves costs. Comparing costs, any individual i will choose not to join the coop if the following condition is satisfied:

$$\beta(\overline{d}+\alpha_i) < (1/J)\sum_{j\in\beta J}\alpha_j, \quad (11)$$

where J is the number of co-op joiners and the summation on the right-hand side is over the βJ lowest cost coop members. The left-hand side is the cost i would experience as a competitive fisherman and the right-hand side is the co-op's minimized average cost, which is what i would incur by joining. If (11) is satisfied for a harvester with cost parameter α_i, it will also be satisfied for any lower cost parameter. This implies

Result 5 In the case where all harvesters have identical efficiency parameters, γ_i, the independent fleet consists of fishermen with the lowest cost parameters, α_i; those who join the co-op have the highest cost parameters.

Proof The preceding argument establishes the result.

We can characterize the factors determining the size of the co-op by rearranging (11). Recalling that the number joining equals N and that $J = K - N$, the number of non-joiners is given by the largest integer N satisfying:

$$\bar{d} < (1/\beta J) \sum_{j=N+1}^{N+\beta J} \alpha_j - \alpha_N \qquad (12)$$

The right-hand side of (12) is the average cost of the βJ lowest cost joiners minus the cost of the highest cost non-joiner. Given that the co-op consists of the highest cost fishermen, the right-hand side of (3) is necessarily positive. Further, it approaches 0 as the number of joiners approaches 0 and increases as the number of joiners increases.

3   Discussion

The analysis presented here is obviously preliminary. Future work on this problem will include providing formal proofs for the Results and an attempt to obtain definite results on the joining vs. not joining decision for the case where effort efficiencies differ across harvesters. For empirical evidence on several of the results presented here, see Deacon, Parker and Costello (2008).

4   References

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